Platinum

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Mineral profile

Definition, mineralogy and deposits

Definition and characteristics

Platinum (Pt) is one of a group of six chemical elements collectively referred to as the platinum-group elements (PGE). The other PGE are palladium (Pd), iridium (Ir), osmium (Os), rhodium (Rh) and ruthenium (Ru). Reference is also commonly made to platinum-group metals and to platinum-group minerals, both often abbreviated to PGM. In this document we use PGM to refer to platinum-group minerals.

Chemically the PGE are all very similar, but their physical properties vary considerably (Table 1). Platinum, iridium and osmium are the densest known metals, being significantly denser than gold. Platinum and palladium are highly resistant to heat and to corrosion, and are soft and ductile. Rhodium and iridium are more difficult to work, while ruthenium and osmium are hard, brittle and almost unworkable. All PGE, commonly alloyed with one another or with other metals, can act as catalysts[1] which are exploited in wide range of industrial applications. Platinum and palladium are of major commercial significance, while, of the other PGE, rhodium is the next most important. Iridium and ruthenium are traded in small quantities for use chiefly in catalysts and electronic applications. Osmium metal is little used because in powdered form it produces a toxic gas when exposed to air.

The PGE are very rare in the earth's crust. The abundance of platinum and palladium in the crust are similar, approximately 5 parts per billion (ppb), by weight. Rhodium, iridium and ruthenium are even scarcer at about 1 ppb. Relative to other rock types in the crust the PGE are enriched in ultramafic[2] lithologies, such as peridotite[3], in which platinum and palladium concentrations are commonly 10–20 ppb.

Mineralogy

In nature the PGE are chiefly held either in base-metal sulphide minerals, such as pyrrhotite, chalcopyrite and

	Pt	Pd	Rh	Ir	Ru	Os	Au
Atomic weight	195.08	106.42	102.91	192.22	101.07	190.23	196.97
Atomic number	78	46	45	77	44	76	79
Density (gcm⁻³)	21.45	12.02	12.41	22.65	12.45	22.61	19.3
Melting point (ºC)	1769	1554	1960	2443	2310	3050	1064
Electrical resistivity (micro-ohm cm at 0º C)	9.85	9.93	4.33	4.71	6.8	8.12	2.15
Hardness (Mohs)	4-4.5	4.75	5.5	6.5	6.5	7	2.5-3

Table 1 Selected properties of the six platinum-group elements (PGE) compared with gold (Au).

pentlandite, or in PGE-bearing accessory minerals (PGM). Cabri (2002) provide mineralogical and chemical data for more than 100 different PGM. Many others have been reported but most of these are poorly characterised on account of their rarity and their occurrence in very fine grains, commonly only a few microns in size. It is significant to note that some PGM are known only from one deposit and that there may be considerable variation
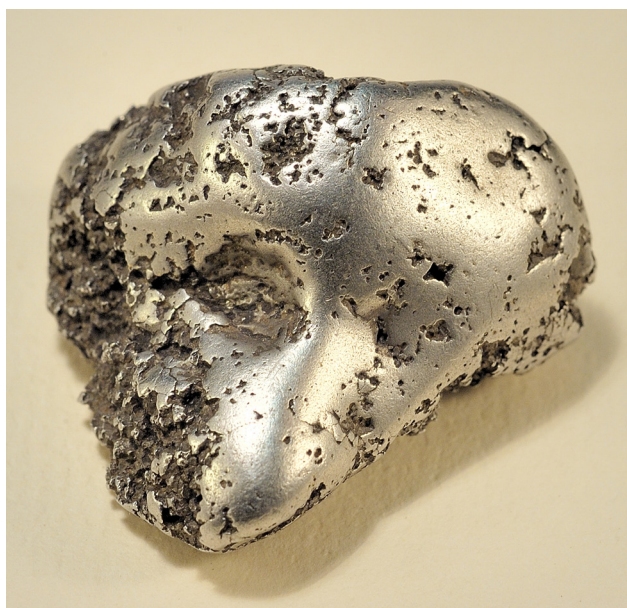
Placer platinum nugget from the Choco River, Colombia. © Museo regionale di Scienze Naturali di Torino.

[1] Catalysts are substances that cause or accelerate chemical reactions without themselves being affected.
[2] Ultramafic: composed chiefly of ferromagnesian (Fe-Mg) minerals, such as olivine and pyroxene.
[3] Peridotite: a class of ultramafic rocks consisting of predominantly olivine, with or without other ferromagnesian (Fe-Mg) minerals.

Group	Name	Formula	Group	Name	Formula
Alloys	Atokite	$(Pd,Pt)_3Sn$	**Arsenides**	Sperrylite	$PtAs_2$
	Isoferroplatinum	Pt_3Fe		Stillwaterite	Pd_8As_3
	Osmiridium	$OsIr$	**Antimonides**	Genkinite	$(Pt,Pd,Rh)_4Sb_3$
	Potarite	$PdHg$		Isomertieite	$Pd_{11}As_2Sb_2$
	Rustenburgite	$(Pt,Pd)_3Sn$		Stibiopalladinite	Pd_5Sb_2
	Tulameenite	Pt_2FeCu		Sudburyite	$(Pd,Ni)Sb$
Sulphides	Braggite	$(Pt, Pd)S$		Geversite	$Pt(Sb,Bi)_2$
	Cooperite	PtS	**Bismuthides**	Froodite	$PdBi_2$
	Erlichmanite	OsS_2	**Tellurides**	Kotulskite	$PdTe$
	Hollingworthite	$RhAsS$		Merenskyite	$(Pd,Pt)(Te,Bi)_2$
	Laurite	$(Ru,Os)S_2$		Michenerite	$Pd(Bi,Sb)Te$
	Ruarsite	$(Ru,Os)AsS$		Moncheite	$(Pt,Pd)(Te,Bi)_2$

Table 2 A selection of the more common platinum-group minerals (PGM).

in the abundance and proportions of individual PGE within a deposit or a district.

The PGE rarely occur in nature as native metal but more commonly form a wide variety of alloys with one another or with other metals, notably with iron, and less commonly with tin, copper, lead, mercury and silver. In other PGM the PGE are bonded to a variety of ligands[4] including sulphur, arsenic, antimony, tellurium and selenium. Some of the more common PGM are listed in Table 2.

Major deposit classes
Enrichment of PGE occurs in a wide variety of geological settings and accordingly PGE are derived from deposits of several types, commonly associated with nickel and copper. A map showing the distribution of selected platinum occurrences, deposits, mines and districts is shown in Figure 1. Most deposits are formed by high temperature magmatic processes and are found in mafic[5] or ultramafic igneous rocks. Magmatic[6] PGE deposits are of two principal types (Table 3): PGE-dominant deposits which are associated with sparse, dispersed sulphide mineralisation; and nickel-copper sulphide deposits in which the PGE occur in association with sulphide-rich ores. A variety of other deposit types resulting from different

processes are also known but these are of relatively minor significance in terms of PGE production (Table 4).

In simple terms PGE-sulphide deposits are derived from magmatic processes of crystallisation, differentiation[7] and concentration. The magma becomes saturated with sulphur and an immiscible[8] sulphide liquid separates from the magma as disseminated droplets. This sulphide liquid acts like a sponge scavenging the PGE from the coexisting silicate magma leading to their extreme enrichment in this sulphide liquid. An ore deposit may subsequently form if this PGE-enriched sulphide liquid accumulates in sufficient quantities at a particular location.

PGE-dominant deposits
In these deposits the PGE are the main economic components with minor by-product Ni and copper derived from sparsely disseminated (up to 5 volume per cent) sulphides, chiefly pyrrhotite, pentlandite and chalcopyrite. Although the processes responsible for the genesis of these deposits are not well understood, the importance of PGE collection by a sulphide liquid is widely accepted and the PGE are believed to have been derived from the mantle where the mafic-ultramafic host rocks were sourced.

[4] Ligand: a molecule, ion, or atom that is bonded to the central metal atom of a coordination compound.
[5] Mafic: composed of one or more ferromagnesian (iron-magnesium), dark-coloured minerals, such as olivine and pyroxene, in combination with quartz, feldspar or feldspathoid minerals.
[6] Magmatic: relating to molten material beneath or within the earth's crust, from which igneous rock is formed.
[7] Differentiation: the change in the composition of magma due to the crystallisation of minerals settling at the bottom of a magma chamber.
[8] Immiscible: referring to liquids not able to be mixed together.

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Southland

Ust-Belaya
Seniav
Kvinum

Inagli
Sukhoi Log
Udokan
Kondyor

Zambales

Coronation Hill
Sally Malay
Radio Hill
Musgrave

Munni Munni
Kambalda District

Noril'sk-Talnakh
Srednefersinskoe
Zyranovskoe
Ojut Tolgoi
Jinchuan
Dali

Urals
Kempirsai

Nuasahi

Pechenga District
Portimo
Mikailovskoe
Yastrebovskoe
Kadzharan
Skouries

Keivitsa
Penikat
Kupferschiefer

Yubdo

Palabora
Great Dyke
Bushveld Complex
(Merrensky Reef+Platreef)
Stella Intrusion

Unst

Freetown

Skaergaard

Pedro Branca
Caraiba
Jacare
Itabire (Jacutinga)
Rincon del Tigre

Sudbury
East Bull Lake
Lac des Iles
Ungava
Thompson
Duluth
New Rambler
Stillwater
Muskox intrusion

Cerro La Pinto
Platina Creek
Serra Pelada
Choco River
Pacajake

Goodnews Bay
Tulameen Complex

N

Legend

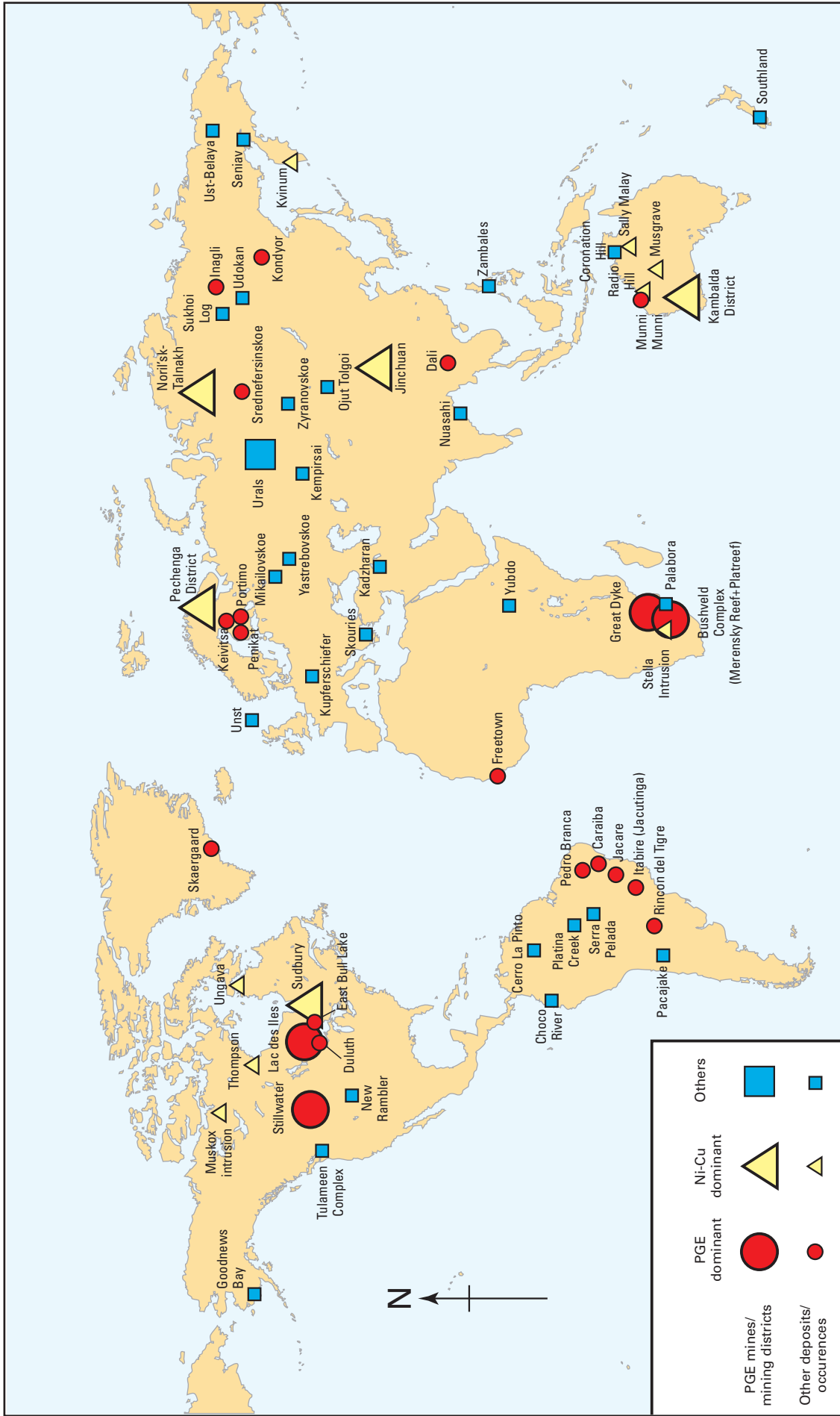|		
PGE mines/ mining districts	PGE dominant ⬤	Ni-Cu dominant ▲
Other deposits/ occurrences	PGE dominant ●	Ni-Cu dominant ▲
	Others ■	Others ■

Figure 1 The distribution of selected PGE mining districts, mines, deposits and occurrences.

Deposit type	Brief description	Typical grades	Major examples
PGE-dominant			
Merensky type	Extensive, laterally continuous, thin layer, or 'reefs', of ultramafic rocks with minor disseminated nickel and copper sulphides. Formed in large layered mafic-ultramafic complexes by magmatic processes.	5–7 g/t Pt+Pd; Pt/Pd[9] = 3 in Merensky Reef. Major source of Pt, Pd and Rh.	Merensky Reef, Bushveld Complex, South Africa; Great Dyke, Zimbabwe; J-M Reef, Stillwater Complex, USA; Munni Munni Complex, Western Australia.
Chromitite type[10]	Similar to Merensky type but comprising thin layers of massive chromite[11] with very sparse base metal sulphide minerals.	4–8 g/t Pt+Pd; Rh 0.3–0.6 g/t in UG2. Pt/Pd = 2.5 in UG2. Major source of Pt, Pd and Rh.	UG2, South Africa; Lower Chromitites, Stillwater Complex, USA.
Contact type	Extensive zones (km) of discontinuous PGE mineralisation with low-grade nickel and copper in heterogeneous basal contact zones of layered intrusions. Commonly heterogeneous, brecciated[12], xenolithic[13].	1–4 g/t Pt+Pd in Platreef, with Pt/Pd ca. 1; by-product Ni and Cu. Major PGE resources.	Platreef, Bushveld Complex; Duluth Complex, USA; Lac des Iles, Canada; East Bull Lake, Canada; Portimo, Finland.
Dunite pipes	High grade platinum mineralisation in discordant pipe-like[14] bodies of dunite, up to 1 km in diameter. Largely worked out.	3 g/t to 2000 g/t. No longer mined.	Onverwacht, Driekop and Mooihoek, Bushveld Complex, South Africa.
Nickel-copper-dominant (with by-product PGE)			
Associated with meteorite impact	Ni-Cu sulphide deposits in impact melt rocks and underlying radial and concentric fracture and breccia zones[15].	1–10 g/t Pt+Pd. Numerous deposits worked mostly for Ni, with lesser Cu and PGE.	Sudbury, Canada.
Related to rift- and continental-flood basalts	Ni-Cu sulphide deposits in sub-volcanic sills which feed flood basalts[16] associated with intercontinental rifting.	2–100 g/t PGE. Average 7.31 g/t Pd and 1.84 g/t Pt in Noril'sk, Russia.	Jinchuan, China.
Komatiite related	Nickel sulphide deposits related to komatiitic[17] (MgO-rich) volcanic and intrusive rocks of Archaean[18] and Palaeoproterozoic[19] age.	Commonly a few hundred ppb, locally greater than 1 g/t. Pt/Pd generally <1.	Kambalda, Western Australia; Pechenga district, Russia; Thompson Belt, Canada; Ungava Belt, Quebec, Canada.

Table 3 Key characteristics and examples of the major PGE deposit types.

[9] Platinum to palladium expressed as a ratio.
[10] Chromitite: an igneous cumulate rock composed chiefly of the mineral chromite.
[11] Chromite: an iron magnesium chromium oxide belonging to the spinel group.
[12] Brecciated: a rock that has been mechanically, hydraulically or pneumatically broken into angular fragments and re-cemented.
[13] Xenolithic: containing xenoliths (discrete and recognisable fragments of country rock in an igneous intrusion).
[14] Discordant pipe-like: a cross-cutting vertical to sub vertical igneous intrusion.
[15] Breccia zones: areas containing abundant fragmented and broken rocks, in this case caused by an impact event.
[16] Flood basalts: a series of thick basalt deposits covering extensive areas of land or ocean floor resulting from a very large scale volcanic eruption or series of eruptions.
[17] Komatiitic: relating to an ultramafic mantle-derived volcanic rock with low SiO_2, low K_2O, low Al_2O_3 and high to extremely high MgO.
[18] Archaean: the period of geological time that is older than 2500 million years ago.
[19] Palaeoproterozoic: the period of geological time from 1600 to 2500 million years ago.

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Four classes of PGE-dominant deposits are recognised:

- Merensky Reef type
- chromitite reef type
- contact type
- dunite pipes

All of these are typically developed in the Bushveld Complex in South Africa, which is the largest layered igneous complex in the world.

Bushveld Complex
The Bushveld Complex hosts about 90 per cent of all known platinum resources in the world and accounts for more than 80 per cent of global platinum production. It covers an area of approximately 66 000 km^2 and is about 9 km thick (Figure 2). The Bushveld Complex is divided into three main sectors: the Western Limb, the Eastern Limb and the Northern Limb. It is saucer-shaped with the layered mafic and ultramafic rocks dipping into the centre of the intrusion where they are covered by felsic[20] lithologies. The platinum-bearing horizons are located within part of the complex known as the Critical Zone which comprises packages, or cyclic units, of repetitively layered chromitite, pyroxenite, norite and anorthosite on a scale of centimetres to tens of metres.

Platinum is currently mined from three horizons in the Bushveld Complex: the Merensky Reef, the UG2 Reef, and the Platreef. The Merensky and the UG2 are extensively worked by both open pit and underground mining methods on the Eastern and Western Limbs. The Merensky Reef has been exploited for PGE for many years with production starting in 1928 in the Rustenburg area. The UG2 Reef was not mined on a commercial scale until 1985 on account of metallurgical problems related to the high chrome and low sulphide contents. At present, however, the UG2 is worked at several localities and accounts for a significant percentage of annual PGE production from the Bushveld. The Platreef is restricted to the Northern Limb of the complex where mining commenced in 1926 but lasted only a few years. Recent increased demand and associated high prices has led to considerable exploration on the Platreef since 2000.
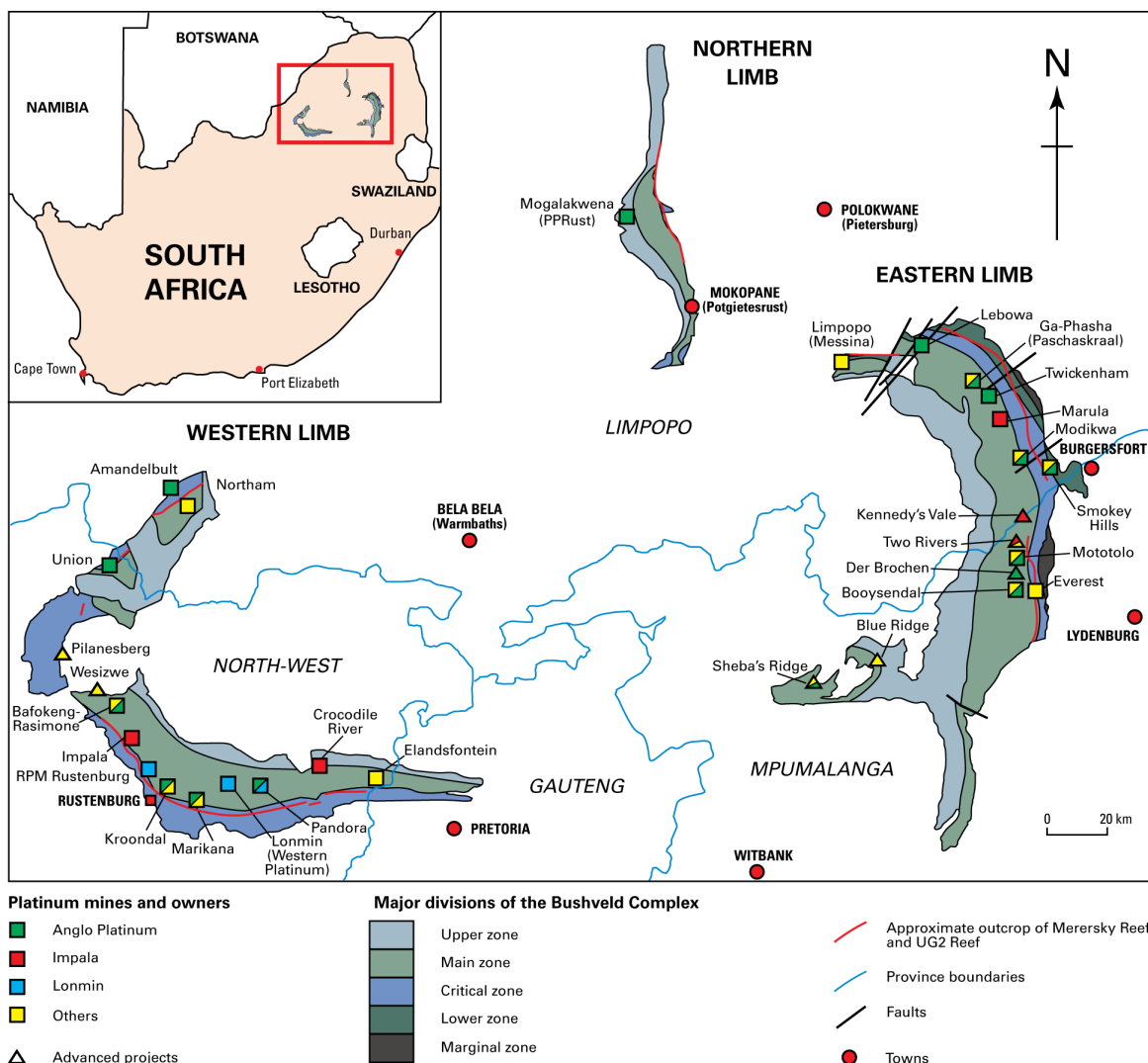

Figure 2 The geology of the Bushveld Complex showing the location of platinum mines and advanced projects.

[20]Felsic: a rock consisting chiefly of feldspars, feldspathoids, quartz, and other light-coloured minerals.

Merensky Reef type

The Merensky Reef is the type example of a PGE-dominant deposit without significant associated sulphide mineralisation. Other important examples are found in the Great Dyke, Zimbabwe and the Stillwater Complex, USA. This class is a major source of global production of platinum and palladium.

These deposits occur as thin, laterally extensive, stratiform[21] zones of sparsely disseminated sulphides within major layered mafic-ultramafic igneous intrusions. In the Bushveld Complex these deposits are typically located about 2 km above the base of the intrusion. There is no consensus on the processes responsible for their genesis but the most widely accepted model involves mixing of a residual magma after partial crystallisation with a new pulse of magma leading to sulphide saturation and separation of immiscible sulphide droplets which scavenge PGE from the silicate magma (Lee, 1996).

The Merensky Reef comprises a pegmatoidal[22] pyroxenite layer about 1 m thick, bounded on both sides by thin chromitite layers and containing up to 3 per cent disseminated sulphides. It can be traced laterally for many hundreds of kilometres and is found on both the Eastern and Western limbs of the Bushveld Complex. The grade of the Merensky Reef averages about 5–7 g/t Pt+Pd (Maier, 2005), although the mineralogy is quite variable and includes a wide range of alloys, sulphides, tellurides and arsenides.

Merensky Reef ore. Scale bar is 50 mm.

Chromitite reef type

The UG2 Reef, one of many thin near-massive[23] chromite layers in the Critical Zone of the Bushveld Complex, is generally regarded as the largest PGE resource in the world. The ruthenium and rhodium content of the UG2 (c. 15 per cent and c. 8.7 per cent of total PGE content, respectively) is also significantly higher than the Merensky Reef (c. 6.2 per cent and c. 2.9 per cent), and hence it is an important source of these rare but useful metals (Lonmin, 2009). The UG2 comprises a chromite layer between 0.7 and 1.3 m in thickness with included sparse disseminated sulphide mineralisation. It is closely associated with a 0.5 m thick pegmatoidal pyroxenite cumulate[24]. The UG2 has a similar lateral extent to the Merensky Reef, occurring below it at depths from 30 m up to about 400 m. The average grade of the UG2 varies from approximately 4 to 8 g/t Pt+Pd. The PGMs in the UG2 comprise mainly sulphides and alloys, including laurite, cooperite, braggite and Pt-Fe alloy.

Platreef

The Platreef is a layer of ultramafic rocks, chiefly pyroxenite, situated along the base of the Northern Limb of the Bushveld Complex. Like the Merensky and UG2 reefs it can be traced for tens of kilometres. However, it is far thicker (up to 300 m) than the Merensky and UG2 horizons and has generally higher base metal contents, particularly nickel and copper, up to about 3 volume per cent. The Platreef is a major PGE resource with mineralisation in both the pyroxenite and sections of the immediate footwall rocks. The mineralisation is 10–30 m thick and is best developed along a 25 km section of strike length. It varies considerably within this interval, in part according to the nature of the footwall rocks which include extensive sections of dolomite, granite, banded iron formation, chert, quartzite and shale. In places the magma has melted and reacted with the footwall giving rise to cross-cutting granitic rocks and widespread xenoliths of dolomite and calc-silicate[25] rocks. The mineralisation in the Platreef is less laterally continuous than the reef styles and is sporadically developed within these heterogeneous lithological packages. The PGE contents are also generally lower than in the reefs, typically in the range 1–4 g/t. The PGE mineralogy of the Platreef is dominated by sulphides, tellurides and arsenides, but this varies significantly both laterally and vertically.

The PGE-dominant mineralisation in the Platreef may be classified as contact-type PGE mineralisation, which are basal accumulations of magmatic sulphides associated with abundant xenoliths and brecciation, and coarse pegmatitic textures. Important examples of this class are recognised in the Duluth Complex, Minnesota, USA, the Portimo Complex in Finland, the Federov Pansky intrusion in the Kola

[21] Stratiform: an ore deposit that occurs as a specific stratigraphic horizon.
[22] Pegmatoidal: a term describing a very coarse-grained igneous rock characterised by crystals >3 cm in length.
[23] Massive (of a mineral deposit): homogeneous mineralised unit.
[24] Cumulate: igneous rock formed by the settling of crystals in a magma chamber.
[25] Calc-silicate: a metamorphic rock consisting mainly of calcite and calcium-bearing silicate minerals.

Peninsula of Russia and in the East Bull Lake intrusive suite, Ontario, Canada, although these deposits are not mined for PGE at present. The Lac des Iles deposit in north-western Ontario, Canada, mined chiefly for palladium between 1993 and 2008, is similar in some respects to contact-type PGE mineralisation. However, certain key features of this class are absent and it is best compared with other PGE-dominant deposits in large layered complexes.

Dunite pipes

A fourth style of PGE-bearing mineralisation in the Bushveld Complex is found in dunite pipes. These are discordant pipe-like bodies, up to 1 km in diameter, of varying composition. Numerous such bodies are found within the Bushveld Complex, but in only four of them have significant PGE mineralisation been discovered. These occur in a 20 km belt on the Eastern Limb to the north-west of Burgersfort. High-grade platinum mineralisation, locally up to 2000 g/t Pt, occurs in discrete zones of the pipes within unmineralised dunite. Discovered in 1924 and largely mined out by 1930, there is little modern information on these deposits. The main PGE-bearing phases were Pt-Fe alloy with subordinate sperrylite, hollingworthite and irarsite (IrAsS).

Other PGE-dominant deposits

The Great Dyke (2600 Ma[26]) is a layered mafic-ultramafic intrusion that can be traced for 550 km in a north-north-easterly direction across central Zimbabwe. The intrusion, which has a width of 4–11 km, was first described in 1867, but it was not until 1918 that platinum, together with nickel and copper, was discovered within it. The Great Dyke is now a world class resource of PGE and also contains major deposits of chromite.

The Great Dyke developed in a series of up to five initially isolated magma sub-chambers that became linked at progressively higher levels as they filled with rising magma. The lower layered rocks of the Ultramafic Sequence of the intrusion are synclinal[27] in cross-section and dip towards the centre of each magma chamber. These zones are overlain by a thick sequence of gabbros and norites comprising the Mafic Sequence. The complexes are known, from north to south, as Musengezi, Hartley, Selukwe and Wedza. Platinum is associated with two layers within the Ultramafic Sequence: a 30–60 m zone of disseminated mineralisation in the Lower Sulphide Zone (LSZ); and a 2–8 m zone of PGE-enriched mineralisation in the Main Sulphide Zone (MSZ). Currently only the MSZ is economic to exploit. The Hartley Complex is by far the largest and economically most

significant and contains approximately 80 per cent of the Great Dyke's total PGE resources.

The *Stillwater Complex* (2700 Ma) in Montana, USA is another of the world's major layered intrusions that hosts important PGE mineralisation. The complex is divided into a Basal Series, an Ultramafic Series, and a Banded Series. The PGE-bearing J-M Reef, which occurs in the Lower Banded Series of norite and gabbronorite, can be traced for 45 km along strike and approximately 1.6 km down-dip. Its vertical depth extent is undefined. The reef consists of a 1–3 metre thick pegmatitic peridotite and troctolite containing sparsely disseminated sulphides (0.5–1 volume per cent) and PGM. In contrast to deposits in the Bushveld Complex and the Great Dyke, the J-M Reef is relatively enriched in palladium with a Pd/Pt ratio of about 3.6. The reef contains an average of 20–25 g/t Pd+Pt over a thickness of about two metres. Most of the palladium is contained within pentlandite, while the platinum occurs mostly in moncheite, braggite, cooperite and Pt-Fe alloy. The J-M reef is worked from two mines with combined production of 499 000 oz[28] of platinum and palladium in 2008 (Stillwater Mining Company, 2009)

The *Lac des Iles Intrusive Complex* (LDI-IC) (2700 Ma) is a suite of mafic-ultramafic intrusive rocks situated approximately 85 km north of Thunder Bay, Ontario, Canada. Mineralisation is hosted in the Roby Zone Ore Body in the compositionally and texturally complex Mine Block Intrusion.

Open pit mining commenced at Lac des Iles in 1993, followed by underground operations in 2006. As a result of low metal prices the mine was closed at the end of October 2008 and placed on care and maintenance. Approximately 212 000 oz of palladium and 16 000 oz of platinum were produced in 2008, at an average grade of 2.49 g/t Pd (North American Palladium Ltd, 2009). Gold, copper and nickel are important by-products.

Nickel-copper-dominant deposits

Magmatic nickel-copper±PGE deposits are the most important source of nickel worldwide. Copper, cobalt and the PGEs, mainly palladium, are important co-products or by-products. In some deposits gold, silver, chromium, sulphur, selenium, tellurium and lead are also recovered from the ores.

The dominant ore minerals are sulphides, pyrrhotite, pentlandite and chalcopyrite, which generally constitute

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[26] Ma: million years ago

[27] Synclinal: relating to a fold in rocks in which the rock layers dip inward from both sides towards the axis.

[28] Throughout this publication wherever 'ounces' (abbreviated to 'oz') are used, this refers to Troy ounces, where one Troy ounce = 31.10 g.

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more than 10 per cent by volume of the host rock. Nickel grades typically range from 0.5–3.0 per cent nickel, with attendant copper in the range 0.2–2.0 per cent. PGE contents vary widely from a few ppb up to, exceptionally, 10 g/t. The size of the deposits ranges from a few hundred thousand up to a few tens of million tonnes. Globally two nickel-copper camps are predominant, each containing more than 10 million tonnes of nickel metal: Sudbury, Ontario, Canada and Noril'sk-Talnakh, Russia.

Magmatic sulphide deposits occur in diverse geological settings in rocks ranging in age from Archaean to Permo-Triassic[29]. They are associated with magmas of various types. As a result of this diversity these deposits have been classified in several different ways. A relatively simple scheme was proposed by Eckstrand and Hulbert (2007) who recognised four principal classes based on the nature of their host rocks:

1. A meteorite-impact mafic melt with basal sulphide ores. Sudbury is the only known example of this type.
2. Rift- and continental-flood basalt, with associated dykes and sills. Important examples include the Noril'sk-Talnakh district in Russia and Jinchuan, China.
3. Komatiitic (magnesium-rich) volcanic flows and related intrusions. Important examples include Kambalda, Australia, Thompson and Raglan, Canada and Pechenga, Russia.
4. Other mafic-ultramafic intrusions. Although deposits of this class contain significant resources of nickel and copper, their PGE contents are generally very low. The major deposits at Voisey's Bay in Labrador, Canada, are the most important nickel resource in this category, but PGE are not recovered in processing the nickel ores. Accordingly this deposit class is not considered further in this review.

Despite the diversity of the settings in which they form nickel-copper sulphide deposits share certain common features that have allowed a generalised genetic model to be developed. They are produced from olivine-rich, primitive magmas and are commonly located in proximity to prominent crustal sutures[30] that focused ascent of the magma allowing transport of their contained metals to high levels in the crust. Their emplacement in the crust was accompanied by contamination with sulphur-bearing sedimentary rocks (commonly evaporites or carbonaceous shales) leading to saturation of the magma with sulphur. This resulted in the segregation of an immiscible sulphide liquid that settled to the lower part of the magma chamber on account of its density. As the sulphide droplets segregated, they scavenged chalcophile[31] elements such as nickel, copper and PGE. Where these sulphide droplets became sufficiently concentrated they may have formed a magmatic sulphide deposit, either in a basal or marginal setting. Particularly favourable sites are the conduits through which new magma flowed into the magma chamber.

Deposits related to meteorite impact
The nickel-copper-PGE deposits of the *Sudbury Igneous Complex* (SIC) are the only known examples of this type of magmatic sulphide deposit the origin of which is attributed to a meteorite impact at 1850 Ma. The impact crater was originally about 200 km in diameter with the mineralisation located at the base and in the footwall of the impact melt. Following later regional deformation the SIC now occupies an elongate basin 65 km long and 27 km wide with rocks along the north flank dipping inwards at about 30° and those along the south dipping inwards at 45°–60°. The nickel deposits, which are present on both the north and south flanks of the basin, are hosted by a basal mafic noritic unit containing abundant fragmental material, referred to as the 'sublayer'. Radiating and concentric fracture and breccias zones, known as 'offsets', in the underlying footwall locally host sulphide-rich orebodies enriched in copper and PGE at depths up to 400 m below the sublayer. The sulphide ores have typical magmatic sulphide mineralogy and textures. A wide range of PGMs are present of which the most abundant are tellurides (michenerite and moncheite) and arsenides (sperrylite).

Deposits related to rift- and continental-flood basalts
The *Noril'sk–Talnakh* region in Russia is the world's largest producer of nickel. The ores here are also very rich in PGE and consequently Noril'sk is the world's largest palladium producer and the second largest platinum producer. The resource in the region has been estimated at more than 1.3 billion tonnes averaging 1.77% Ni, 3.57% Cu, 0.06% Co, 1.84 g/t Pt and 7.31 g/t Pd (Naldrett, 2004). The Noril'sk Talnakh deposits are associated with the huge Permian[32] flood basalt suite known as the Siberian Traps, which developed in major intra-continental rift zones[33]. The nickel-copper-PGE ores are hosted by thin (<350 m) gently-dipping sub-volcanic differentiated gabbroic sills. The massive sulphide ores occur as flat-lying sheets at the base of the sills and in the underlying footwall sediments. Other ore types, mostly stringers[34] and disseminations, are

[29] Permo-Triassic: the period of geological time from 280 to 205.1 million years ago.
[30] Crustal sutures: the area where two continental plates have joined together through continental collision.
[31] Chalcophile: elements that have an affinity for sulphur.
[32] Permian: the period of geological time from 299 to 251 million years ago.
[33] Rift zones: a large area of the earth in which plates of the earth's crust are moving away from each other.
[34] Stringers: a small vein or seam of ore.

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found both within, and at the upper contacts of, the sills. The most widely accepted model for the genesis of the Noril'sk deposits involves the passage of deep, mantle-sourced magmas along major faults extending to the base of the crust. Interaction of these magmas with sulphur-bearing sedimentary rocks is believed to have led to sulphur saturation of the magmas and caused precipitation of nickel and PGE.

Another major deposit of this type is *Jinchuan* in China which contains more than 500 million tonnes of ore grading 1.1 wt% Ni and 0.7 wt% Cu (Su et al., 2008). It has been mined for nickel and copper since 1964, although in recent years platinum and palladium production has assumed major importance. It currently accounts for about 95 per cent of China's PGE production. The deposit is hosted by the Upper Proterozoic[35] Jinchuan Intrusion which is located at the northern margin of the elongate, fault-bound Longshoushan thrust belt. The intrusion, about 6.5 km long and 0.5 km wide at surface, comprises predominantly olivine-rich cumulate rocks and is disposed in a number of en echelon[36] fault-bound slices. The ores are chiefly disseminated and net-textured[37] copper-nickel-iron sulphides comprising between 1 and 10 volume per cent of the rock. The most common PGM are sperrylite, froodite, michenerite and various Pd-Pt tellurides.

Deposits related to komatiitic rocks
Nickel-copper deposits associated with komatiitic volcanic flows and sills are widespread in Archaean and Palaeoproterozoic terranes in Australia, Canada, Brazil, Finland and Zimbabwe. Two principal types of ores have been recognised: high grade (1.5–4.0 % Ni) massive, breccia and matrix ores occurring in small deposits, up to a few million tonnes, at the basal contacts of ultramafic flows and sills; and large (up to 500 million tonnes), low grade (0.6% Ni) deposits comprising disseminated sulphide internal lenticular zones. Both types are found in the Norseman–Wiluna Greenstone Belt of the Archaean Yilgarn Craton of Western Australia and have been mined at many localities.

Basal contact massive sulphide deposits are exemplified by deposits in the Kambalda district. The type example is Mount Keith, which is a large tonnage, disseminated deposit. Palladium and platinum are by-products of nickel mining in this belt although the PGE content of these ores is relatively low. Values in the range 0.1 g/t Pt and 0.1–0.5 g/t Pd have been reported for nickel sulphide ores of the Black Swan area, about 70 km north-east of Kalgoorlie

(Barnes, 2004). In northern Quebec, Canada, several basal contact nickel-copper deposits with minor attendant PGE occur in the Raglan district of the Cape Smith foldbelt and are mined at four sites (Lesher and Keays, 2002).

Other important nickel mining districts which work komatiite-associated deposits include the Thompson Nickel Belt of Manitoba, Canada and the Pechenga district of the Kola Peninsula in Russia, close to the border with Norway. Values up to 1.3 g/t Pt and 1.2 g/t Pd have been reported in the Pechenga ores but values below 1 g/t are more typical of this district (Brugmann et al., 2000).

Other deposit types
Enrichment of PGE to concentrations markedly above typical crustal values has been documented in a wide range of other geological settings. In most cases these are not currently economic to mine using large-scale modern techniques, although in the past some have supported small-scale bedrock mining operations. Elsewhere shallow high-grade deposits are currently worked by mostly small-scale or artisanal operations.

Alaskan or Alaskan-Ural type
A variety of zoned ultramafic intrusive complexes, referred to as 'Alaskan' or 'Alaskan-Ural' type, named after the areas where these deposits were first described, are commonly enriched in PGE. These dome- or pipe-shaped bodies are generally small, up to 40 km^2, and comprise a central core of dunite passing outwards to pyroxene-rich units and an outer rim of gabbro. Although many of these complexes contain primary PGE mineralisation, often associated with chromite, only a few have been mined for PGE e.g. the Nizhny Tagil Complex in the Urals, which was worked until 1935.

Other deposits of this type are found in British Columbia, Alaska, Koryakia in north-east Russia and in the Kondyor intrusion in the Siberian Platform. These locations are, however, best known for the important platinum-rich alluvial placer deposits derived from their erosion and which have supported mining operations for more than a hundred years.

Placers
Alluvial placer deposits are concentrations of heavy minerals transported and deposited with sand and gravel by rivers. Dense platinum-bearing mineral grains are concentrated at certain sites from where they may be extracted by shallow excavation and/or dredging. Placer

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[35] Proterozoic: the period of geological time from 2500 to 542 million years ago.
[36] En echelon: parallel or sub-parallel, closely-spaced, overlapping or step-like structural features in rock.
[37] Net-textured: a network of sulphides within a rock.

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Deposit type	Brief description	Typical grades	Major examples
Alaskan or Alaskan-Ural type	PGE enrichment in small zoned ultramafic complexes. Primary mineralisation mined at a few localities.	Generally low grade, but with local extreme enrichment.	Nizhny Tagil, Urals; Tulameen Complex, Canada.
Placer type	An accumulation of dense PGM in sand and gravel deposits laid down in a river system.	Generally low grades with sporadic rich pockets.	Urals, Russia; Choco River, Colombia; Goodnews Bay, Alaska; Southland, New Zealand.
Ophiolites	PGE enrichment chiefly with podiform[38] chromitite deposits in lower sections of ophiolite[39] complexes. Later hydrothermal[40] enrichment may upgrade PGE contents.	Values in g/t range reported from Unst.	Unst, UK; Zambales, Phillippines; Kempirsai, Russia; Al Ays, Saudi Arabia.
Laterites	Residual enrichment of PGE caused by intense tropical weathering of ultramafic rocks.	0.5 g/t Pt.	Yubdo, Ethiopia.
Veins	Polymetallic[41] veins and/or hydrothermal remobilisation of nickel, copper and PGE in mafic-ultramafic rocks with re-deposition of PGE along shear zones[42].	Tens of g/t Pt+Pd. Hundreds of g/t at Waterberg.	New Rambler, USA; Waterberg, South Africa; Rathbun Lake, Canada.
Unconformity-related	Hydrothermal PGE enrichment with gold ± uranium in metasedimentary[43] rocks at or close to an unconformity[44] with younger, oxidised sedimentary rocks. Commonly focused along faults.	0.19 g/t Pt, 0.65 g/t Pd, 4.31 g/t Au at Coronation Hill (Carville et al., 1990). Tens/hundreds g/t Pt and Pd at Serra Pelada.	Coronation Hill, Australia; Serra Pelada, Brazil.
Porphyry deposits	Local PGE enrichment with gold in porphyry[45] style copper deposits hosted by igneous intrusions.	Generally less than 1 g/t PGE. 0.16 g/t Pd, 0.038 g/t Pd from Santo Tomas.	Elatsite, Bulgaria; Skouries, Greece; Aksug, Russia; Santo Tomas II, Phililppines.
Shales and other sedimentary rocks	PGE enrichments in metalliferous black shales. Generally thin but may be laterally extensive.	Generally < 1 g/t, but local very high values in the Kupferschiefer.	Kupferschiefer, Poland; Yukon, Canada; Sukhoi Log, Siberia.
Carbonatite and alkaline complexes	PGE enrichment in small carbonatite-phoscorite igneous complexes. Disseminated copper-palladium-rich sulphide mineralisation in gabbro at Coldwell.	Few hundred ppb in Palabora; few g/t in Brazilian examples. 0.76 g/t Pd, 0.23 g/t Pt and 0.27% Cu in Marathon deposit.	Palabora, South Africa; Catalão and Ipanema, Brazil; Kovdor, Russia. Coldwell Complex, Canada; Marathon, Canada.

Table 4 Key characteristics and examples of other PGE deposit types.

[38] Podiform: an elongate lenticular or rod-like shaped orebody.
[39] Ophiolite: a section of the earth's oceanic crust and the underlying upper mantle that has been uplifted or emplaced to be exposed within continental crust.
[40] Hydrothermal: related to processes involving heat and water.
[41] Polymetallic: a rock composed of a combination of different metals.
[42] Shear zones: microscopic to regional-scale domains across which deformation and/or displacement has occurred.
[43] Metasedimentary rock: a sedimentary rock that shows evidence of having been subjected to metamorphism.
[44] Unconformity: a surface of erosion or non-deposition representing a gap in the geological record.
[45] Porphyry : a mineral deposit comprising veinlets and disseminated grains of ore minerals, commonly hosted by an igneous rock, known as a porphyry, in which relatively large crystals are set in a fine-grained groundmass.

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deposits of PGE have been worked for centuries and were the principal source of platinum until the discovery of the deposits in the Sudbury area of Canada and the Merensky Reef in South Africa. Significant platinum was extracted as a by-product from the alluvial gold working in western USA in the nineteenth century. Platinum was also previously worked by dredging river gravels beneath the Salmon River, near Goodnews Bay, in western Alaska. This deposit produced an estimated 644 000 oz of platinum by 1975 (Barker et al. 1981). The operation closed in 1990. PGE were also formerly extracted from alluvial deposits in New Zealand and British Columbia, Canada. Among the earliest exploited platinum placer deposits, which are still worked today, are those in the Choco District on the west coast of Colombia. Russia still produces significant quantities of platinum from similar sources. Although recent data are scarce, half of all Russian platinum production was derived from placer deposits in 1997 (Valtukh et al., 1999).

Ophiolites
Ophiolite complexes are important sources of a number of metals including copper and chromium. The basal mantle harzburgite and overlying ultramafic cumulate rocks within ophiolites host important podiform chromite deposits in many countries, including Turkey, Russia, Albania and Greece. Most early investigations suggested that the PGE associated with podiform chromite were dominated by Os, Ir and Ru. However, in the past 25 years significant enrichment in Pt and Pd has been documented in association with deposits of this type in a number of ophiolite complexes. In the Unst ophiolite in Shetland, UK, high PGE concentrations, locally exceeding 100 ppm Pt+Pd, have been reported at various stratigraphical levels (Gunn and Styles, 2002). The highest values occur in the lower mantle harzburgite close to the basal emplacement thrust of the complex. High Pt and Pd values have also been reported in association

Disseminated chromite ore with very high PGE grades, Unst ophiolite, Shetland, UK. Scale bar 50 mm.

with sulphide-bearing chromitite in the lower sections of ophiolites at Leka in Norway, Thetford in Canada, Al 'Ays in Saudi Arabia, Albania and New Caledonia. Although the concentrations of Pt and Pd in these ophiolites are locally comparable with those in other magmatic settings, the size of these occurrences is too small to support mining under current economic conditions.

Laterites
Laterites are in situ residual deposits derived from prolonged tropical weathering which leads to the breakdown of many rock-forming minerals, leaching of certain elements and enrichment in others, chiefly iron and aluminium. Under certain conditions and where the parent rock is ultramafic in composition, nickel may be enriched to form an economic deposit. Exceptionally nickel laterites may also contain elevated platinum concentrations, high enough to permit commercial extraction. Little data is available on PGE in nickel laterite deposits, but the most well known example of a platinum-bearing laterite deposit is at Yubdo in Ethiopia. Platinum has been mined on a small scale at Yubdo since 1926 and current production is only about 100 oz per annum (Minerva Resources, 2009).

Veins and breccias
Small quantities of PGE have been reported in association with base-metal vein deposits in some areas. The New Rambler deposit in Wyoming, USA, is a vein deposit of copper sulphide minerals with high levels of palladium, platinum and gold. The deposit is interpreted to have formed by hydrothermal fluids that leached palladium and platinum from the surrounding mafic rocks before precipitating them at the intersection of a faulted mylonite and a major shear zone (McCallum et al., 1976). When the mine closed in 1918 total platinum production was estimated to have been 950 oz, with a further 16 870 oz of palladium (Hausel, 1997). Significant hydrothermal enrichment of platinum and palladium has also been reported in the copper-nickel sulphide occurrence at Rathbun Lake, Ontario, Canada. Here, average values of about 20 g/t Pd and 10 g/t Pt have been reported from copper-nickel ores hosted by sheared and altered gabbronorite (Rowell and Edgar, 1986). PGE have also been found in quartz veins with gold, silver and copper-nickel sulphides in north Westland, New Zealand (Challis, 1989).

The Waterberg deposit in Limpopo Province, South Africa, is a quartz-vein hosted platinum deposit that was mined between 1923 and 1926. The PGE mineralisation is hosted by post-tectonic quartz veins with fabrics similar to epithermal[46] style deposits. They are thought to have been produced by a hydrothermal event focused along a nearby

[46]Epithermal: relating to a mineral deposit formed within approximately 1 km of the earth's surface and at temperatures between 50–200°C

major regional fault system. Grades up to 900 g/t Pt+Pd have been reported in the Waterberg lodes.

Unconformity-related
Unconformity-related deposits host major resources of uranium, mainly in Northern Territory, Australia, and in Saskatchewan, Canada. Enrichment in gold and PGE has been reported in some of these deposits. The most important example is the Coronation Hill deposit in the Pine Creek inlier of Northern Territory, Australia. PGE-gold and uranium-gold-PGE mineralisation occur at and below a major unconformity that separates a deformed and metamorphosed basement complex from a cover sequence of haematitic quartz sandstone and sedimentary breccias. The mineralisation is thought to have been formed due to interaction between low temperature oxidised brines from the cover sequence and reducing rocks and fluids from the crystalline basement (Mernagh et al. 1994). Although a significant resource of gold, palladium and platinum was defined in the 1970s, this has not been mined because Coronation Hill was included in the Kakadu National Park in 1994. The PGE occur in a range of Pt-Pd-Se-Sb minerals unlike the mineral assemblages found in most other PGE deposits. PGE enrichment, locally to very high grades, has also been reported in the Jabiluka unconformity-related uranium deposit in Australia.

The Serra Pelada gold-PGE deposit in the Carajás mineral province of north-east Brazil was discovered by local prospectors in the early 1980s. A major gold rush ensued with more than 100 000 people working the shallow sections of the deposit at its peak. Modern scientific studies of this deposit are few and consequently its genesis is poorly understood in detail although an epigenetic[47] origin, overprinted by supergene enrichment[48], is clearly evident. A recent estimate of the deposit size is 3.7 million tonnes @ 15.20 g/t Au, 4.09 g/t Pd, and 1.89 g/t Pt (Cabral et al., 2002). The largest part of the resource is hosted by hydrothermally altered carbonaceous and calcareous siltstones which unconformably overlie an Archaean greenstone sequence. Other ores occur within iron-rich breccias and siliceous alteration zones. The precious metal contents of the ores are commonly in the g/t range, with bonanza grades up to 110 000 g/t Au and 16 000 g/t Pd+Pt locally reported.

Porphyry deposits
Porphyry deposits are large, low-grade copper orebodies of stockwork to disseminated mineralisation that typically have grades of 0.4–1% Cu and can reach 1000 million

tonnes or more in size. Certain porphyry deposits may contain economically important quantities of other elements such as molybdenum, gold, silver and, less commonly, PGE. PGE-enrichment has been reported at several localities including: Elatsite, Bulgaria; Skouries, Greece; Santo Tomas II, Philippines; and Afton, Canada. The PGE contents of these deposits are generally low, less than 1 g/t, although locally values of a few g/t have been reported. PGE are recovered as a by-product from copper refineries processing ore from porphyry deposits in the US and Canada. Reserves in the Elatsite deposit have been estimated to be 185 million tonnes @ 0.38% Cu, 0.21 g/t Au, 0.07 g/t Pd and 0.02 g/t Pt (Bogdanov et al., 2005).

Shales and other sedimentary rocks
PGE enrichments occur in metal-rich black shales in a number of geological settings, generally associated with continental rifting and sometimes accompanied by contemporaneous volcanic activity. PGE are not mined from these occurrences as, in most cases their contents are low, up to a few hundred ppb, and the enrichment is restricted to thin beds, only a few cm thick. Examples are found in Early Cambrian shales in southern China with nickel-molybdenum, in Devonian shales at the Nick property in the Yukon, Canada with attendant nickel-zinc, and in Neoproterozoic[49] shales in the Czech Republic associated with zinc and copper.

Much higher PGE values have been documented in the metalliferous deposits of the Permian Kupferschiefer sedimentary rocks that underlie much of Germany, Poland and Holland. The Kupferschiefer has long been exploited for its copper, silver, zinc and lead. More recently PGE and gold enrichments have been found in shales over strike lengths in excess of 1.5 kilometres. Exceptionally high precious metal values, up to 1900 g/t Au, 1900 g/t Pd and 600 g/t Pt, have been reported in thin organic-rich black shales (Kucha, 1982). PGE are also a significant constituent of the major unworked gold deposit at Sukhoi Log in Russia. Here the precious metals are also hosted by carbonaceous shales but later magmatic activity has been proposed to account for the observed mineralisation (Distler et al., 2004).

Carbonatites and alkaline complexes
Phoscorite-carbonatite complexes are small, pipe-like bodies up to 3–4 km in diameter comprising complex multistage deep-sourced intrusive igneous rocks of two principal types: carbonatite, an igneous rock composed of calcium and magnesium carbonate phases, and phoscorite, an igneous

[47] Epigenetic (in this context): a mineral deposit post-dating the age of the country rocks.
[48] Supergene enrichment: a mineral deposit produced by near-surface processes of leaching and transportation of metals followed by re-precipitation.
[49] Neoproterozoic: the period of geological time from 1000 to 542 million years ago.

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rock composed of three main mineral phases, magnetite, forsterite and apatite. These complexes are economically important as sources of phosphate, iron, copper, uranium and niobium in South Africa, Brazil and Russia. Parts of some of these complexes also contain significant enrichments in PGE: at Palabora in South Africa platinum and palladium are present in concentrations up to about 0.5 g/t and are recovered as a by-product of copper production. Osmium and iridium are present in greater abundance (few g/t) at Palabora. Values up to ca. 3 g/t Pt and 1 g/t Pd have also been reported in the Catalão and Ipanema complexes in Brazil. A wide range of PGM has been reported in sulphide concentrates from the phoscorite-carbonatite at Kovdor in the Kola Peninsula, Russia. However, the PGE abundance in these ores is not well known.

PGE mineralisation also occurs in some composite alkaline intrusive igneous complexes. The most well known example is the Coldwell Complex in north-western Ontario where several prospects are under evaluation. The most advanced is the Marathon deposit where a resource of 79 million tonnes @ 0.76 g/t Pd, 0.23 g/t Pt and 0.27% Cu has been defined (Marathon PGM Corporation, 2008).

Extraction methods and processing

Extraction methods

The method used to mine platinum-bearing deposits is dependent on their size, grade and morphology. The high price commanded by platinum and its high concentration in units such as the Merensky Reef allow it to be mined using either open-pit methods or underground methods, or a combination of both.

Underground mining

Underground extraction uses a variety of standard mining methods depending on the characteristics of the orebody. The deepest currently operating platinum mine is at Northam in South Africa where mining takes place at a maximum depth of 2.2 km. Due to the high temperatures at this depth, Northam employs 'hydropower' technology which uses water, cooled on surface to 5°C, to power its drilling machines and cool working places. Hydropower is also employed by other companies including Lonmin Plc and Anglo Platinum Ltd. Other underground operations in the Bushveld Complex include the Anglo Platinum's Rustenburg and Union Mines, and Impala's Crocodile River Mine. Typically, these operations use labour-intensive drilling and blasting techniques,

though attempts are being made to introduce more mechanisation into the workplace. Ore is blasted using explosives then transported to the shaft using an underground rail system. Old workings are backfilled with waste material to improve ventilation by forcing air to travel through only those areas that are being worked, as well as providing more roof support. Underground mining is also employed in the Noril'sk-Talnakh, Sudbury and Stillwater deposits.

Opencast and underground mining are sometimes combined at a single mine, and may take place simultaneously in order to access shallow and deeper parts of an ore body. The open-pit mine may be in operation while the underground workings are being developed. Recently there has been a sharp rise in the number of combined surface and underground operations in South Africa working the lower-grade, but larger resource, of the UG2 reef. Other examples include the Amandelbult and Marikana mines in South Africa, and the Lac des Iles mine in Canada.

Northam Platinum Mine, South Africa. © Northam Platinum

Open-pit mining

Surface mines are generally cheaper and safer to operate than underground mines. Open-pit mining is most appropriate for near-surface (<100 m), lower-grade, steeply

[50] Overburden: waste material that lies above a mineral deposit.
[51] Gangue: the undesirable or unwanted minerals in an ore deposit.

dipping or massive ore bodies where large-scale surface excavations would not cause significant environmental impact. This method typically involves removing the overburden[50], digging the ore or blasting with explosives, then removing the ore by truck or conveyor belt for stockpiling prior to further processing.

Examples of surface mining operations for PGE include the Mogalakwena (formerly PPRust) operation in South Africa, and the Yubdo laterite deposit in Ethiopia.

Processing
After mining the ores are processed to increase their platinum content. Concentration is normally carried out at, or close to, the mine site and involves crushing the ore and separating platinum-bearing and gangue[51] minerals, using a range of physical and chemical processes. Subsequent smelting and refining may be carried out at or near the mine, or concentrate may be transported or exported for processing to metal. Different procedures are used for processing sulphide-poor ores (e.g. Merensky and UG2) and sulphide-dominant ores (e.g. Noril'sk) due to their chemical, mineralogical and physical differences.

PGE-dominant ore

Comminution[52] and concentration
Ores from the Merensky Reef and UG2 reef are generally sulphide-poor with platinum and other PGE present in a large variety of discrete PGM. The initial phase of processing both reef type ores is identical. Ore is fed into a primary crusher from where it undergoes one or more stages of secondary crushing. At each stage vibrating screens allow material of the appropriate size to pass on to the next part of the processing circuit. Crushing, followed by fine grinding, also known as milling, is used to maximise separation of the ore minerals from the gangue. The crushed ore is mixed with water to create a slurry which is fed into a series of grinders until a powder of the required grain size is produced.

Some mines have introduced one or more additional stages after crushing and milling to optimise PGE recovery. These include magnetic separation and dense media separation. Where the PGE are known to be present within the crystal structure of pyrrhotite, then pyrrhotite may be magnetically separated, collected and treated separately. Dense media separation is used to remove lighter silicate minerals from the denser chromite and PGM after initial crushing and prior to milling. This significantly reduces the volume of ore to be milled and subsequently floated without reducing PGM recoveries.

[52] Comminution: the process of crushing and grinding a rock into powder.

Following milling, additional water is added to the powdered ore to produce a suspension and air is blown upwards through the tanks. Chemicals are added to the mix, making some minerals water-repellent and causing air bubbles to stick to their surfaces. Consequently, these minerals collect in froth at the surface and are removed as a metal concentrate. This process is known as froth flotation.

The greatest losses of PGM occur during crushing, milling and flotation, mainly due to the highly variable mineralogy and mode of occurrence of PGM, which may be associated with base-metal sulphides, silicate minerals or chromite. For this reason metallurgical operations normally treat UG2 and Merensky ore separately to maximise PGM recovery. Many operations employ two stages of milling and floating conducted in series, known as mill-float-mill-float or MF2 operations, in order to maximise PGM recovery.

Following flotation, the final concentrate is dried to less than 0.5 per cent moisture before smelting.

Smelting
The purpose of smelting is to recover as much metal as possible from the concentrate. The matte-smelting process produces a silicate melt (slag) from which an immiscible sulphide melt (matte) separates due to density differences. Matte smelting takes places in furnaces at temperatures exceeding 1300°C. Fluxes such as limestone are added to the smelter to reduce the melting temperature of the

Smelter complex, Western Platinum Mine. © Lonmin.
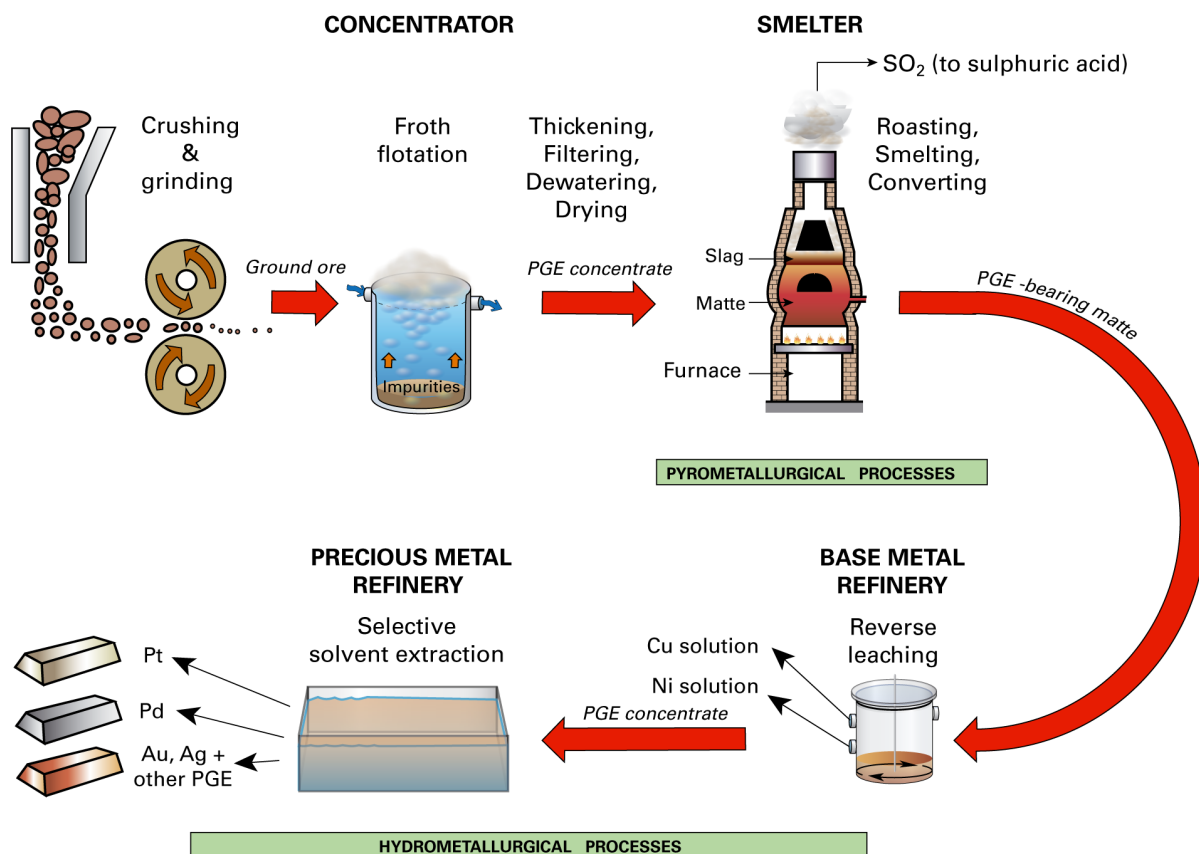
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Figure 3 Schematic flowsheet for typical processing of PGE-dominant ores.

platinum and base-metal sulphides which accumulate in the matte, known at this stage as green matte.

UG2 ore, which is low in sulphur and high in chromite, requires special treatment. Its high chromium content can cause significant operational problems and lead to higher losses of PGM within the slag. UG2 ore is not smelted on its own because an immiscible matte will not form. It is usually blended with Merensky concentrate, or rarely with other sulphur-rich ores, to produce the matte. The percentage of chromite in the smelted ore must be carefully managed to prevent PGE losses.

Once the matte has been tapped from the smelting process, the liquid metal undergoes a process known as converting. This involves blowing air, or oxygen, into the matte over a period of several hours to oxidise contained iron and sulphur. Silica is added to the matte to react with the oxidised iron to form a slag that can be easily removed, while the sulphur is collected to produce sulphuric acid. The converter matte, known as white matte, consists of copper and nickel sulphide with smaller quantities of iron sulphides, cobalt and PGE. This is usually cast into ingots and is then sent to the base metal treatment plant for recovery of the base metals. However, matte treated by Anglo Platinum, the largest platinum producer in the world,

is treated differently and the matte is slow cooled to promote the production of a copper-nickel alloy containing the PGE. The resulting matte is then crushed and the sulphide component separated magnetically. It is then sent directly to the precious metal refinery.

Refining
Refining to produce high-purity platinum products is a very lengthy and complicated process. The methods involved differ from company to company and for commercial reasons the techniques used are closely guarded secrets. However, in general, the process consists of a series of hydrometallurgical operations. Initially, the white matte is transferred to the base metal refinery for base metal removal. The PGE-bearing residue from the base metal refinery, containing over 60 per cent PGE, is transferred to the precious metal refinery for separation and purification of the PGE.

All commonly used refining processes separate and produce individual PGE by utilising differences in their chemistry. Refining is achieved either through a series of dissolution and precipitation stages involving PGE salts, or by using a technique known as total leaching, which is followed by sequential metal separation with the aid of solvent extraction. This process is shown in Figure 3.

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Nickel-copper-dominant ore

PGE-bearing nickel-copper-dominant ores, such as those from Noril'sk and Sudbury, are treated somewhat differently to PGE-dominant ores due to their higher sulphide content and different mineralogy. Several types of ore are recognised depending on their sulphide concentration and textures, including massive ores with in excess of 70 volume per cent sulphides. PGE occur in a wide variety of PGM in these ores.

At Noril'sk, the ore is crushed and milled before undergoing gravity concentration in a centrifugal-type concentrator to recover up to 40 per cent of the PGE. Froth flotation is then used to produce a metal concentrate prior to treatment at the smelter. This process involves mixing the finely ground ore with water and special chemicals to make the valuable minerals hydrophobic. The mixture is then agitated and air blown through to produce bubbles to which the ore minerals attach themselves and which rise to the surface where they are skimmed off. This metal concentrate, once dried, is sent to the smelter where it is roasted, smelted and converted to produce a copper-nickel-PGE matte, together with slag as a waste product. The matte is granulated, wet-ground and then treated in the base metal refinery where pressure oxidation leaching is used to produce concentrates of nickel, copper and cobalt. The copper concentrate, containing 70% to 71% copper, 0.2% to 0.6% iron, 0.4% to 0.7% nickel, 26% to 28% sulphur and almost all the PGE and gold, is then smelted in furnaces to produce copper blister (98.5% to 99.5% copper) with PGE and gold. The copper is then further refined using electrowinning to produce pure cathode copper with the PGE remaining in the anode slimes. The

Platinum smelting. © Lonmin.

anode slimes are then added to other slimes produced from the production of nickel, together with the gravity concentrate produced after the initial crushing and milling. This mixture is smelted again to produce a PGE-bearing matte. The matte is then pressure-leached to produce a silver concentrate (AgCl), and two PGE concentrates containing platinum and palladium and the other PGE. This process is shown in Figure 4.
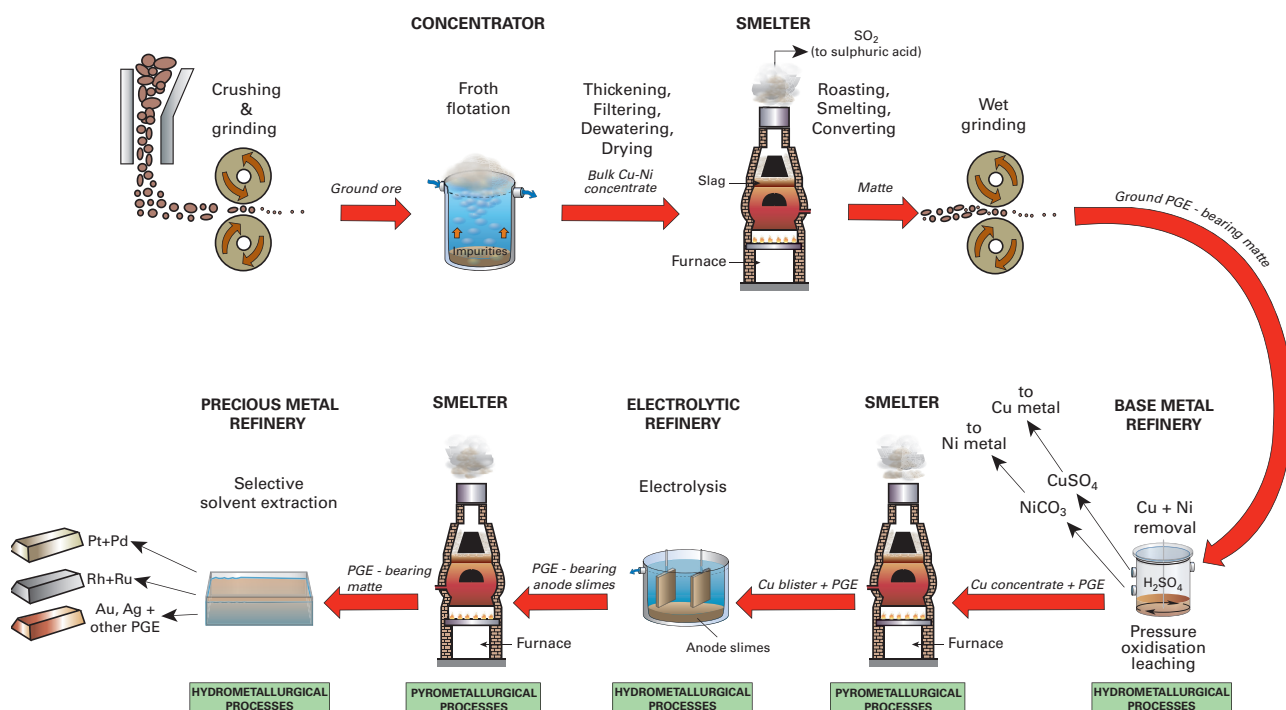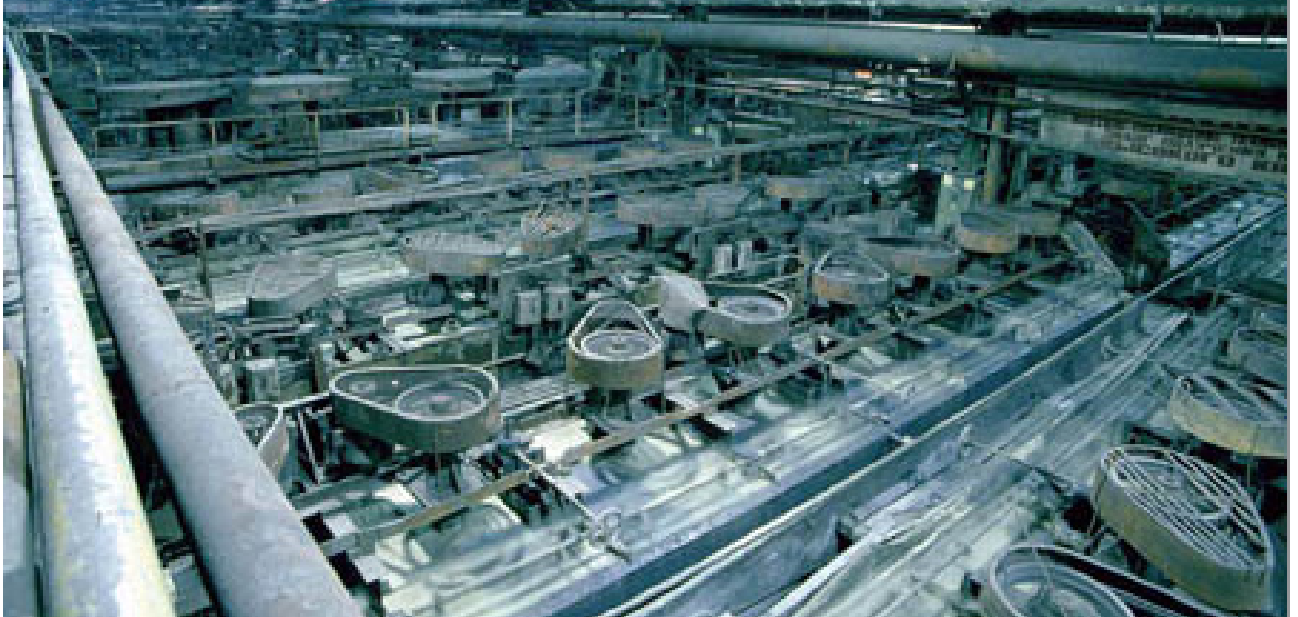

Figure 4 Schematic flowsheet for typical processing of nickel-copper-dominant ores.

Froth flotation plant at Noril'sk. © Johnson Matthey Plc.

Other PGE sources

In many operations the PGE are extracted as a by-product of nickel, copper and cobalt production. The metallurgical process is therefore designed around the main product, normally nickel, whilst maximising PGE recoveries.

Several methods are used to extract PGE from base metal ores. However, they all treat the matte produced at the smelting stage. At Vale's Sudbury operations, the matte is treated by flotation and magnetic separation to produce separate nickel, copper and precious metal concentrates. The precious metal concentrates are treated in a two-stage pressure leaching process to dissolve first the nickel and cobalt, and then the copper, selenium and tellurium. This concentrate, containing 60% to 80% PGE + gold, together with small quantities of silver and base metals, is then refined to produce high-purity individual elements.

Another method, used by Xstrata's Sudbury operations, recovers base metals and PGE by treating the nickel-copper-cobalt matte with chlorine. The nickel and cobalt are recovered as pure metals whilst the copper is contained in a sulphate solution. After removal of the copper the PGE remain in the residue. This is smelted to matte in an electric furnace before being granulated and leached with hydrochloric acid and chlorine to obtain the individual PGE metals.

The copper concentrates derived from many copper ores contain small quantities of PGE. In processing these ores the PGE will be present, together with gold and silver, in the anode slimes. Most large copper refineries therefore normally operate a precious metals recovery plant to treat these slimes. The processing varies from plant to plant but generally involves leaching, smelting and refining. The quantities of platinum produced by these copper refineries, although relatively small, are highly significant in economic terms. For example, 3.85 tonnes of palladium-platinum concentrate was produced by Noranda (now Xstrata) in 1988, and 2 tonnes of palladium-platinum sponge was produced in 1983 from the copper refinery at Pori, Finland, formerly owned by Outokumpu (now Boliden).

Specifications and uses

PGE are sold in a number of forms including pure metal and a variety of compounds, solutions and fabricated products. These are produced by a small number of specialist companies such as Johnson Matthey and BASF.

The catalytic properties of the PGE, which are the basis of most of their important applications, are exploited in two main sectors: emission control systems and process catalysts for industrial applications. Other important properties of the PGE that make them useful for many additional purposes include their strength, high melting point, and resistance to corrosion. The major applications of platinum and palladium are shown in Figures 5 and 6.

Autocatalysts

The largest use of platinum, palladium and rhodium is in autocatalysts, which are used to convert noxious emissions (carbon monoxide, oxides of nitrogen and hydrocarbons) from car exhaust systems to harmless non-toxic products. Demand for PGE in autocatalysts has grown markedly from the 1970s onwards as various countries
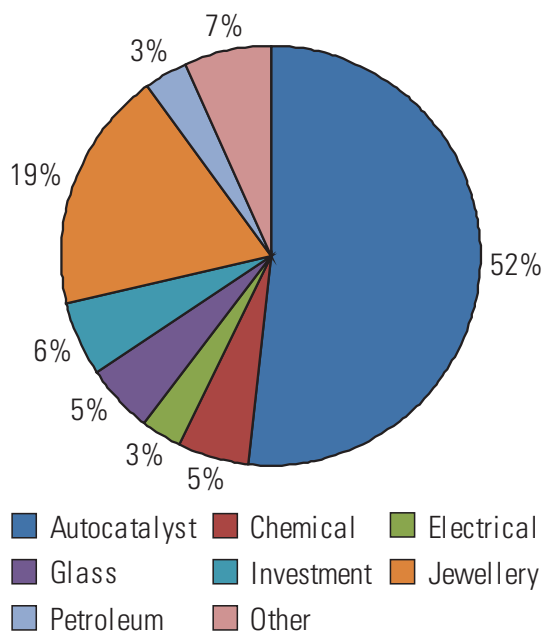
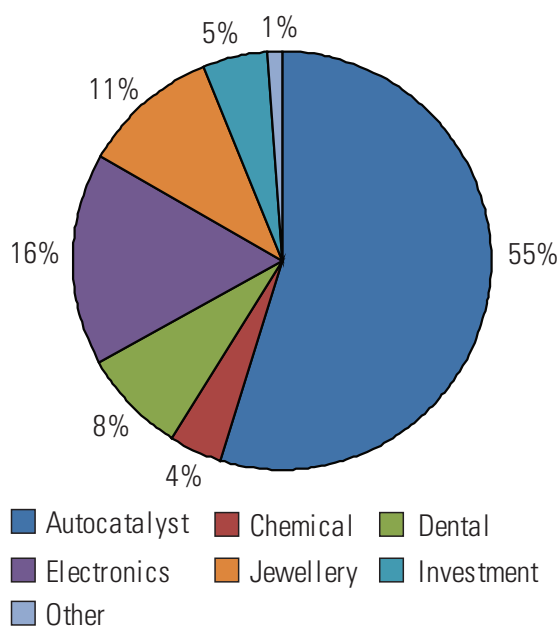Figure 5 Applications of platinum, 2008 (Johnson Matthey).

Figure 6 Applications of palladium, 2008 (Johnson Matthey).

followed the lead of USA and Japan and introduced legislation setting standards for emissions from motor vehicles.

The quantities and proportions of platinum and palladium used in autocatalysts have varied considerably over time in response to technological changes and price variations. Currently palladium is the major constituent of catalysts used in gasoline-powered vehicles chiefly on account of its longstanding price advantage over platinum. However, platinum is the material of choice in Asia where the

quality of gasoline supplies is variable and platinum is preferred on account of its higher sulphur tolerance. Platinum is also the chief active component in catalysts and filters fitted to diesel-powered vehicles. Consequently this is the main contribution to platinum demand in Europe where more than 50 per cent of all new cars have a diesel engine. More stringent emission controls in Europe, North America and Japan have also led to significantly increased demand for platinum in medium- and heavy-duty diesel trucks. There has also been a significant increase in the amount of palladium used in the diesel sector in response to its price advantage over platinum, but the latter is still predominant.
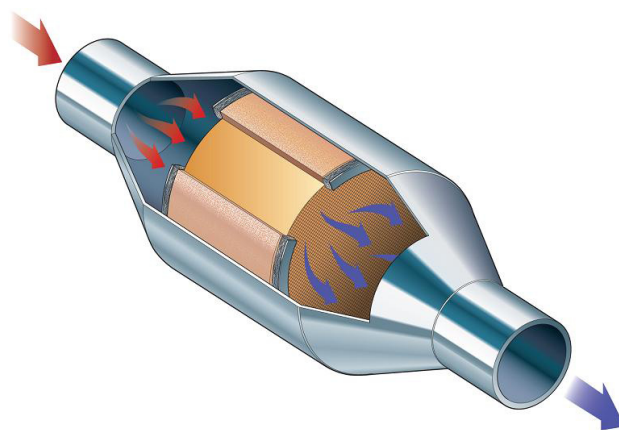
Simplified cut-away through an autocatalyst.
© Johnson Matthey Plc.

Although global demand for rhodium in 2008 (689 000 oz gross) is only about 5 per cent of that for platinum and palladium, rhodium is a critical component of autocatalysts which account for more than 80 per cent of its use. Other areas where rhodium is important include the manufacture of specialist glasses and the chemicals sector.

Jewellery

Platinum has long been widely used in jewellery, especially in Japan. In recent years it has become increasingly popular in Europe and China, although overall demand for platinum in jewellery has fallen considerably in the last decade from 2.88 million oz in 1999 to 1.37 million oz in 2008. Palladium is also used in jewellery, either as a component of white gold and, increasingly, as palladium jewellery itself, where it enjoys considerable price advantages over platinum and gold. Although demand for palladium in jewellery is significantly less than for platinum it remains the third most important use of palladium after autocatalysts and electronics applications.

Platinum jewellery. © Johnson Matthey Plc.

Chemicals

Platinum has many uses in the chemicals industry. The most important are in the manufacture of fertilisers and explosives where platinum is used as a catalyst in the conversion of ammonia to nitric acid. Platinum is also important in process catalysts for the fabrication of speciality silicones for water repellent coatings, high consistency rubbers and liquid silicone rubbers which are used in the aerospace, automotive, construction and many other sectors. Well known examples include pressure-sensitive adhesives (PSA) which are designed to allow the surface on which they are coated to stick to other materials and to peel away cleanly without tearing.

Platinum is used in hard disks to increase their storage capacity. © Johnson Matthey.

Electrical and electronics

Platinum is an important component of the magnetic coating on computer hard disks. As the market for electronic devices of all types has increased so has the requirement to increase the storage capacity of hard disk drives, especially for video and audio applications. Accordingly the demand for platinum for this purpose has risen considerably in recent years. However, in 2008 demand from the global electrical sector fell by 11.8 per cent to 225 000 oz, largely as a result of reduced purchasing by hard disk manufacturers.

The electronics industry is the second largest consumer of palladium where it enjoys a significant cost advantage over rivals such as gold. A large proportion of this palladium is used in multi-layer ceramic capacitors (MLCC), while other important applications are in hybrid integrated circuits (HIC), used mainly in the automotive sector, and in plating of connectors inside computers.

Glass

Platinum and platinum alloys are used in the fabrication of vessels that hold, channel and form molten glass. These materials are able to withstand the abrasive action of molten glass and do not react with it at high temperatures. Rhodium is an important component of these alloys contributing to improved performance and longer life of the equipment. Platinum-based equipment is used in the manufacture of a large range of glass products, the most important of which are flat panel screens and fibre glass.

Petroleum refining

Platinum is critical to the refining of petroleum and the production of petrochemical feedstocks used in the manufacture of plastics, synthetic rubber and polyester fibres. These processes use catalysts made by coating platinum onto an alumina substrate in the form of small pellets or beads. Without these catalysts it would be very difficult to meet the demands of growing economies worldwide for products derived from petroleum.

Investment

Like gold and silver, platinum is a tangible asset which is accepted as a means of exchange by virtue of its internationally standardized form and purity. During the last thirty years a number of bars, ingots and coins have been introduced to meet demand for platinum which can be bought and kept as a repository of value, often for long periods. Various platinum coins have been issued including the American Eagle, the Australian Koala and the Canadian Maple Leaf.

In the 1980s concern over the security of platinum supply from South Africa led to a significant proportion of global demand to be accounted for by sales of platinum bars and coins. However, in the last decade investment demand fell away, with sales in 2005 accounting for only about two per cent of global demand. In 2007 and 2008 the situation changed again with increased investment in both platinum and palladium through two exchange-traded funds (ETFs) launched in 2007 and increased sales of large platinum bars, especially in 2008. Net investment demand for platinum and palladium in 2008 were 425 000 oz and 400 000 oz, respectively.

Platinum ingots are used a store of wealth for investment purposes. © Lonmin.

Dentistry

Palladium and, to a much lesser extent, platinum are important components of dental alloys used in inlays, bridges and crowns. The palladium and platinum are usually mixed with gold or silver in varying ratios. The choice of alloy depends on many factors including the technical performance, price and the preferences of dentists and their patients. Small amounts of ruthenium or iridium are sometimes added.

Platinum-containing high gold alloys have been used by dentists for many decades. However, from the 1980s onwards the use of palladium has increased chiefly in response to cost considerations. Most platinum-containing dental alloys are used in Germany and North America, while Japan is the largest consumer of palladium in dental applications.

Others

Platinum is also used in minor amounts in a host of other applications. The most important of these are in the non-catalytic automotive and biomedical sectors.

Non-catalytic automotive

A growing use of platinum is in the electrodes of spark plugs in gasoline engines where it has a much longer life and better performance than traditional base metal electrodes. It therefore contributes to lower service costs, more efficient combustion and reduced pollution. All new vehicles in North America are fitted with platinum plugs and their use in Europe and Japan is increasingly steadily.

Platinum is also an important constituent of oxygen sensors in the engine management systems of modern cars. These sensors are fitted to all cars equipped with an exhaust gas catalytic converter to ensure that the correct air-fuel mixture is burned and, in some countries such as the USA, a second sensor is used to monitor emissions. In the future demand for platinum in this application will grow as environmental regulation is increased worldwide.

Biomedical

The ability of platinum, in certain chemical forms, to inhibit cell division is the basis of its use in a range of anti-cancer drugs. The first of these, cisplatin, was introduced in 1977 and is widely used in the treatment of testicular, ovarian, bladder and lung cancers. Two other platinum-based drugs, carboplatin and oxaliplatin, which are less toxic than cisplatin, have since been introduced for the treatment of various cancers and are both now more widely used than cisplatin.

On account of its chemical inertness, high electrical conductivity and its ability to be fabricated into very small complex components, platinum is also an important component of various biomedical devices that are implanted in the body. Platinum electrodes are used in heart pacemakers and in implantable cardioverter defibrillators (ICD) used in the treatment of irregular heartbeat. Platinum marker bands and guide wires are also important components of catheters which are introduced into the arteries for the non-invasive treatment of heart disease.

Uses of ruthenium, iridium and osmium

Global demand for ruthenium (669 000 oz in 2008) is broadly comparable with that of rhodium. The main growth area for ruthenium is in perpendicular magnetic recording technology which is used in hard disk drive manufacture. Other applications include the electronics and chemical industries, and the production of flat plasma display screens. Small amounts are also used in jewellery and in fountain pen nibs.

Annual demand for iridium is considerably smaller (102 000 oz in 2008). It is used chiefly in process catalysts in the chemical industry and in spark plug tips. Osmium is used in small amounts in an alloy with platinum and iridium, which is used in pen tips, electrical contacts, filaments in light bulbs and in medical implants.

New technologies and expanding markets

Sophisticated emission control systems are being developed for modern diesel engines in line with the adoption of increasingly stringent environmental legislation in North America and the EU. Similar standards are due to be introduced in Russia, China, Brazil and India from 2010 onwards and it is very likely that similar measures will be adopted elsewhere in the future. In addition to the control of gaseous emissions, various systems employing platinum or platinum-palladium filters have been developed for cars in order to remove soot particles from exhaust emissions. In the future it is likely that gas and particulate emissions will be controlled by a single system known as a 'four-way catalyst' (Twigg and Phillips, 2009).

The use of platinum-group metal catalysts in emission controls from stationary applications is another area with significant growth potential. These applications include generators and turbines as well as many industrial processes such as cement, glass and nitric acid manufacture.

Considerable growth of demand for platinum, and possibly also palladium, is anticipated in the fuel cell sector as the demand for fuel efficient and non-polluting transport becomes an imperative. A fuel cell is an electrochemical device that converts the energy of a chemical reaction directly into electricity with heat as a by-product. A catalyst comprising platinum-group metals is a key component of these devices. The fuel, normally hydrogen, and oxidant (oxygen or air) are supplied externally so that, unlike batteries, they do not run out of power but continue to produce electricity while oxygen and fuel are supplied. Fuel cells offer major advantages over other technologies used for power generation, most notably their clean operation, but also their potentially greater fuel efficiency.

A huge amount of public and private research is underway to develop fuel cell technology, with most attention to date focussed on devices for powering cars, houses and portable electrical equipment. Commercialisation of fuel cell technology began in earnest in 2007 although the current manufacturing capacity is small and the units remain relatively expensive.

Various fuel cell-powered demonstration vehicles have been developed in recent years but the first commercially available fuel cell car, the Honda FCX Clarity, was launched in California in 2008. These vehicles appear now to be truly practical alternatives to gasoline-powered cars. Battery technology currently offers only limited range and takes several hours to recharge. In contrast fuel cell cars can be refuelled in minutes and have a range exceeding 200 miles on a single tank of hydrogen. The UK's first hydrogen fuel station opened in 2008 at the University of Birmingham to aid in the evaluation of its fuel cell vehicle fleet.

There are many other opportunities for the future utilisation of fuel cells. These include consumer electronics, such as laptop computers and mobile phones, where the potential is huge, to combined heat and power supply in stationary applications such as houses and businesses, both as a primary source and a backup source of supply. Another potentially large use of fuel cells is in military applications where they could replace generators and batteries.

The use of platinum-group metals in a range of specialist alloys is another area of expected growth. Ruthenium, together with rhenium, is increasingly being used in nickel-based superalloys in turbine blades for jet engines. The ruthenium and rhenium are used to improve the strength, durability and resistance to creep of these alloys, which may comprise 3 to 6 weight per cent of these two elements. As the market for air travel expands so will the demand for ruthenium for this purpose.

The Mercedes F-Cell A class is a fuel cell vehicle currently on customer trials around the world. © Mercedes-Benz.

The use of platinum in biomedical applications is also expected to continue to grow. New anti-cancer drugs are being developed, such as satraplatin for the treatment of prostate cancer. Increased use of ICDs for the treatment of heart diseases is also expected.

Like gold, platinum is viewed by many as a safe haven for storing wealth in times of economic uncertainty. Consequently, given the current global economic turmoil, the increased demand for platinum and palladium from the investment sector in 2008 may continue in the short- and medium-term. The availability of exchange-traded funds (ETFs) makes investment in platinum and palladium simpler and easier than in the past.

World resources and production

Resources
The Merensky, UG2 and Platreef in South Africa dominate world platinum resources. It is difficult to give a reliable estimate for the total quantity of platinum in the Bushveld Complex due to its enormous size. One study estimated that proven and probable reserves of platinum are in the order of 204 million oz, with potential resources of 937 million oz, or 75 per cent of the world's total platinum resources (Cawthorn, 1999). This alone would be sufficient to meet global needs for at least 40 years based on current production rates. However, these estimates are based only on resources in the Merensky, UG2 and Platreef down to a depth of approximately two kilometres. Platinum mining below two kilometres is already taking place at Northam, and there is therefore significant potential to exploit further platinum resources at greater depth. In addition, there are several other units in the Bushveld Complex that could potentially be exploited for PGE if market conditions were favourable.

Whilst the majority of PGE resources are located in South Africa, there are also considerable resources in other parts of the world, notably in the Great Dyke in Zimbabwe, the Stillwater Complex in the USA, and in nickel-copper deposits, for example in the Sudbury area of Canada and in the Noril'sk-Talnakh district of Russia. In addition, the general rise in the price of platinum over the last 20 years has led to renewed interest in several areas and deposits previously thought to be uneconomic. These include the Skaergaard Complex in Greenland, the Duluth Complex in the USA, and the Penikat and Keivitsa Complexes in Finland.

Proven and probable ore reserves in the Noril'sk-Talnakh area are reported as 63 million oz of palladium and 16 million oz of platinum at a combined grade of 7.54 grams per tonne. Measured and indicated mineral resources contribute

an additional almost 140 million oz of palladium and over 40 million oz of platinum (Norilsk, 2006). The Stillwater Mining Company has a reported 23 million oz of palladium and platinum in the proven and probable reserve categories in the Stillwater Complex in Montana, USA (Norilsk, 2006).

Production
Global demand for platinum fell by 5 per cent to 6.35 million oz in 2008, although demand still exceeded supply and caused a deficit of 375 000 oz in 2008 (Johnson Matthey, 2009). World platinum production declined for the second consecutive year, principally due to lower production from South African mines caused by unscheduled maintenance shutdowns, safety concerns, geological problems and labour disputes.

South Africa is the largest platinum producer, accounting for almost 78 per cent of world production (Figure 7). Other major suppliers of platinum include Russia, from the Noril'sk operations, and the Stillwater Mine in Montana, USA. Small quantities of platinum are produced in Zimbabwe, Canada (Lac des Iles mine and Sudbury), and in Australia, as a by-product of nickel mining. Platinum is also produced from the Jinchuan Complex in China, although recent production figures are unknown.
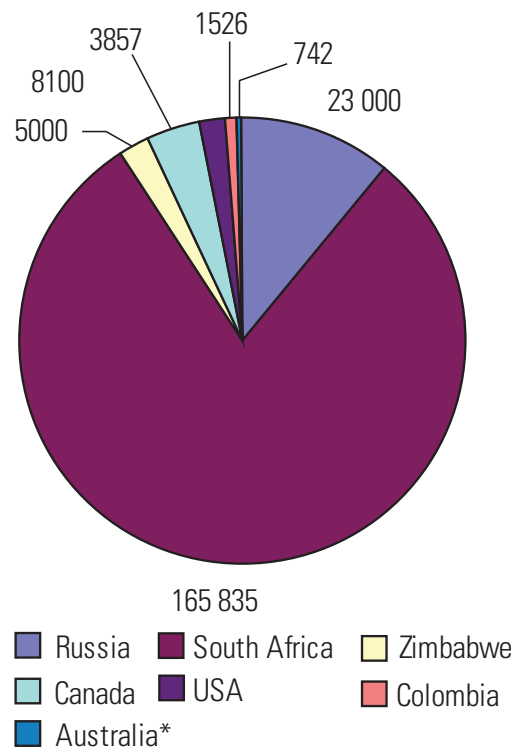
*Australia figure includes platinum and palladium

Figure 7 World mine production of platinum 2007 (kilograms). Source: British Geological Survey World Mineral Statistics database.

13 312   742
14 100
4000

96 800

86 461

■ Russia   ■ South Africa   □ Zimbabwe
■ Canada   ■ USA   ■ Australia*

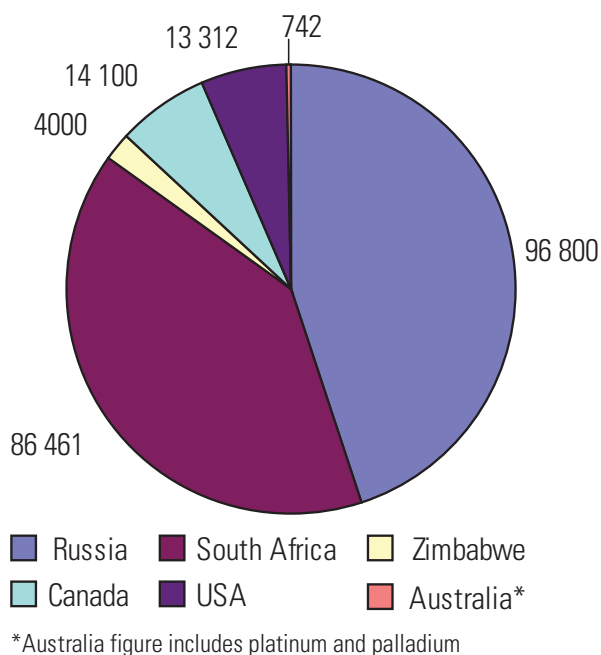*Australia figure includes platinum and palladium

Figure 8 World mine production of palladium 2007 (kilograms). Source: British Geological Survey World Mineral Statistics database.

As in recent years, platinum production from South Africa rose slightly in 2007. This increase is attributed to the continuing expansion of existing platinum mines, restarting of mothballed operations and new platinum mines coming

on stream. The new mines include several on the Eastern Limb of the Bushveld Complex (e.g. Anglo Platinum's Twickenham and Lebowa mines), as well as the previously dormant Crocodile River mine (Impala) on the Western Limb.

Australia produced slightly less PGE in 2007 than in 2006, whilst Canada produced marginally more from the Lac des Iles operation, though this mine temporarily closed at the end of October 2008.

Production of palladium is dominated by Russia and South Africa (Figure 8). World palladium production dipped slightly in 2007 compared with 2006 figures caused by a slight fall in production from Noril'sk and Stillwater.

In the decade up to 2006 production of platinum rose steadily in response to increased demand in autocatalysts and a shortfall in stocks. In 2007 there was a slight decrease in platinum production and this trend is expected to continue in 2008 in response to reduced demand and lower prices brought about by the global economic recession.

Overall the production of palladium has declined in the past decade (Figure 9). There was a sharp fall in 2002 as a result of the high price level, leading to substitution of palladium by platinum in autocatalysts. The rise in palladium production since 2002 is due to vehicle manufacturers again substituting palladium for platinum due to the significant

Figure 9 World mine production of platinum and palladium 1997–2007. Source: British Geological Survey World Mineral Statistics database.

price differential between the two metals. It is anticipated that the global economic recession will lead to significantly reduced palladium demand in 2008 and 2009.

World trade

Platinum is traded in many forms, generally in either unwrought (ores, concentrates, powders) or in manufactured or semi-manufactured forms (e.g. ingots, wire, mesh). Platinum trade is complex as significant quantities of mattes are processed in countries other than those in which they have been produced. For example, many nickel-copper mattes from Canada are processed in the UK and Norway.

Imports of platinum are dominated by leading industrialised nations. These include the UK, (>90 000 kg in 2008), the USA (>67 000 kg), Switzerland (>67 000 kg) and Japan (>65 000 kg) (Figure 10). The majority of imported metal is used to make catalytic converters for vehicles, but some is also used for investment. Significant quantities are also consumed in the jewellery business in the Far East, although in recent years demand has fallen slightly. In the UK platinum is refined at the Johnson Matthey refinery in Royston, Hertfordshire, and at several other small refineries that mostly process high-value secondary scrap items.

Exports of platinum are dominated by South Africa, which is also the world's leading producer (Figure 11). South Africa exported almost 157 000 kg of platinum in 2007, more than twice the quantity from the next biggest exporter, Switzerland, which is not a primary producer. Many of the world's leading industrial nations, including the UK, USA, Germany and Japan, also export significant quantities of platinum. However, of these countries, only the USA is a primary producer
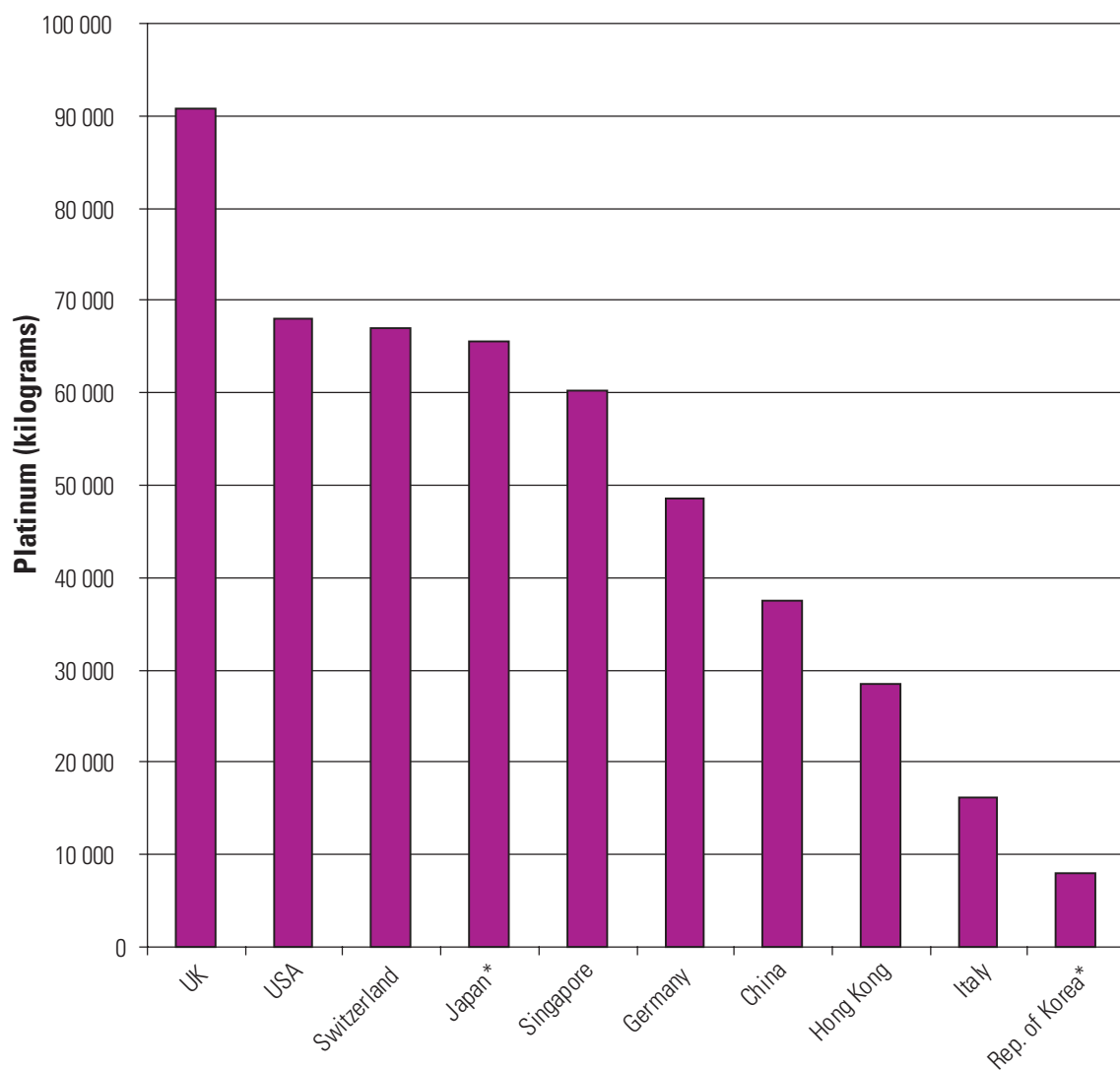

*Figure 10 Major importers of platinum metal, concentrates and intermediate products, 2008. Source: United Nations Commodity Trade Statistics Database (UN Comtrade). Trade figures for Indonesia have been excluded from the import and export charts due to uncertainties regarding the reliability of the data. Nations with * indicate 2007 figures.*
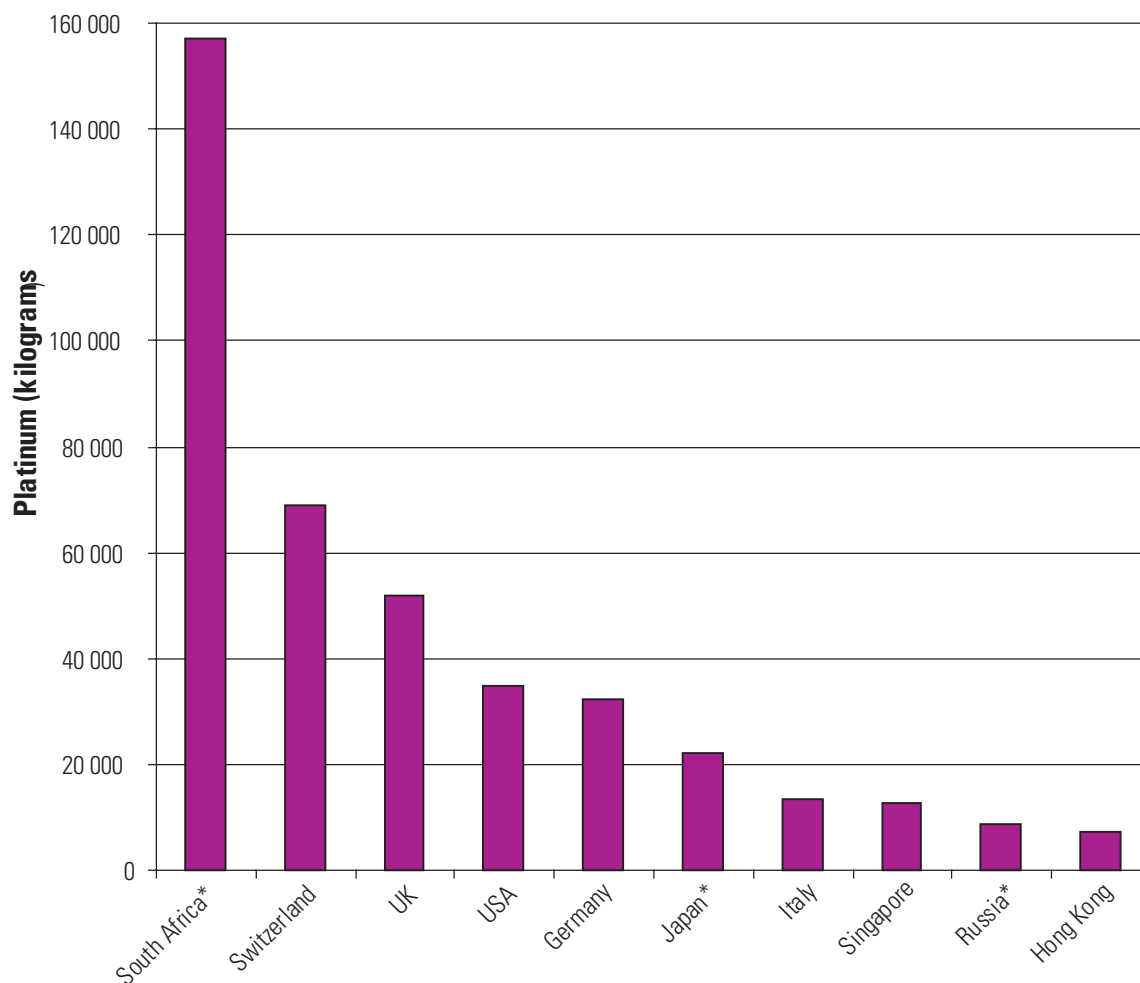
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*Figure 11 Major exporters of platinum metal, concentrates and intermediate products, 2008. Source: United Nations Commodity Trade Statistics Database (UN Comtrade). Trade figures for Indonesia have been excluded from the import and export charts due to uncertainties regarding the reliability of the data. Nations with * indicate 2007 figures.*

Prices

A number of daily market prices are quoted for the pure (minimum 99.9 per cent) metals in US dollars per troy oz. These include the LME settlement price, the European free market price, the Engelhard base price, the Johnson Matthey base price and the London Platinum and Palladium Market prices. In the spot market platinum and palladium are sold for cash and immediate delivery in plate or ingot form.

Unlike gold, platinum is an important and widely used metal in industry. Consequently the price of platinum is predominantly determined by normal supply and demand relationships, although movements in the gold price do have a marginal effect on the platinum price.

The price of platinum has experienced periods of volatility over the last decade (Figure 12). Throughout the 1990s, the price hovered around US$400 per oz, approximately US$250 per oz lower than the highest price for platinum in

the early 1980s. However, after legislation requiring cars to produce less pollution was introduced towards the end of the twentieth century, demand for platinum and palladium in catalytic converters increased markedly. This led to a dramatic increase in the price of platinum from US$420 per oz in August 2001, to just over US$1500 by December 2007. The price continued to rise through the first quarter of 2008 and reached a record level of US$2276 per oz in March 2008 (Metal Bulletin, 2009) attributed to a combination of rising demand, principally by vehicle manufacturers, and a shortage in supply. However, the global financial crisis, which began in the middle of the year, caused a dramatic fall in the price of platinum to just over US$800 per oz by mid-December (Mining Journal, 2008). The price began to rise again in 2009 reaching just over US$1200 by the end of June.

The price of palladium peaked at over US$1000 per oz in early 2001 and was almost double the price of platinum at the time. This was due to the high level of use by vehicle manufacturers in catalytic converters. However, since

Figure 12. Platinum and palladium price (Johnson Matthey base price (unfab) $ per troy oz (Metal Bulletin).

2001, the price of palladium has fallen back to between US$200 and US$400 per oz. The price briefly surpassed US$500 per oz in 2008, but had fallen back to just under US$200 per oz by the end of the year as the economic downturn reduced demand for the metal. At the end of June 2009 the price had rallied to US$250 per oz.

Recycling, thrifting and substitution

Recent high prices have ensured a growing interest in recycling and in thrifting of the PGE i.e. using less material in a particular application with little or no reduction in performance. For example, technological advances in recent years have allowed a considerable reduction in the quantities of PGE used in automotive catalysts. Considerable research is also devoted to finding alternative cheaper materials to substitute for the PGE in certain applications.

In the late 1990s, 85 per cent of palladium was used in the electronics industry to produce multi-layer ceramic capacitors (MLCCs), which are widely used in mobile phones. The rapid rise in palladium's price in the early 2000s saw manufacturers switch to using nickel, and at one stage more than half of the MLCCs produced were made with nickel. The use of palladium pastes for the conductive elements of hybrid integrated circuits (HIC) was

also affected by the higher price of the metal in the early 2000s and demand declined as manufacturers moved to silver-palladium pastes with higher silver contents. In addition to the substitution of PGE for other metals, some PGE have been substituted for others, particularly due to fluctuations in prices. For example, in recent years there has been increased use of palladium in three-way catalysts for petrol cars with manufacturers moving to increase the proportion of palladium to platinum in diesel catalysts which formerly used platinum as the sole catalytic metal.

In certain sectors, such as the automotive, electronics and glass industries, there has been very strong growth in demand for PGE in recent years. Although the global economic recession has had a significant impact, especially on the automotive industry, it is likely that in the medium and long term demand for PGE in these sectors will continue to grow strongly.

The high prices commanded by PGE have led to considerable recycling in many applications. Autocatalysts are particularly important sources for recycled PGE, and quantities have risen from 420 000 oz Pt and 195 000 oz Pd recovered in 1999 to just over 1 million oz Pt and 1.1 million oz Pd in 2008 (Johnson Matthey, 2009). There is no universal technique for recovering PGE from post-consumer scrap, such as electronic items, jewellery, and autocatalysts. Scrap autocatalysts are melted at a very

high temperature with iron or copper in order to fuse the catalyst substrate and dissolve the PGE. The alloy obtained from this process is then leached to dissolve the copper or iron, and the resulting PGE concentrate is refined at a precious metals refinery.

Focus on Britain

Occurrences and potential

There are no deposits of PGE in Britain that are of current economic interest. However, in-situ PGE-bearing mineralisation of magmatic, hydrothermal and near-surface origin has been documented (Gunn and Styles, 2002). In addition, grains of platinum-group minerals and other phases containing PGE have been found in overburden and stream sediments, without any identified bedrock source. Significant occurrences are shown in Figure 14.

The Caledonian mafic-ultramafic intrusions of north-east Scotland have been the major focus of exploration for magmatic nickel-copper±PGE mineralisation. Deposits of this type, with up to 0.5 g/t Pt+Pd, have been identified in the Knock intrusion, near Huntly, and at Arthrath, near Ellon, in contaminated and xenolithic gabbroic rocks. A magmatic origin, subsequently modified by hydrothermal reworking at high temperatures in shear zones, is proposed for the mineralisation in these areas. PGE enrichments, up to 280 ppb Pt+Pd, also occur in clinopyroxene-bearing ultramafic rocks in deformed mafic-ultramafic intrusions along a major shear zone in the Upper Deveron valley near Huntly.

On the north-western margin of the Caledonian orogenic belt[53] in Scotland, PGE mineralisation, up to 878 ppb Pt+Pd, occurs over a 2 km strike length within the Loch Borralan alkaline intrusive complex. Two phases of mineralisation are evident: a late-magmatic phase comprising base-metal sulphides and rare PGE sulphides; and a later, low-temperature phase with PGE tellurides and antimonides associated with shearing, brittle fracturing and veining. A hydrothermal origin involving the introduction of arsenic and antimony and the redistribution of early-formed sulphides is proposed for this mineralisation.

High PGE concentrations occur at several stratigraphical levels in the Unst ophiolite, Shetland. Pt and Pd both exceed 100 ppm close to the basal thrust of the ophiolite in a zone of talc-carbonate alteration. An origin related to late hydrothermal processes focused in fault zones has been proposed to explain this PGE enrichment and the associated copper, arsenic and nickel (Gunn and Styles, 2002). Lower grade Pt-Pd-dominant mineralisation has

also been reported in the cumulate sequence of the complex. Elsewhere on Unst, PGE mineralisation more typical of ophiolites, dominated by Os, Ir and Ru, occurs in association with chromitites.

PGM have also been identified in layered ultramafic rocks in the Tertiary igneous centres on Rum, Mull and Skye in north-west Scotland. In each case abundant and diverse PGM assemblages have been recorded. They are most widespread on Rum where they occur as thin, laterally extensive concentrations, in the range 1–2 g/t total PGE,
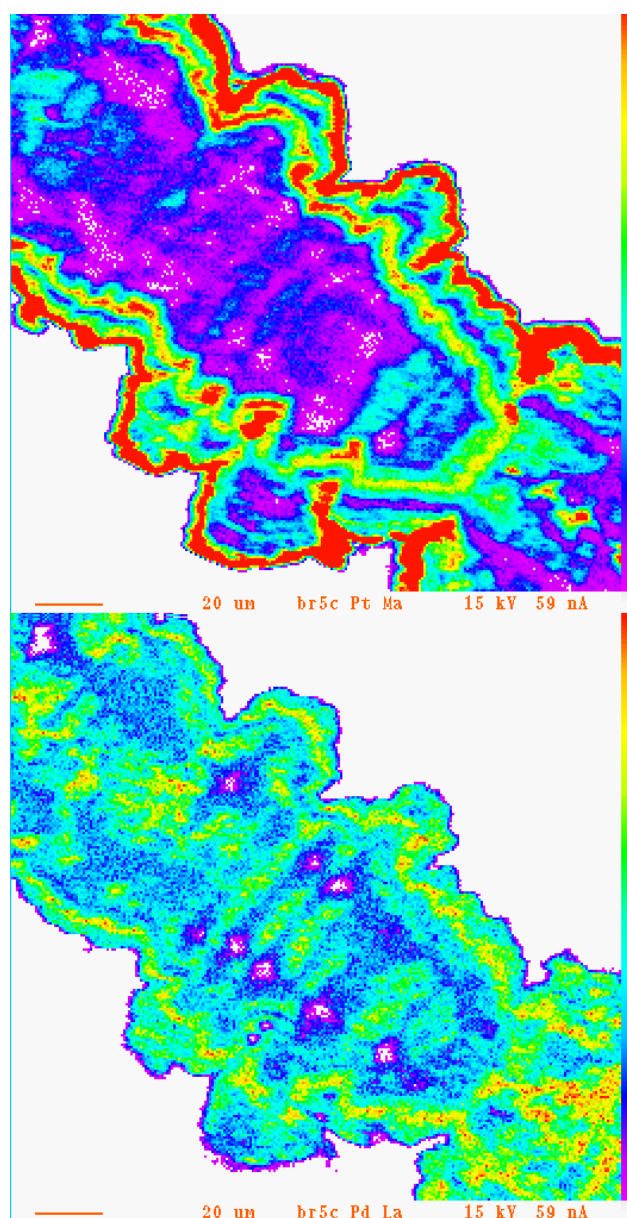

Figure 13 Microchemical maps showing the distribution of platinum (top) and palladium (below) in a gold grain from South Devon. Note the field of view is approximately 200 µm across. Red and yellow indicate high concentration of PGE, blue and green low concentrations.

[53] Caledonian orogenic belt: a mountainous area covering the northern British Isles, western Scandanavia, eastern Greenland and parts of north-central Europe formed during the closure of the Iapetus Ocean, approximately 490-390 million years ago.

Shetland Islands

Unst

Loch Borralan

Knock

Upper
Deveron

Arthrath

Skye

Rum

Mull

Corrycharmaig

PGE occurrences

★ Intrusion-related

▲ Ophiolite

■ Unconformity-related

● PGE refineries

Mauchline Basin

Thornhill Basin

Leicester

Royston

Harlow

Enfield

Acton

Chessington

Cowbridge

Crediton Trough
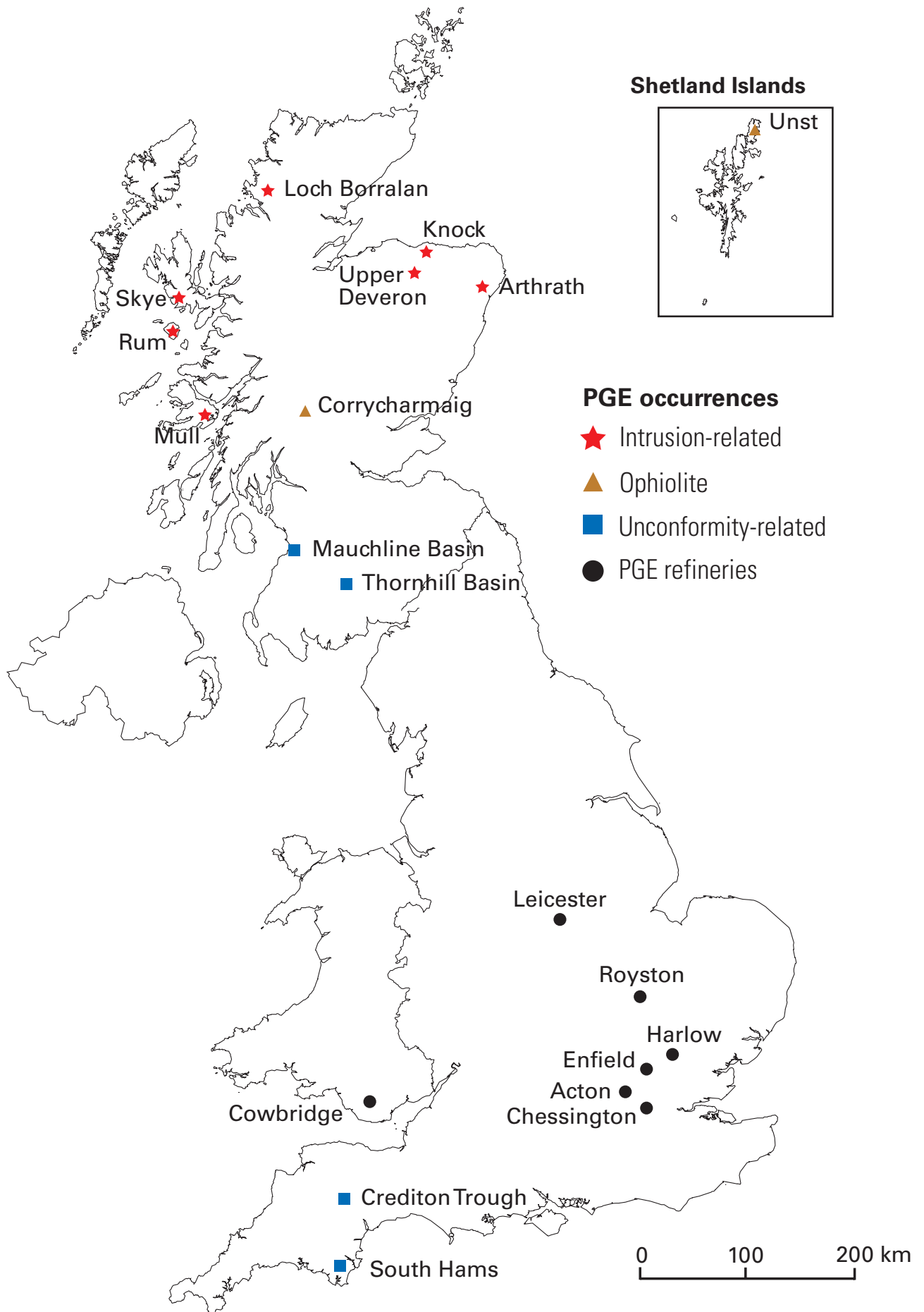
South Hams

0   100   200 km

Figure 14 Significant PGE occurrences and the location of PGE refineries in Britain. (OS topography © Crown Copyright. All rights reserved. BGS 100017897/2009).

associated with thin chromitite laminae containing trace amounts of iron-copper-nickel sulphides.

In several parts of Britain, a gold-PGE association has been identified at the unconformable boundary between Permian red-bed basins and underlying reduced strata. Complex gold-platinum-palladium grain (Figure 13) and discrete PGM are widespread in drainage sediments and overburden derived from the Lower Devonian and Permo-Triassic rocks in the South Hams and the Crediton Trough in Devon, and the Mauchline and Thornhill basins in southern Scotland. The genesis of the precious metal grains is attributed to metal transportation in saline oxidising fluids with deposition along faults and in favourable host rocks due to mixing with reduced rocks or fluids.

Refineries

A number of companies produce refined PGE in Britain, mostly by recycling spent catalysts and other secondary sources (Figure 13). Johnson Matthey Plc is a global leader in this sector but it is also prominent in the refining of precious metals from primary sources, with refineries at Royston in Hertfordshire and at Brimsdown, London Borough of Enfield. Johnson Matthey is also a major producer of PGE chemicals, materials for autocatalysts and components for fuel cells. It also produces a wide range of fabricated products for industrial and medical applications. Several other smaller companies operate refineries in Britain where PGE are recovered from a wide range of secondary materials including scrap and waste from the electronics, jewellery, dental, mining, chemical and petrochemical sectors. The UK has historically been a net exporter of refined PGE, based on the processing of scrap. In 2008 Britain exported over 51 tonnes of platinum, 56 tonnes of palladium and 12 tonnes of rhodium (UN Comtrade).

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Platinum

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