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Geology and economics of platinum-group metals in Australia

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ABSTRACT

Interest in the further discovery and exploitation of the platinum-group metals (PGMs) has intensified in recent years with increasing use of these metals in autocatalysts, fuel cells, petroleum refining, jewellery, coinage, etc., based on their rare or unique properties. Currently South Africa meets 80% of Western-world platinum demand, from the large deposits associated with the Bushveld Complex, the largest layered intrusion in the world. Australia's current production of PGMs, contained in nickel concentrates produced at Kambalda, is insignificant in world terms, and Australia is a net importer of these metals.

Recent discoveries, notably at Munni Munni, WA, Fifield, NSW, and Coronation Hill, NT, have highlighted the geological potential of Australia for discovery of PGMs, although, because of difficulties associated with recovery techniques and economics it would be some years before economic production could commence. Although the Bushveld Complex is almost certainly uniquely large and richly mineralised, a number of layered Precambrian mafic-ultramafic intrusions in cratonic terranes in Western Australia have potential for geologically similar mineralisation. Potential also exists in eastern Australia for small surficial deposits related to Alaskan-type and ophiolite-alpine intrusions, where cost-effective mining techniques can be quickly brought to bear during periods of favourable metal prices. The recent discovery at Coronation Hill, NT, of potentially economic grades and amounts of PGMs in host rocks not obviously associated with mafic-ultramafic magmas has led to the recognition of a 'hydrothermal-remobilised' class of deposit with a potential yet to be fully evaluated.

It is recommended that an expanding database should be compiled covering PGM exploration, ore genesis, reserves, mining, processing/metallurgy, and marketing economics. This would be a major contribution to the discovery of economic PGM deposits in Australia.

ECONOMICS OF PLATINUM-GROUP METALS IN AUSTRALIA

(L. M. Glaser)

Introduction

In any review of the economics of metal commodities, a large number of variables must be examined and quantified. There is a lack of definitive, quantitative information for the platinum-group metals on factors such as ore grades and reserves, metal recovery, production rates, mining costs, marketing practices, etc. However, enough information can be obtained from PGM consumers and traders, and historical records, to formulate a broad picture of the economics of these very rare metals. As with other commodities, the dynamic nature of the world economies acts to continually affect the parameters used in defining the economics of the PGMs.

The six platinum-group metals — platinum (Pt), palladium (Pd), rhodium (Rh), ruthenium (Ru), osmium (Os), and iridium (Ir) — share certain similarities in physico-chemical characteristics. They may be divided into the the heavy metals, Os, Ir, and Pt, and the lighter metals, Ru, Rh, and Pd. All six metals generally occur together in various geological environments, although their abundance ratios vary appreciably among types of deposits.

Historical perspective

Although the first identified use of Pt was in Egyptian hieroglyphics, it appears that this was simply an accidental substitute for Au. Platinum, first known by Europeans upon the colonisation of South America by the Spanish, was recovered by Colombian Indians during alluvial Au mining operations, but was discarded because it could not be shaped into objects. Between 1730 and 1772, the extensive counterfeiting of Spanish doubloons by Au coating Pt, spurred the authorities to order the disposal of all Pt into the sea, but by 1788, the Spanish government was purchasing Pt at 8 shillings per pound.

Colombia was the world's major supplier of Pt until 1824, when Pt alluvial deposits were first mined in the Urals. Because of low demand, the Russian Government supported these operations by incorporating almost half the production in the minting of Pt coins between 1828 and 1845. Three-rouble (10.35 g Pt), six-rouble (20.70 g Pt), and twelve-rouble (41.41 g Pt) coins were minted. About 75% of the 1 400 000 coins minted (14.75 t of Pt) were returned to the Soviet treasury at a later date. This early Pt production came from alluvial operations in the Miass, Bogoslov, Tagil, Biser, Goroblagdat, and Issovsk districts. The largest Pt nugget ever discovered (9.624 kg) was recovered from the Tagil operation in 1843. Russia remained the world's major supplier of Pt until the eventual depletion of these reserves, and the commencement of Ni-Cu mining in Canada in 1934, in which the PGMs are recovered as by-products.

In 1923, Pt was discovered in the Bushveld Igneous Complex in South Africa, and mining soon began. Since that time, Soviet production of PGMs has switched from Pt-dominant alluvials in the Urals, to Pd-dominant PGMs recovery as a byproduct of hardrock Ni-Cu mining. The Soviet Union remains the major world supplier of Pd.

The historical supply-demand structure for Pt is closely linked to the rise in Western world industrialisation since the second half of the 19th century. Although periodic price rises for Pt over this period can be attributed to various military conflicts and associated minor supply disruptions, significant price fluctuations more accurately reflect the time lapse between increased demand for Pt, due to advances in industrial technologies during and immediately after military conflicts, and increases in primary production. During this period, only Pt and Pd were of industrial value; use of Rh, Ru, Os, and Ir was limited to laboratories. During the 1980s, Rh has acquired a significant industrial use as a replacement for Pd in three-way automotive catalytic converters. Ruthenium, Os, and Ir are still only of value as alloying agents with Pt, Pd, and a few other metals. The market forces behind Ru, Rh, Os, and Ir are poorly constrained because of their minor production and consumption levels in comparison to Pt and Pd. The volatility of their prices may, in part, reflect the inelastic supply (dependent on the production of other metals) versus an elastic demand (periodic purchases for stockpiles and/or consumption in new applications).

The historical price structure of Pt is unlike that of Au, despite similarities since 1970. Platinum has never been subject to international monetary policies, and price fluctuations thus reflect normal market forces. Between 1900 and 1960, the price of Pt ranged between US$4.00 and $42.00 /oz, and annual fluctuations of 50% were not uncommon. Historically, price fluctuations have resulted from episodic growths in demand resulting from industrialisation of the Western world, and to a lesser degree, from political instability in source regions. There appear to be no fundamental differences in the 1980s Pt market in comparison to historical markets, aside from investor hoarding. Historically, Pt production has been dominated by one or two nations, while market concerns for supply disruptions, new discoveries, etc., have also always been in evidence.

Table 1. Properties of the platinum-group metals

	Platinum	*Iridium*	*Osmium*	*Palladium*	*Rhodium*	*Ruthenium*
Chemical symbol	Pt	Ir	Os	Pd	Rh	Ru
Atomic number	78	77	76	46	45	44
Atomic weight	195.09	192.22	190.2	106.4	102.91	101.07
Crystal structure (a)	FCC	FCC	HCP	FCC	FCC	HCP
Density ($g.cm^{-3}$)	21.45	22.65	22.61	12.02	12.41	12.45
Melting point (°C)	1 769	2 443	3 050	1 554	1 960	2 310
Vickers hardness	41	220	—	41	101	—
Electrical resistivity at 0°C (microhm.cm)	9.85	4.71	8.12	9.93	4.33	6.80
Thermal conductivity ($W.m^{-1}.°C^{-1}$)	73	148	87	76	150	105
Tensile strength (MPa)	139.0	1 096.5	—	169.9	695.0	556.0

(a) FCC — face-centred cubic; HCP — hexagonal close-packed.
Source: Johnson Matthey's *Platinum 1985*.

Properties and applications

The unique properties of the PGMs (Table 1) account for their use in a diverse number of industries and markets. Their high electrical and thermal conductivity, high resistance to corrosion and wear as alloys, selective resistance to acids, and extremely high melting temperatures, make them particularly well suited for use as electrical contacts in integrated circuits, in high-temperature electrical circuitry and thermocouples, as bushings in glass and glass fibre manufacture, and in laboratory vessels. Alloys are used extensively in jewellery, dentistry, and medical hardware, and certain Pt compounds are now being used in anti-cancer chemotherapy.

However, the catalytic properties of the PGMs constitute their major value in industry and agriculture. Platinum-rhodium alloys are used to oxidise ammonia to nitric acid, an intermediate step in the production of fertiliser. Platinum-group metals are also used for the production of sulphuric acid, and can convert alcohol to formaldehyde. In the automotive industry, currently the largest consumer of Pt, PGMs are used in catalytic converters to oxidise toxic carbon monoxide and hydrocarbons in exhaust gases to carbon dioxide, while reducing nitrogen oxides. The ratios and amounts of the PGMs used in catalytic converters vary with engine and fuel types, although conventional systems use Pt, Pd, and Rh. More recent systems, known as three-way catalysts, use only Pt and Rh in a ratio varying between 5:1 and 10:1.

Platinum fuel cells, which convert oxygen and hydrogen to water and electricity through the catalytic activity of Pt, are used in Shuttle spacecraft. Research on such fuel cells is increasing in the United States and Japan; although they are currently subeconomic, advances in efficiency are predicted, and a major new market for Pt and Pt alloys may develop by 1995.

Platinum was discovered as an element in 1735, and named *platina* (from the Latin for silver, after its silvery-white colour). It is malleable and ductile, does not oxidise in air, and has a melting point of 1769°C. Its coefficient of expansion is similar to that of soda-lime-silica glass and thus it is used to make glass-sealed electrodes. The pleasant colour, rarity, and hardness of Pt have led to its use in jewellery (generally as an alloy with other PGMs), particularly in Japan, while its high melting point and chemical inertness make it a valuable element in a diverse number of laboratory, medical, and defence-aerospace applications. Platinum is used in crucibles, thermocouples, high-temperature electric furnaces, coatings for missile nose cones, jet engine fuel nozzles, and other applications where long periods of operation at high-temperatures are required. Platinum's high conductivity is integral to its use in electrical contacts, particularly where alloys are used and resistance to both erosion and corrosion are required. Platinum-cobalt alloys are used in high-power magnets. Platinum can absorb large quantities of hydrogen and is used in hydrogen gas purification. However, its most important property, used in a wide range of industries, is as a catalyst to produce formaldehyde, and sulphuric and nitric acids. Platinum is also used in petroleum cracking, in catalytic converters for emission control on motor vehicles and has potential to be used commercially in electricity-generating fuel cells.

Palladium, named after *Pallas,* the Greek goddess of wisdom, was discovered as an element in 1803. It does not tarnish in air, has the lowest density and melting point of the PGMs, and is soft and ductile, although it can be work-hardened. It has the peculiar but important property of being able to absorb up to 900 times its own volume of hydrogen, which is released on heating, and therefore provides a means of purifying hydrogen gas. Ductile like Au, Pd can be beaten to a leaf thinness of 0.1 μm, and is also used in jewellery for white gold (an alloy of Au and Pd). Important applications include dentistry, watchmaking, surgical instruments, and electrical contacts. More recently Pd is being used in multi-layer ceramic capacitors and integrated circuits for domestic appliances, and in the military and telecommunication industries. In many instances, Ag is being alloyed with Pd in electrical applications where previously Pd alone was used. Although Pd has traditionally been used with Pt in catalytic converters for motor vehicles, advances in catalytic metallurgy are being incorporated in new-generation converters which use primarily Pt and Rh.

Rhodium, from the Greek, *rhodon,* a rose, was first discovered as an element in 1803–4. Rhodium has a melting point of 1960°C, is silver-white in colour, is hard and durable, and has high reflectance. It is used extensively as an alloying agent to harden Pt and Pd for furnace windings, thermocouples, bushings for glass fibre production, electrodes for aircraft spark plugs, and laboratory crucibles. Rhodium has a very low electrical resistance and is resistant to corrosion, thus being used in electrical contacts. Rhodium plating is exceptionally hard and is used as a reflective surface in optical instruments. More recently, increasing amounts of Rh are being used in place of Pd in new-generation catalytic converters with Pt.

Ruthenium, from *Ruthenia,* Middle Latin for Russia, reflects the early recognition of this and most other PGMs from alluvial operations in the Urals. It has a melting point of 2310°C, is hard, is white in colour, and only oxidises in air above 800°C. Ruthenium is the most effective hardening alloy agent for Pt and Pd where electrical contacts require severe wear resistance. Ruthenium-molybdenum alloys may be used as superconductors in a specific temperature range. The corrosion-resistance of Ti is improved 100 times by the addition of 0.1% Ru. Although it is a versatile catalyst, Ru can be highly toxic in certain forms.

Osmium, from the Greek, *osme,* a smell, was not discovered as an element until 1903. It is lustrous, bluish-white, extremely hard and brittle, and has the highest melting point of the PGMs, 3050°C. Osmium is also the second-densest element known, close to iridium. It can be highly toxic and is difficult to work with. Osmium has been used to detect fingerprints and to stain fatty tissue for microscope work, although it is more commonly used as a hardening alloy agent with other PGMs for fountain-pen points, instrument pivots, record player needles, and electrical contacts.

Iridium, from the Latin, *iris,* meaning rainbow, refers to the multiple colours of Ir salts. Iridium has a melting point of 2443°C, is white to slightly yellow, very hard, brittle, and thus difficult to work. It is the densest and most corrosion-resistant element known and is used to make high-temperature crucibles and apparatus, and electrical contacts, and is principally used as a hardening agent for Pt. When alloyed with Os, Ir may be used in the production of pen points and compass bearings. Iridium is used in the electro-chemical, aerospace, petroleum, and defence industries.

Potential substitutes

The current demand for Pt jewellery in Japan may be switched to Au should Pt prices increase significantly, or the attraction of Au increase, as a result of aggressive marketing. In certain applications in electrical contacts and capacitors, where pure Pd has traditionally been used, a Pd-Ag alloy is now in common use. Gold and W may also substitute for PGMs in electrical applications, while Au and ceramics may replace PGM alloys in dentistry, depending on the market and consumer preference. Research is currently under way into the use of rare-earth metals, Ni, V, Ti, and molecular sieves in place of PGMs in automotive catalytic converters, while continuing improvements in lean-burn engines, fuels, and ignition systems will probably lead to a reduction in the amount of PGM used per unit in emission control systems. The Pt and Pd gauze used in the production of nitric acid as an intermediate step in the manufacture of agricultural fertiliser cannot be replaced in current facilities, although new facilities, especially those planned for Third World countries, will probably use a PGM-free process in the production of urea. Also dependent upon marketing and political factors, investor demand for precious metals, which has been on the increase for Pt and Pd, may be substituted by a return to Au.

Table 2. World platinum and palladium supply and demand ('000 oz)

	1979	1980	1981	1982	1983	1984	1985	1986	1987
PLATINUM									
Supply									
South Africa	2 180	2 320	1 800	1 960	2 070	2 280	2 340	2 350	2 520
USSR(a)	460	340	370	380	290	250	230	290	400
Canada	130	130	130	120	80	150	150	150	140
Others	30	30	30	30	40	40	40	40	40
Total	2 800	2 820	2 330	2 490	2 480	2 720	2 760	2 830	3 100
Demand									
Japan	920	940	1 150	1 050	950	1 140	1 250	1 010	1 650
N. America	1 340	980	700	710	720	910	1 010	1 190	900
W. Europe	430	290	420	330	330	410	400	470	560
China	30	30	30	30	20	30	30	40	30
Others	160	120	160	230	180	170	170	170	180
Total	2 880	2 360	2 460	2 350	2 200	2 660	2 860	2 880	3 320
PALLADIUM									
Supply									
South Africa	...	...	...	820	790	980	1 010	1 040	1 090
USSR (a)	...	...	...	1 550	1 560	1 700	1 440	1 600	1 760
Canada	...	...	...	160	110	190	190	190	190
Others	...	...	...	70	80	90	90	90	90
Total				2 600	2 540	2 960	2 730	2 920	3 130
Demand									
Japan	...	...	...	890	1 220	1 250	1 080	1 230	1 420
N. America	...	...	...	860	830	990	940	965	1 100
W. Europe	...	...	...	350	470	520	520	540	555
Others	...	...	...	170	180	200	200	175	175
Total				2 270	2 700	2 960	2 740	2 910	3 250

Source: Johnson Matthey's *Platinum 1986, 1987, 1988.*
(a) Sales.

Supply

The world's supply of PGMs (Table 2) is dominated by South Africa and the Soviet Union, with lesser production from Canada, and only minor production from Colombia and the United States. Other countries, including Australia, produce only very minor amounts of PGMs as by-products of hard-rock Ni-Cu and/or alluvial mining.

Statistics on world PGMs supply from government publications need to be read with care because of differences between national primary production, secondary production, and national sales. Countries such as Great Britain, Japan, and Switzerland refine and sell but do not mine PGMs, while the sales of PGMs recovered from secondary scrap of previously imported PGMs also affects these figures. Additionally, there is little published information on production rates from the Soviet Union and South Africa, and much of the supply information must be gathered from traders and consuming industries.

South African production of Pt is derived from the Bushveld Complex, a major geological feature north of Johannesburg. *Johnson Matthey's 1988 Interim Platinum Review* estimates that South Africa will provide 2.54 million oz of Pt in 1988, equivalent to 80% of the total supply of 3.17 million oz from all market economy countries. The three largest South African Pt producers in descending order of production are Rustenburg Platinum Mines, Impala Platinum Holdings, and Westplat Holdings. This standing may be changed by 1991 with full production from Gold Fields' new Northam mine, also on the Bushveld Complex, making it the third-largest Pt producer in the world. All of the remaining PGMs are also recovered from these mines, although the ores are generally Pt-dominant. A number of planned expansions of existing operations and new mines were announced during 1987. These include:

— Lefkochrysos mine, near Brits in the western Transvaal, which is to exploit the Merensky and UG 2 horizons on a reserve base of 450 Mt. Operations are estimated to produce 5 t PGMs/year at a recovery ratio of 49 : 25 : 8 : 12 / Pt : Pd : Rh : other PGMs. Production is to commence in the year ending June 1989.

— Rhodium Reefs mine, near Steelpoort in the eastern Transvaal has reserves in exceess of 125 Mt at a grade of 6.28 ppm PGMs + Au (recovery grade of 4.36 ppm PGMs). Production is to commence in late 1992 at an initial rate of 180 000 t/month, to later expand to 270 000 t/month.

— Impala Platinum Holdings plans to open a new Pt mine (Karee mine near Marikana) in early 1988 on the UG 2 (180 Mt @ 5.3 ppm PGMs) and Merensky (130 Mt @ 5.5 ppm PGMs) horizons, near existing operations at Rustenburg. Production is planned to commence in early 1990, with reserves of 310 Mt, and production of 100 000 oz (3.1 t)/year Pt.

— Western Platinum Mines (Lonhro) plans to double output of PGMs to 500 000 oz (15.5 t)/year over a 5 to 6 year period commencing in 1988 with expansion on the UG 2 chromitite. Platinum production will increase from 165 000 oz (5.1 t)/year at present, to 270 000 oz (8.4 t)/year, which will maintain the mine's ranking as the third-largest in South Africa.

— Johannesburg Consolidated Investment is to expand output at the Lebowa (formerly Atok) Pt mine, from 30 000 t/month to 50 000 t/month during 1989 to 1990. The company also intends to commence production on the Maandagshoek Pt deposit in the eastern Transvaal.

Soviet PGM production and sales decreased from approximately 265 000 oz in 1982 to 200 000 oz in 1985, but rose to 383 000 oz in 1987. Total 1987 production, however, was probably close to 1 000 000 oz. All Soviet-bloc production comes from the Soviet Union (i.e. no Soviet satellite countries produce PGMs), originally from placer operations associated with Au in the Urals. Most production now comes from Ni-Cu mines in the Noril'sk–Talnakh region. The latter deposits are estimated to contain 0.47% Cu, 0.31% Ni, 0.1% Co, and 3.8 ppm total PGMs. Table 6 (p. 16) gives the relative concentrations of the PGMs in these and other deposits.

The remaining world production of PGMs is as by-products from Ni-Cu deposits in Canada and other countries, mines in the Zambian Copper Belt, certain volcanogenic Cu-Pb-Zn mines, and alluvials, while a new source of Pt may shortly be available from Cr mine residues in South Africa (G. Von Gruenewaldt, personal communication, 1987). Additionally, it is estimated that operations on the Stillwater Complex in Montana, USA will contribute 26 000 oz (0.8 t) Pt per annum, plus up to 75 000 oz (2.5 t) Pd, with minor amounts of Rh, Ru, Os, and Ir. The mine operators have announced plans to double output from 1989.

Although not currently a significant factor for Pt, the recycling of automotive catalytic converters, which each contain between 1.6 and 2.2 g combined PGMs (Pt, Pd, and Rh) may become an increasing secondary source of metals, although the future size of this secondary market is uncertain. Additionally, with the increase in investor hoarding of Pt and Pd since 1981, supplies of Pt and Pd may reach the market any time disinvestment is encouraged by market conditions, such as occurred in Japan in 1986.

Demand

The applications and useage rates of the PGMs reflect their many unique properties. Table 3 is a review of the PGMs consumption pattern for 1987. Although variations in applications and consumption with time are not shown, projections for future demand (and its effect upon future Australian PGM production) may be based upon historical variations in applications and rates, coupled with projections for the future strength of the US economy, and the growth of other industrialised and agricultural nations. Other factors, such as the introduction in Europe of emission-control devices on vehicles, petroleum prices, changes in acceptance of Pt jewellery, etc., must also be examined in more thorough studies on PGM demand rates. *Johnson Matthey's 1988 Interim Platinum Review* forecasts a 10% growth in demand for Pt in 1988, but only a 2.3% increase in primary supply. Total demand is predicted to attain 3.64 million oz, which would represent a 0.3 million oz rise over the record set in 1987. In 1988, it is estimated that demand will exceed newly mined supplies by 450 000 oz.

Table 3. Western world consumption pattern for platinum-group metals in 1987 (%)

Application	*Pt*	*Pd*	*Rh*	*Ru*	*Ir*
(Auto)catalyst	35	6	73	—	7
(Electro)chemical	6	—	7	36	13
Electrical	5	50	5	53	—
Glass	4	—	5	—	—
Hoarding	15	—	—	—	—
Jewellery	30	5	—	—	—
Petroleum	2	—	—	—	12
Dental	—	31	—	—	—
Other	3	8	10	11	68
	100	100	100	100	100

Source: Johnson Matthey's *Platinum 1988*.

The two largest consuming industries for Pt are the automotive industry (USA, Europe, and Japan) and jewellery (Japan). Neither consuming market is expected to increase markedly, although European policies on automobile emission control systems have increased PGM consumption in this sector since 1986. In the future, this increase may be offset by decreases in per-unit consumption in new-generation catalytic converters through advances in metallurgical technology. The Japanese jewellery market is traditionally price-sensitive, and significant increases in Pt and Pd prices may result in a transition to Au jewellery. During 1986 however, despite increases in Pt prices, consumption of Pt by the Japanese jewellery market increased, and new variables, such as acquisition of Pt jewellery instead of refined Pt bars by smaller investors, may have been responsible.

The demand for PGMs in the chemical, electrical, glass, and petroleum industries is strongly correlated with the growth of industrial and agricultural economies, although the application in the production of fertilisers is waning with the use of urea rather than nitric-acid-based components. No significant growth in PGM consumption in these industries (except petroleum) is estimated by Johnson Matthey Plc; only the petroleum industry may increase demand moderately.

The most distinct trend in Pt demand is the high growth in investor hoarding, from almost zero in 1981, to 9% of total annual PGMs production in 1985, and 16% in 1986. The metal is available as wafers, bars, and ingots minted by a few Swiss refiners, major producers such as the Soviet Union and South Africa, and major traders in the metal, e.g. Johnson Matthey Plc; and as medallions and coins, e.g. the Noble issued by the Isle of Man Government. During 1988, Canada, Australia, and the Soviet Union released plans to issue new platinum coins. The Canadian Maple Leaf and Australian Koala coins are minted with 99.95% pure platinum in 1.0 oz, 0.5 oz, 0.25 oz, and 0.10 oz weights. The first year's sales objective for the Maple Leaf is 150 000 oz, and for the Koala 100 000 oz. Because of the volatility of the investor market, projections for future demand are highly speculative. However, this is an important aspect of the market in that a sustained increase in investor hoarding will introduce a significant new factor to the Pt market. Hoarding increases above-ground reserves of the metal. As this is pure refined metal, it is readily disposable and may be traded quickly on the market during periods of increased prices, thus changing the conventional producer-fixed supply situation, and possibly volatilising Pt prices through rapid dumping of Pt on the market, such as occurred during October-November 1987. The future of Pt and Pd investment hoarding is reliant upon increases in disposable income and prices.

As Johnson Matthey Plc point out in their *1987 Platinum Review*, many of the 500 g to 1 kg Pt bars bought by Japanese investors in 1985 were sold during periods of high Pt prices in 1986. This disinvestment and resultant new supply source was offset by increases in Pt consumption by the Japanese jewellery market, and thus the supply-demand balance was not seriously effected. In North America where Pt hoarding has grown faster than in Japan, oversupply may occur in the future should disinvestment of refined metal upset the conventional supply versus demand balance.

Although there are currently no commercial fuel-cell electricity generating facilities, fuel cells, which use Pt as a catalyst, are currently used in the defence and aerospace industries, while research is being carried out in Japan and the USA in developing this new technology. The widespread use of fuel cells may have the same effect on the market as did the introduction of automobile emission control devices.

Prices, sales, marketing, and trading

The bulk of PGM primary production and sales are influenced by the centralised governments of the Soviet Union and South Africa. South African sales are primarily to Japan, the United States, and Europe, and much is sold on a long-term producer fixed-price contract basis to individual automobile manufacturing, jewellery fabrication, and electro-chemical firms. However, with the expected expansion of South African production from 1990, the structure of the traditional Pt sales arrangements will probably change, with a greater free-market trading influence.

Soviet sales are diverse, in part as a security measure to prevent the detailed assessment of production and marketing information by buyers and distributors. During 1985, 50% of Japanese Pd purchases were direct shipments from the Soviet Union, while the remainder was sold through Switzerland, Great Britain, and other PGM trading nations and corporations.

Most world PGM production is sold via contracts with individual consumers, and only a small percentage of the metal is ever available to brokers, traders, or investors.

Shares in publicly listed PGM producers are traded on most major exchanges, most notably London, New York Mercantile, Tokyo, Zurich, and Frankfurt. Koalas and older mintings of coins, such as the Soviet Pt coins, are available to investors. Platinum and Pd wafers, bars, and ingots are available to consumers in sizes ranging upwards from 5 g wafers. Ingots, bars, and wafers are sold with a purity ranging from 99.95% to 99.99%. A few organisations, such as Johnson Matthey and several European banks with strong precious-metal trading divisions and/or their own refineries, and brokerage houses, also sell Pt certificates.

To date, only Pt and Pd are minted into investor-sized bars; Os, Ir, Rh, and Ru are not commonly available to the investor market, partly owing to lack of demand and limited supply.

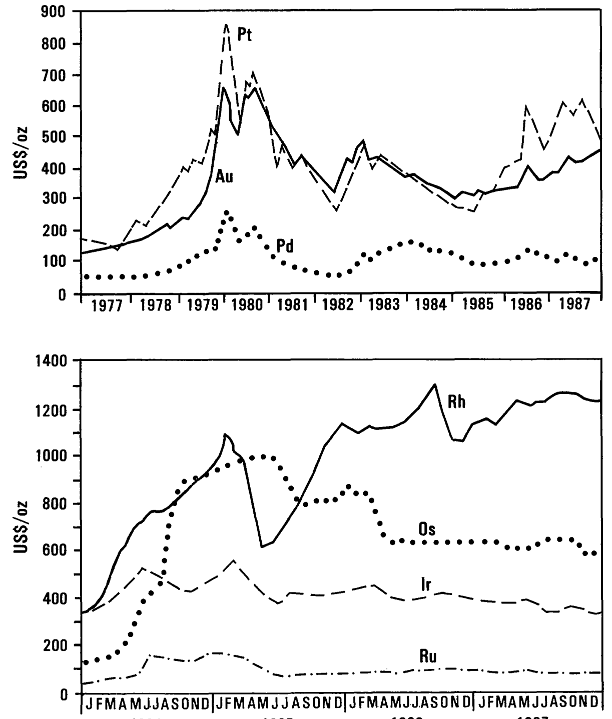

Fig. 1. Monthly average New York Dealer prices for the PGMs and gold (from *Johnson Matthey & Platinum 1988*).

Figure 1 shows variations in the monthly average New York Dealer prices for the PGMs and Au. It should be noted however that most PGM production is bought and sold by industrial users under long-term fixed-price contracts that may bear little resemblance to these figures. While Pt, Pd, and Au prices have historically a strong positive correlation, Pt and Au displayed minor reversals in relative values during 1980–81, 1985, and 1987. The price movements of the other PGMs display some mutual correlation, but because of the very small supply and resultant minor market activity, price fluctuations reflect periodic supply-demand imbalances created by fluctuations in industry demand. In November 1987, Pt and Au were once again at price parity.

Possible effects of world supply disruptions

A number of scenarios have been proposed to illustrate the likely effects of various forms of potential PGM supply disruptions. The root cause of these potential disruptions is the political-economic situation in the Republic of South Africa and disruption would range from short-term strikes by miners to complete closure of the mines. Although Soviet production is prone to sales fluctuations as dictated by the central government, there is no economic reason why Soviet supply disruptions, primarily of Pd, would occur.

There are two 'end-member' models for possible disruptions in South Africa, one of which has already been tested in part by strikes at the Impala mine. The first was suggested by the South African Government in 1986: that in the event of severe economic sanctions being imposed against South Africa, suspension of sales of PGMs might be considered in retaliation. However, in reality, this seems improbable in view of the economic damage that would be caused to South Africa, and the lack of support for international economic sanctions by the major PGM-consuming nations. The second model is worker action in the Pt mines and refineries, most likely in conjunction with strike action on the goldfields. The miners' unions (National Union of Mineworkers — NUM, and United Workers Union of South Africa — UWUSA), which were officially recognised by the government in 1979, have been actively representing the miners in negotiations for better working conditions and compensation. The 1986 strike at the Impala Pt mine, and more pervasive strikes at the mines in the second half of 1987 are examples. This concern for supply disruptions has had some effect on the PGM market during 1986 and 1987, and may account for the increased level of metal hoarding since 1981.

The effects of supply disruptions would be complex in view of the diverse uses of the PGMs. Although the market is able to adapt to substantial supply disruptions through decreased consumption, recycling, and substitution, the time factor has never been tested for this group of metals, i.e. we do not know the rate of response to disruptions in the ability to significantly increase recycling of catalytic converters, the rate at which fabricated Pt might be recycled, or new supply sources obtained. From market experiences during times of rapid Au and Ag price increases, the response rates between price rise and recycling of Au and Ag from fabricated jewellery, industrial scrap, etc., have been quite short, of the order of several months. However, compared with Au and Ag, the amount of above-ground Pt not being functionally used is low. Industry is already minimising PGM consumption and waste through recovery systems, so the ability to offset supply shortfalls through extensive temporary recycling seems unlikely. Decreases in consumption would be necessary, while moves to effect legislation requiring catalytic converters on vehicles in Europe, that would increase future Pt-Rh consumption, might be dropped. Conceivably, temporary legislation could remove the requirement for catalytic converters on vehicles in North America, while other uses, such as in dentistry, jewellery, and electronics, would depend more heavily on substitute metals where possible. Because of the growing Au production from non-South African sources, Au would be the most likely substitute for Pt and Pd. However, many of the physical properties of the PGMs are unique and they cannot be replaced in many strategic applications. Supply disruptions would clearly increase prices over the short term, and if sustained, would be a major contributing force behind decreases in consumption in the mid to long term.

Research on fuel cells, although perhaps curtailed, would probably continue, with more emphasis on non-PGM containing units.

There are other effects of threatened supply disruptions that are pre-emptive, and it is these which have influenced the Australian market most since 1983. In particular, the rate of exploration for PGM deposits in Australia, and worldwide, has increased not directly in proportion to PGM prices but rather to fluctuations in concerns about possible future South African supply disruptions, which would cause significant future price rises. Under such circumstances, larger exploration expenditures for PGMs are justified. Taking into account the time lapse between the commencement of exploration and the discovery and development of a significant reserve, current efforts seem well timed to take advantage of any possible major supply disruptions. However, it must be noted that assuming a stable production base in South Africa, any significant growth in the demand side of the market, e.g. the possible development of an economically viable fuel cell, may be met by increased primary production from South Africa, thus limiting upward price movements caused by increased demand.

Political-economic-strategic factors

In the 1980s the PGMs market has been dominated by increased industrial growth rates, internationally perceived threats to the stability of the production base, and changes to the economic viability of existing and planned mining operations, with implications for supply disruptions upon the automotive, electronics, and defence sectors. These factors include South African Government export sanctions, primary production shortfalls created through miners' strikes, increased production costs due to increased wages, and closure of the mines due to loss of key personnel. New primary supplies, such as from the Stillwater Complex and above-ground reserves in the form of refined bars, jewellery, and ore concentrates, are not sufficient to offset supply shortages from South Africa at current consumption levels.

Because of the unique properties of the PGMs, and their integral necessity in the functioning of defence-related items, e.g. integrated circuitry, aircraft and aerospace components, their strategic value remains a point of national concern to the Western world. Despite this, in a 1986–87 revision of the United States National Security Council report on policies regarding strategic mineral and metal stockpiles, no provision was made for enlarging PGMs stockpiles. This decision was based on a perceived lack of necessity to maintain stocks for a protracted conventional war, and assumes, in part, that the Stillwater Complex may be used as a domestic in-ground strategic reserve.

Australian production, refining, sales, and trade

Australian mine production, exports, and imports for the last 10 years are given in Table 4. The Australian production is contained in nickel concentrate produced at Kambalda, WA, by WMC Ltd; only minor amounts were recovered from other mining operations. Some of the Pt and Pd is recovered overseas during refining of exported Ni matte smelted at Kalgoorlie. The amount of Pt and Pd recovered during refining is not included in the statistical summary of Australian production. Palladium with Pt is recovered in Australia during treatment of copper sulphide residues from the Western Mining Corporation Kwinana Ni refinery, at the Port Kembla, NSW smelting-refining facility. The ERS Port Kembla refinery is the only operational primary PGM recovery facility in Australia.

Australian PGM recovery is Pd-dominant, as in the Soviet Union where the PGMs are also by-products of Ni and Ni-Cu operations. The ratio of recovered PGMs from these Ni operations is approximately 1 : 6.2 : 0.07 for Pt : Pd : Ru. Geochemical analyses of the ores indicate higher Pt concentrations than the recovery rates suggest.

The overseas trade figures reflect the net PGM importer status for Australia, which accounts for less than 1% of world trade. Imports are in refined bars, sponge, powder, and wire, primarily for domestic fabrication and consumption. Statistics of PGM demand patterns in Australia are not available, although the jump in imports since 1985 can be largely attributed to the demand for catalytic converters for motor vehicles.

Export figures are not entirely accurate, as much of the exported Pt and Pd was initially imported from overseas for fabrication in Australia.

Future Australian production: economics

Based on the results of the 4-year exploration period in Australia 1984–87, a strong case may be made for the discovery of one or more PGM hard-rock deposits capable of turning Australia into a PGM net exporting nation. During this period several prospects have generated considerable exploration interest; these include the Windimurra and Munni Munni layered intrusions of Western Australia, the Fifield intrusions of New South Wales, the Adamsfield and Heazlewood intrusions of Tasmania, and the Coronation Hill deposit of the Northern Territory. Additional interest in Os-Ir and Pt alluvials in eastern Australia suggests that this type of mineralisation may also have potential for small-tonnage deposits, which can be brought into production quickly. Since the sharemarket crash of October 1987, evaluation of these prospects has been continuing at a reduced intensity. How analogous these possible deposits will be to known PGM deposits such as the Bushveld and Stillwater Complexes, or alluvial deposits elsewhere in the world, remains uncertain. Although the Au mining boom in Australia since 1983 has demonstrated the

Table 4. Recent Australian mine production of platinum and palladium, and trade in platinum-group metals, alloys, and compounds (kg)

	1978	*1979*	*1980*	*1981*	*1982*	*1983*	*1984*	*1985*	*1986*	*1987*
Mine production										
Platinum	n.a.	86	64	65	74	55	66	95	115	130
Palladium	n.a.	214	328	401	416	461	523	476	428	490
Imports	4 669	4 157	25 663	23 422	3 831	1 904	576	1 217	967	5 848
Value ($'000)	2 578	3 892	4 540	3 171	3 422	2 940	3 309	12 130	18 628	27 200
Exports	1 838	339	256	146	895	296	18 727	313	4 888	6 769
Value ($'000)	925	986	1 175	652	2 071	1 360	3 720	1 684	4 178	5 448
of which,										
Re-exports	n.a.	n.a.	n.a.	72	634	55	18 282	32	3 871	85
Value($'000)	n.a.	n.a.	n.a.	297	973	228	1 227	209	110	1 340

Source: *Australian Mineral Industry Annual Review.*
n.a. Not available.

ability of the Australian mining industry to discover and profitably mine gold deposits over a very short time span in comparison to other nations, the recovery techniques and economics differ greatly for PGMs. Some analysts suggest that Australia will be producing moderate amounts of PGMs, comparable in production to Canada, within 10 years, but this seems unlikely in view of the specific problems associated with the mining techniques, economics, smelting, refining, metallurgy, and concentration, etc. of the PGMs. The mining and recovery technology unique to PGMs is not readily available to Australian industry or scientific institutions. The technologies associated with almost all facets of PGM mining and recovery are not published by either of the two major PGM-producing nations, South Africa and the Soviet Union. The problems posed by this lack of available information may be very substantial, and their solution will be expensive and time-consuming for any potential developer and will define the economics of the operation. Even in the United States, concentrates from the Stillwater mine are shipped to Belgium for refining, the purified metal then being shipped back to USA.

It is important to note that a moderate increase in international demand for PGMs will not significantly change the market in favour of Australian production because current developments in South Africa are geared towards increasing primary supplies from that country. Alternatively, any potential new Australian producers may be favourably situated because of the high-risk nature of South African supplies. It is possible that Japan might offer significant incentives to promote Australian production to ensure a stable PGM source for their domestic automotive, jewellery, and electronics industries. These incentives might include initial financing of mining and processing facilities, access to Japanese refineries and smelters, and also, importantly, a market for production which is currently tightly controlled by South Africa and USSR. Australian production might receive a marketing premium over South African prices because of the political acceptance of Australian policies compared to those of South Africa.

To estimate future Australian PGM production from as yet unidentified reserves is highly speculative and therefore impractical. Based on the historical perspective and experience gained from the Stillwater Complex and the effect of fluctuations in PGM prices, it seems probable that the wide range of problems inherent to PGM production, and the lack of an industry infrastructure for PGMs, coupled with the lack of any substantial known reserves in Australia, will hinder any significant rise in Australian PGM production through to 1995. Even assuming a substantial increase in PGM prices as a result of speculative supply disruptions in South Africa, Australia's ability to accelerate exploration, discovery, and development to yield production for export within a more favourable producers' market is speculative in view of the current limited geological database. It seems likely that a stabilisation of prices above the 1987–88 levels would be a prerequisite for sustained development of a PGM industry in Australia, if indeed significant PGM mineralisation can be discovered. A temporary movement in prices similar to that experienced in 1979–81 would probably be missed by proposed producers in the period to 1995, and a stabilisation at higher prices, such as has occurred with Au, would pose a more realistic market for potential growth of an Australian PGM industry. Sustained, successful Australian production may be effected by either (1) a sustained elevation in PGM prices measured in US dollars, caused by either sustained supply disruptions or unexpected and sustained increases in consumption, (2) discovery of a PGM deposit(s) enriched in one or more specific PGMs, such as Pt and Rh, coinciding with increased prices for those individual metals, (3) a favourable Australia/US currency exchange rate such as has supported the Australian Au industry, or (4) discovery of a major high-grade deposit(s) capable of operating viably under depressed market prices due to the market oversupply created — assuming no South African or Soviet supply disruptions.

Because one of the major factors currently supporting exploration in Australia is an expectation of future price rises resulting from possible South African supply disruptions and/or increased South African mining costs, the future of Australia's PGM exploration and possible development is closely linked to political-economic forces in South Africa. As this variable is the least amenable to quantification in any modelling exercise, any projections for future Australian PGM production remain speculative. Projected increases in South African production with the development of new mines, and increases in output from existing mines, are geared towards maintaining the supply-demand equilibrium, thus limiting the volatility of the PGM market and increased prices. Assuming continuance of this equilibrium, potential Australian PGM producers must fully exploit variations in the Australia/US currency exchange rate, economic bonuses from multi-element deposits, and possible discoveries of new-type deposits that may be profitable under current market conditions.

WORLDWIDE GEOLOGICAL SETTING OF PLATINUM-GROUP-METAL DEPOSITS

(D. M. Hoatson)

INTRODUCTION

Platinum-group-metal deposits, like most metalliferous deposits, have diverse geological-tectonic settings. However, the large, layered, mafic-ultramafic intrusions, and to a lesser degree the placer deposits associated with Alaskan and ophiolitic intrusions, dominate the world's resources. Hydrothermal-remobilised deposits have only been recently recognised and represent another important potential source. Von Gruenewaldt *in* Von Gruenewaldt & others (1987a) has modified the classification of PGM-bearing mafic-ultramafic bodies proposed by Naldrett (1981b) to the scheme outlined in Table 5. Additional subgroups relating to hydrothermal-remobilised and sediment-hosted deposits have been added to Naldrett's (1981b) tectonically based classification.

The following summary is restricted to the large layered intrusions (B1, Table 5), ophiolite-alpine intrusions (C2a, Table 5), Alaskan-type intrusions (C2b, Table 5), and hydrothermal-remobilised settings (E, Table 5), since it is believed these deposits offer the greatest potential for discovery of a major PGM resource in Australia. Sudbury is generally considered unique, while the PGMs in many of the other deposits listed in Table 5 represent a minor component of the main Ni-Cu mineralisation.

LARGE LAYERED INTRUSIONS OF CRATONIC TERRANES (B1, Table 5)

The large layered mafic-ultramafic complexes, which dominate the Western world's PGM production (notably the Bushveld and Stillwater complexes), were emplaced during anorogenic periods in tectonically stable cratonic environments. The intrusions cover a wide age range, but the main PGM-hosting complexes were formed between 2000 and 2900 Ma ago, and exceed 5 km in stratigraphic thickness. The stable tectonic setting of these intrusions is also reflected in the lateral continuity of their layering and rock types, and the large conical or lopolithic form of the bodies. The intrusions vary from broadly concordant saucer-shaped bodies (Bushveld), to sectors of steeply dipping inverted cones (Skaergaard) or sheets (Stillwater), to funnel shaped bodies overlying narrow feeder dykes (Muskox and Great Dyke). The variable forms, attitudes and levels of erosion produce different surface geometries, and control whether the boundary contacts are regionally concordant or discordant to the magmatic layering within the body. Post-emplacement deformational and tectonic events as well as pre-existing structures such as major lineaments or sedimentary basins influenced the forms and locations of the intrusions. Many of the larger complexes are composite and consist of multiple lobes of contiguous but spatially separated smaller complexes. The magmas involved had a high normative orthopyroxene-to-clinopyroxene ratio, the crystallisation order generally being olivine, orthopyroxene, chromite, and plagioclase-plus-clinopyroxene. Rock types are diverse, from dunite, harzburgite, bronzitite, chromitite, norite, gabbro, and anorthosite, to granitic-granophyric roof rocks. The bulk composition of most intrusions approaches gabbroic.

The platinum-group minerals occur as native alloys, bismuthides, tellurides, or arsenides, or as solid solutions in sulphides, arsenides, and sulpharsenides. They generally have a close spatial relationship with Cu-Ni-Fe sulphides (the mineralised host rocks usually have < 2 volume-% sulphides) and/or cumulus chromite. Economic grades are generally in the range 8–22 ppm total PGMs for stratabound Merensky Reef-type mineralised horizons, although cross-cutting dunite pipes attain grades of 2000 ppm PGMs in the Bushveld Complex.

The stratigraphic level of PGM enrichment varies, and various styles of PGM mineralisation occur at different stratigraphic levels both within and between the major PGM-hosting complexes. For example, in the Bushveld Complex, PGMs occur in thin (1 m wide) sulphide-bearing stratabound horizons, 400 to 500 m above the stratigraphic level where plagioclase first becomes a cumulus phase and in the vicinity of cumulus augite joining cumulus orthopyroxene (Merensky Reef). Chromitite horizons (UG 2 and UG 3 chromitite layers), cross-cutting dunitic pipes (Onverwacht, Mooihoek, Driekop), and contaminated pyroxenites along the basal contact of the intrusion (Platreef) are also settings for PGM mineralisation in the Bushveld Complex. In the Stillwater Complex, PGMs are enriched in chromitites in the ultramafic zone, in a number of discontinuous horizons stacked above, along, and below the contact between an olivine-bearing zone and a lower gabbronorite zone (J-M Reef), and in felsic rocks 3 km above the J-M Reef (Picket Pin Zone). In the Great Dyke of Zimbabwe, and the Munni Munni Complex, Western Australia, elevated PGM values coincide with cumulus augite joining cumulus bronzite directly below the advent of cumulus plagioclase in gabbros (Prendergast & Keays, 1987). Thus, it is important when assessing the PGM potential of layered intrusions, to consider various models of PGM mineralisation, and to evaluate the total mafic-ultramafic stratigraphy for stratigraphically controlled and/or discordant PGM mineralisation.

OPHIOLITE AND ALPINE INTRUSIONS, AND ASSOCIATED PLACERS (C2a, Table 5)

Ophiolite complexes are fragments of oceanic crust and upper mantle that were emplaced during plate collision, i.e. the early, solid-state intrusive stage in tectonically unstable terranes. Irvine & Findlay (1972) consider that the ultramafic portions of ophiolites are composed of: (1) a lower part consisting of residual mantle material depleted by earlier partial melting, and (2) an upper crustal sequence, represented by an olivine-cumulus-rich differentiate derived from a partial melt of the mantle, generated at mid-ocean ridges. The complete ophiolite sequence includes a basal zone of tectonised peridotite overlain by a cumulus sequence ranging from peridotite to gabbro, followed by pillow lavas, feeder dykes, and marine cherts. Chromitites are typically podiform, and may occur either with dunites in the lower, mantle-derived, peridotite, or in the crustal cumulate sequence, or more commonly at the transitional zone between the depleted upper mantle peridotite and the layered mafic cumulate rocks. Enrichment of PGMs may accompany either the mantle chromitite succession or the crustal chromitites.

Alpine serpentinite bodies represent incomplete sequences of ophiolite complexes: they have similar tectonic settings and geochemical features to the ophiolites, but the volcanics and chemical sediments are absent.

Podiform chromitite deposits associated with ophiolite and alpine intrusions have been mined for their metallurgical-grade Cr throughout the world, but there has been only very minor exploitation of PGMs from this type of hard-rock source. Page & others (1986) documented PGM concentrations for 280 podiform chromitite deposits of Palaeozoic to Mesozoic age in California and Oregon: maximum concentrations were 2.53 ppm Pt, 0.2 ppm Pd, 0.14 ppm Rh, 4.93 ppm Ru, and 2.93 ppm Ir. They concluded that the low grades of the PGMs and the relatively low volumes of total PGMs indicate that the potential supply of by-product PGM from hard-rock mining of podiform chromite in ophiolitic intrusions is small.

Table 5. Classification of worldwide platinum-group metal deposits, with examples

A. SYNVOLCANIC DEPOSITS OF PRECAMBRIAN GREENSTONE BELTS	
1. Komatiitic association	
(a) Lava flows	Langmuir, Ontario; Kambalda, Western Australia (Green & Naldrett, 1981; Gresham & Loftus-Hills, 1981)
(b) Dunite-peridotite lenses	Agnew and Mount Keith, Western Australia (Marston, 1984)
(c) Uncertain type	Thompson, Manitoba (Peredery, 1979)
2. Tholeiitic association	
(a) Synvolcanic picritic layered intrusions	Carr Boyd, Western Australia; Pechenga, USSR (Marston, 1984; Gorbunov & others, 1985)
(b) Uncertain association	Lac des Iles, Ontario (Macdonald, 1987)
3. Uncertain parentage	
(a) Stratiform intrusions	Montcalm Gabbro, Ontario
(b) Tectonically reworked	Selebi–Phikwe, Botswana (Gallon, 1986)
B. INTRUSIONS EMPLACED IN CRATONIC TERRANES	
1. Unrelated to flood basalts	
(a) Large sheetlike layered intrusions	Bushveld Complex, South Africa; Stillwater Complex, Montana (Anhaeusser & Maske, 1986; Csamanske & Zientek, 1985)
(b) Dykelike intrusions	Great Dyke, Zimbabwe; Jimberlana Dyke and Munni Munni Complex, Western Australia (Wilson & Prendergast, 1987; Keays & Campbell, 1981; Hoatson & Keays, 1987)
2. Related to flood basalts	Noril'sk-Talknakh, USSR; Insizwa–Ingeli Complex, Transkei; Duluth Complex, Minnesota (Genkin & Evstigneeva, 1986; Lightfoot & others, 1984; Ripley, 1986)
C. INTRUSIONS EMPLACED DURING OROGENESIS	
1. Synorogenic intrusions	Råna, Norway; La Perousse, Alaska (Boyd & Nixon, 1985; Himmelberg & Loney, 1981)
2. Tectonically emplaced (plus associated alluvial deposits)	
(a) Ophiolite and alpine intrusions	Shetland Ophiolite, Scotland; Zambales Ophiolite, Philippines; Beni Bousera, Morocco; Ronda, Spain (Prichard & others, 1986; Santos, 1986; Leblanc & Gervilla-Linares, 1987)
(b) Alaskan-type intrusions	Tulameen, British Columbia; Goodnews Bay, Alaska; Choco, Colombia; Urals, USSR (St Louis & others, 1986; Mertie, 1969; Von Gruenewaldt & others, 1987)
D. ASTROBLEME-RELATED ?	Sudbury, Ontario (Pye & others, 1986)
E. HYDROTHERMAL-REMOBILISED	
1. Mafic-ultramafic host	New Rambler, Wyoming; Rathbun Lake, Ontario; Hitura, Finland; dunite pipes, Bushveld Complex (McCallum & others, 1976; Rowell & Edgar, 1986; Piispanen & Tarkian, 1984; Von Gruenewaldt & others, 1987)
2. Non-mafic-ultramafic host	Messina and Waterberg, South Africa; Coronation Hill, Northern Territory; Porphyry Cu-Mo deposits, Arizona and Little Caucasus, Armenia (Mihalik & others, 1974; Von Gruenewaldt & others, 1987; Faramazyan & others, 1970)
F. SEDIMENT-HOSTED	Kupferschiefer-Zechstein, Poland; Zambian copper belt; manganese nodules, Pacific Ocean (Kucha, 1982; Freeman, 1983; Hodge & others, 1985)

However, isolated occurrences of enriched PGM + Au levels have been documented in ophiolites, notably in the Cliff and Harold's Grave chromitite deposits of the island of Unst in the Shetlands, and the Acoje mine on Luzon Island in the Philippines. The Shetland ophiolite consists of a basal sequence of mantle-derived harzburgite with lenses of chromitite-bearing dunite, followed by a lower crustal sequence of dunite with chromitite pods and an overlying cumulate sequence of pyroxenite and gabbro. The chromitites are typically podiform, with a maximum thickness of 5 cm and strike length of 10 m. Gunn & others (1985) report that the PGMs from the mantle-derived chromitites are erratically distributed, but attain 82 ppm. Nine samples of the Cliff chromitites averaged 11.69 ppm Pt, 1.76 ppm Pd, 2.09 ppm Ru, 0.67 ppm Rh, 1.23 ppm Ir, and 0.87 ppm Os. Prichard & others (1986) noted alloys and sulphides of Ru, Ir, and Os in the Shetland ophiolites.

For the Zambales ophiolite, Luzon Island, Philippines, Bacuta & others (1987) document maximum PGM values in chromitites from the crustal cumulate dunite-wehrlite sequence as 5.96 ppm Pt, 8.35 ppm Pd, 1.10 ppm Ru, 0.76 ppm Rh, and 0.46 ppm Ir. The PGM-enriched chromitites are associated with base-metal sulphides, and contain up to 1100 ppm S. Bacuta & others (1987) consider the PGM–base-metal-sulphide mineralisation to be a primary magmatic feature, overprinted by postmagmatic alteration. Von Gruenewaldt *in* Von Gruenewaldt & others (1987a) highlighted several ophiolite complexes having Cu-Ni-Fe-Co-sulphide enrichment features. Detailed PGM studies of these unusual associations are lacking; however, total PGM + Au levels in ophiolitic sulphide or Ni-As ores from Troodos (Cyprus), Eretria (Greece), Acoje (Philippines), Illinois River (Oregon), Beni Bousera (Morocco), and La Gallega and Los Jarales in Spain have been reported in the 1.5 to 16.8 ppm range. Studies of Chinese podiform chromitite deposits show that the sulphide and sulpharsenide minerals, which are most common in the serpentinised parts of the ore, have resulted from the metasomatic and hydrothermal alteration of the Os-Ir-Ru alloys that occurred in less serpentinised ores. The economic potential of the ophiolite-sulphide association is unclear at this stage.

In contrast to the hard-rock deposits, placers derived from ophiolitic intrusions have been widely exploited for their PGM content. Cabri (1981) found that the platinum-group minerals are similar in the chromitites and the placers, both of which are enriched in Ru-Os-Ir with respect to Pt-Rh-Pd. The dominant phases are Ru-Os-Ir alloys such as rutheniridosmine, iridosmine, and osmiridium, with the sulphide and sulpharsenide minerals laurite, ruarsite, ruthenarsenite, irarsite, anduoite, and sperrylite uncommon to very rare (for compositions of minerals see Appendix 1).

ALASKAN-TYPE INTRUSIONS AND ASSOCIATED PLACERS (C2b, Table 5)

Concentrically zoned or 'Alaskan-type' complexes intrude orogenic zones during or after the late stages of the main deformation event, but before the emplacement of granite batholiths. Notable zoned intrusions with economically important associated placer deposits occur in southeast Alaska, the Urals, south-central British Columbia, Venezuela, and western Ethiopia.

Alaskan-type intrusions generally have a crude concentric zoning that consists of a dunitic core bordered by successive shells of olivine clinopyroxenite, magnetite-rich clinopyroxenite, and hornblendite, and are distinguished from alpine or layered intrusions in having a highly calcic diopsidic clinopyroxene, highly magnesian olivine (Fo_{75-95}), no orthopyroxene or plagioclase in the ultramafic rock units, abundant hornblende, and more Fe-rich chromite and magnetite (Naldrett & Cabri, 1976). Syenodiorite, syenogabbro, and monzonitic rocks of alkaline affinities are common felsic differentiates. The intrusions range from late Precambrian to Tertiary, most complexes being subcircular to elongate in outcrop, and covering less than 30 km^2.

They generally form well defined belts, e.g. the eleven Ural intrusions that occur over a strike extent of about 450 km.

St. Louis & others (1986) noted that Alaskan-type complexes tend to have a higher PGM content than alpine complexes, although their average Pt/(Pt + Pd) ratio (0.68) is slightly lower than that of the alpine complexes (0.73). Both types have considerably higher Pt/(Pt + Pd) ratios than the large layered complexes (0.51). The greater degree of fractionation of the Alaskan complexes compared with the alpine complexes is also reflected by their higher Pt/(Pt + Ir + Os) ratios. St. Louis & others (1986) reported that the chromitites of the Tulameen Complex in British Columbia contained the highest PGM contents, with average Pt levels of 3.41 ppm, and less than 0.1 ppm for the other PGMs. They also noted that the olivine-bearing rocks had relatively high Pt, Ir, Os, Rh, and Au and very low Pd concentrations compared to the other rocks. Palladium was concentrated in later differentiates and hornblende pyroxenite rock types. Clark & Greenwood (1972) found similar trends for the southern Alaskan intrusions, where the PGM levels were proportional to the olivine content of the host rock. Generally, in order of decreasing PGM content, the rock types were dunite, peridotite, pyroxenite, and hornblendite, although, conversely, in some intrusions, the hornblendites contained the maximun Pt and Pd concentrations. This led them to conclude that, although the PGMs are closely associated with sulphide and oxide phases, their distribution was largely controlled by olivine. They also noted there was a close correlation of Pt and Pd with Fe, Ni, Cr, Cu, and V.

Chromite forms masses and disseminations generally in the dunitic rocks and less commonly in olivine clinopyroxenites near the central region of the zoned intrusion. The massive chromite typically forms irregular lenses, veins and schlieren of less than 2 m strike extent. Cabri (1981) emphasises the irregular distribution of the PGMs in Alaskan-type intrusions, which is thought to be due to crystallisation of chromite and Pt-Fe alloys in brecciated, partly congealed dunite, during the later stages of crystallisation that involved more fluid magmatic components. This has created small discrete deposits having lengths ranging from 30 cm to 120 m and characterised by abundant chrome-rich accessory minerals. Fine-grained sulphides often form a minor component of most rock types. Mertie (1969) describes a small pod in the Nizhniy–Tagil district of the Urals as a mass of high-grade chromite-platinum ore that extended only for a distance of 2 m near the top of the orebody. A total of 965 oz (30 kg) of native platinum metals, which included masses up to nearly 14 oz (0.4 kg), was recovered from the deposit. Such deposits were typically widely spaced and rare.

The most important PGM placer deposits are assoociated with Alaskan zoned intrusions. These occur in the Tulameen region of British Columbia, Ural Mountains, Goodnews Bay in Alaska, and the Choco area in Colombia. Von Gruenewaldt *in* Von Grunewaldt & others (1987a) has summarised four categories of placer deposits in the Urals. These include: (1) residual and eluvial deposits (Lojok alluvials) containing weathered dunitic and pyroxenitic debris and grading downstream into headwater fluvial deposits, (2) placers in present valley floors, with PGM-bearing deposits up to 20 m thick and dispersion trains up to 50 km long from the dunite source, (3) Pleistocene terrace deposits on the sides of the main streams, but at no great distance above the valley floor, and (4) higher alluvium of restricted extent and possibly Tertiary in age.

The placer concentrates are dominated by Pt (85–95%), with minor Os and Ir (2–13%), and low Rh ($\leq$2%), Pd ($\leq$0.8%), and Ru ($\leq$0.2%). The Au contents of the Alaskan-type placers are variable: in the Choco area of Colombia Au predominates over the PGMs, but in most other placer deposits it is clearly subordinate to the PGMs. Platinum-group minerals are similar for the hard-rock and placer deposits. Platinum-Fe alloy, notably isoferroplatinum and platiniridium, are the most common minerals, with rarer osmiridium, iridosmine, cooperite, sperrylite, tulameenite, laurite, tetraferroplatinum, and irarsite. In the hardrock occurrences the Pt-Fe alloys are commonly enclosed in chromite, with the other platinum-group minerals generally interstitial to the chromite and associated with base-metal sulphides.

HYDROTHERMAL-REMOBILISED DEPOSITS (E, Table 5)

During the past 20 years there has been considerable debate about the relative importance of magmatic processes versus fluid-volatile processes in the formation of PGM deposits. Boudreau & others (1986), Stumpfl (1986), Stumpfl & Ballhaus (1986), and Schiffries & Skinner (1987) have used the occurrence of pegmatoidal horizons, discordant dunite pipes, potholes, vein systems, and petrological evidence, such as the distribution of Cl-rich phases, intergrowth of sulphides with intercumulus hydrous phases, graphite, and fluid inclusions in postcumulus quartz and feldspar to highlight the importance of fluid-volatile systems in the transport and concentration of PGMs in layered intrusions. In these models, Cl-rich fluids, which were generated by vapour exsolution from the intercumulus melt, liberated and transported PGMs upwards from the trapped liquid in the underlying cumulus pile, to interact with S in the reefs to produce PGM-rich sulphides. Barnes & Campbell (1988), however, argued that these hydrothermal-type features are the result of postcumulus processes superimposed on layers whose extensive, uniform PGM concentrations were formed by magmatic cumulus processes. In defence of a magmatic origin, i.e. the formation of PGM reefs from the accumulatiuon of immiscible sulphide droplets that were mixed with large volumes of silicate melt, Barnes & Campbell (1988) noted the close association of PGMs with the bases of cyclic units and with chromite horizons, which indicate a genetic relation to new magma influxes; the lateral persistence of grade of the Merensky Reef and UG 2 chromitite; and systematic stratigraphic controls on PGM tenors of sulphides within the UG 2 chromitite.

It is generally well recognised that large stratabound deposits, such as the Merensky Reef and chromitite horizons of the Bushveld, and the J-M Reef of the Stillwater Complex, are largely of magmatic origin, but it is also evident that late-magmatic and hydrothermal processes have also played a role in some deposits. There appears to be a spectrum of enrichment mechanisms, ranging from primary magmatic processes, through magmatic deposits which have various degrees of hydrothermal overprinting, to deposits that are largely hydrothermal. In this latter subgroup, the PGMs are commonly intimately associated with base-metal and/or gold-uranium ores deposited from solutions in regions that have a favourable structural framework and without spatial relationship to mafic-ultramafic rocks.

Hydrothermal-remobilised PGM occurrences are diverse in their settings, and encompass a wide range of temperatures and fluid compositions. They include C-O-H-S-Cl volatile-fluid systems at temperatures greater than 600°C in pegmatoidal pyroxenite horizons in layered intrusions, to chlorine brines around 300°C, down to temperatures of 4°C in seawater (Stumpfl, 1986). Examples of the lower-temperature environments include anomalous PGM levels in ferromagnesian nodules (Hodge & others, 1985), bituminous coal (Chyi, 1982), black shales of the Zechstein copper deposits (Banas & others, 1978; Kucha, 1975, 1982, 1985) and Zambian copper belt (Mertie, 1969; Unrug, 1985), in laterites (Bowles, 1986; Davies & Bloxam, 1979), and in a Salton Sea brine (Harrar & Raber, 1984).

Given favourable physico-chemical conditions, hydrothermal processes are potentially a very efficient mechanism for mobilising and transporting PGMs from an extensive source rock having background levels of PGMs to a site of deposition that may attain economic grades. This is indicated by deposits such as Coronation Hill, the Beaver Lodge Pt-Au prospect in Saskatchewan (Coronation Hill-type, with mineralised veins in cherty dolomites having grades of 1 m @ 361 ppm Au and 9.3 ppm Pt; *The Australian Geologist,* March 1988, 66, 11), the Waterberg district of central

Transvaal, and the crosscutting dunite pipes of the Bushveld Complex.

The creative setting of remobilised PGM deposits, ranging from low-temperature environments, to hotter, more volatile-rich hydrothermal systems, is often characterised by erratic mineralisation, making delineation and mining difficult. The mineralising systems at Coronation Hill were obviously of considerable magnitude and intensity, allowing scope for bulk, open-cut mining of disseminated-type ores. However, in many hydrothermal PGM deposits the mineralisation is more localised, e.g. in veins or pipes, and consequently mining has been selective and small scale.

Examples of hydrothermal-related PGM occurrences include: the Artonvilla mine at Messina, South Africa (Pt and Pd bismuthinides and tellurides in chalcocite, clausthalite, bornite, quartz, epidote, and chlorite-bearing veins in altered quartzites and gneissic host rocks: Mihalik & others, 1974); the Driekop dunite pipe, Eastern Transvaal (ferroplatinum, sperrylite, geversite, hollingworthite, and irarsite derived from the high-temperature aqueous fluids that formed the pipe: Tarkian & Stumpfl, 1975; Peyerl, 1982); the Waterberg district of the Transvaal (native Pt, Pt–Pd alloy, and stibiopalladinite in brecciated quartz, chalcedony, sericite, chromiferous chlorite, kaolin, hematite, and pyrolusite veins in felsite and tuffs of the Rooiberg Group: Ramdohr, 1969); the Hitura nickel-copper deposit of western Finland (sperrylite, michenerite, and Pd-bearing irarsite in chloritic rocks, serpentinites: Hakli & others, 1976); the Kollismaa layered complex, Finland (sperrylite, michenerite, and Pd-Bi melonite with Cu-Ni-Fe sulphides in alteration spots in gabbronorite: Piispanen & Tarkian, 1984); the Wanapitei intrusion, Rathbun Lake, Ontario (sperrylite and Pd-bismuthotelluride minerals in association with chlorite, quartz, epidote, sericite, and biotite in altered gabbronorite: Rowell & Edgar, 1986); the New Rambler copper mine, Medicine Bow Mountains, Wyoming (native platinum, sperrylite, and Pd and Pt tellurides and bismuthotellurides in association with chalcopyrite in sheared metagabbro: McCallum & others, 1976); Nicholson-Fish Hook Bay region of Saskatchewan (U-PGM-Au mineralisation in carbonate-hematite-pitchblende infills in sheared dolomitic quartzite, in proximity to peridotites: Hulbert & others, 1988); and various Cu-Ni deposits on the Kola Peninsula, and in the Noril'sk-Talnakh region of western Siberia (Yushko-Zakharova & others, 1967). Molybdenum-Cu mineralisation in skarn and hydrothermal veins in China contains anomalous Os, Pt, and Pd levels (Yang & others, 1975), and hydrothermally altered rocks in the porphyry Cu-Mo deposits in Armenia have elevated Pd and Pt concentrations (Faramazyan & others, 1970).

FOUR IMPORTANT DEPOSITS

The Bushveld and Stillwater Complexes have dominated research and concepts of PGM mineralisation since their resource potential was realised in 1923 and 1967, respectively. Despite the long history of multidisciplinary research on these deposits, many fundamental aspects such as parental magma types, the origin of layering, and the genesis and transport of the PGMs remain controversial. This uncertainty is particularly evident now that the PGMs are recognised to be chemically more mobile, and widespread in their occurrence, than originally conceived. Deposits such as the New Rambler, Nicholson Bay, and Coronation Hill, have broken new ground in our understanding of the behaviour of the PGMs.

The following section describes PGM mineralisation in the Bushveld and Stillwater Complexes, and the New Rambler and Coronation Hill deposits which represent the 'new thinking' in PGM genesis.

Bushveld Complex

(Naldrett, 1981a; Campbell & others, 1983; Von Gruenewaldt & others, 1985; Hulbert & others, 1988)

Geological setting

The Bushveld Complex, in the Kaapvaal craton of southern Africa, is the largest layered intrusion in the world, occupying approximately 65 000 km^2 (Fig. 2). This Early Proterozoic complex (2050 ± 22 Ma, Rb/Sr age, recalculated with ∂^{87} Rb = 1.42 x 10^{-11} yr^{-1}; Hamilton, 1977) intrudes Early Proterozoic (2260 Ma; Hamilton, 1977) shale, dolomite, quartzite, banded ironstone, conglomerate, intermediate volcanics, and acid pyroclastics of the Transvaal basin, which overlies Archaean crystalline basement. The Transvaal rocks were thermally metamorphosed and deformed during the emplacement of the intrusion. Gravity data have shown that up to seven separate conical intrusions have transgressed to form a composite body comprising three magma chambers. These three basin-like masses of arcuate trending rock sequences are disposed east-west, and are referred to the eastern, western, and northern Bushveld. The layered igneous rocks and the enclosing country rocks dip inwards towards the centre of the complex at angles of 10 to 30°. Various sills also intrude the Transvaal rocks. These include the amphibolitic pre-Bushveld sill suite, and syn-Bushveld sills ranging in composition from peridotite, through pyroxenite, to gabbro. These later sills are believed to be offshoots of the Bushveld magma and their total thickness and areal extent considerably increase the dimensions of the exposed layered rocks of the complex. Magmatic ore deposits related to the complex are diverse and some rank among the largest of their kind in the world. They include PGMs (approximately 80% of the world's Pt reserves), chromite, vanadium, gold, copper, nickel, and manganese, with tin-fluorite in discordant granites, and lead-zinc-fluorite in the sedimentary country rocks.

The mafic-ultramafic rocks of economic significance form a diverse 9 km-thick sequence which has been subdivided into four zones on the basis of regional marker units. These markers include the Main Chromitite Seam (also called the Steelpoort Layer in the eastern Transvaal and the Magazine Seam in the western Transvaal), the Merensky Reef, and the Main Magnetite Layer. The stratigraphy of the Rustenburg Layered Suite of the eastern Bushveld Complex is shown in Figure 3. The basal contact rocks of the complex are chilled noritic rocks that transgress, and are commonly contaminated by, the sedimentary rocks of the Transvaal Basin. The chilled norites are of variable thickness and contain no mineralisation of economic importance. The **Lower Zone** of the complex (1700 m thick) comprises dominantly harzburgite and bronzitite, with minor norite and dunite. The **Critical Zone** (1400 m thick) can be broadly subdivided into a lower pyroxenitic subzone, and an upper anorthositic subzone. In detail the Critical Zone contains a number of cyclic units, in ascending order, the UG 1, UG 2, Pseudo Reef, Merensky Reef, and Bastard Reef cycles. Each is characterised by a similar sequence of cumulus minerals (chromite ± olivine, bronzite ± plagioclase, plagioclase), and can be traced for about 250 km along strike. Minor sulphides with variable PGM contents occur near the base of each cycle, and are associated with either chromite or pyroxenite. The rocks are strongly layered and range in composition from bronzitite, norite, and anorthosite to chromitite. Gabbro, norite, gabbronorite, anorthosite, and magnetitite comprise the thick **Main Zone** (3650 m thick). The **Upper Zone** (2250 m thick) is persistently layered with twenty-one magnetite horizons, that are up to 10 m in thickness. It is dominantly gabbro and magnetite gabbro, with minor troctolite, pyroxenite, anorthosite, and ferrodiorite. Rooiberg felsite-granophyre, leptite (fine grained silica-rich rock), and microgranite form the roof of the layered complex. These roof rocks were formed by a number of processes involving the residual melt derived from the differentiation of the mafic-ultramafic sequence, and the anatexis, metamorphism, and metasomatism of the sedimentary country rocks.

From geochemical and isotope studies of basal contact rocks and sills it is generally believed that two major magma types were involved in the evolution of the Bushveld Complex. These have been termed the U (Ultramafic) and A (Anorthositic) types, which

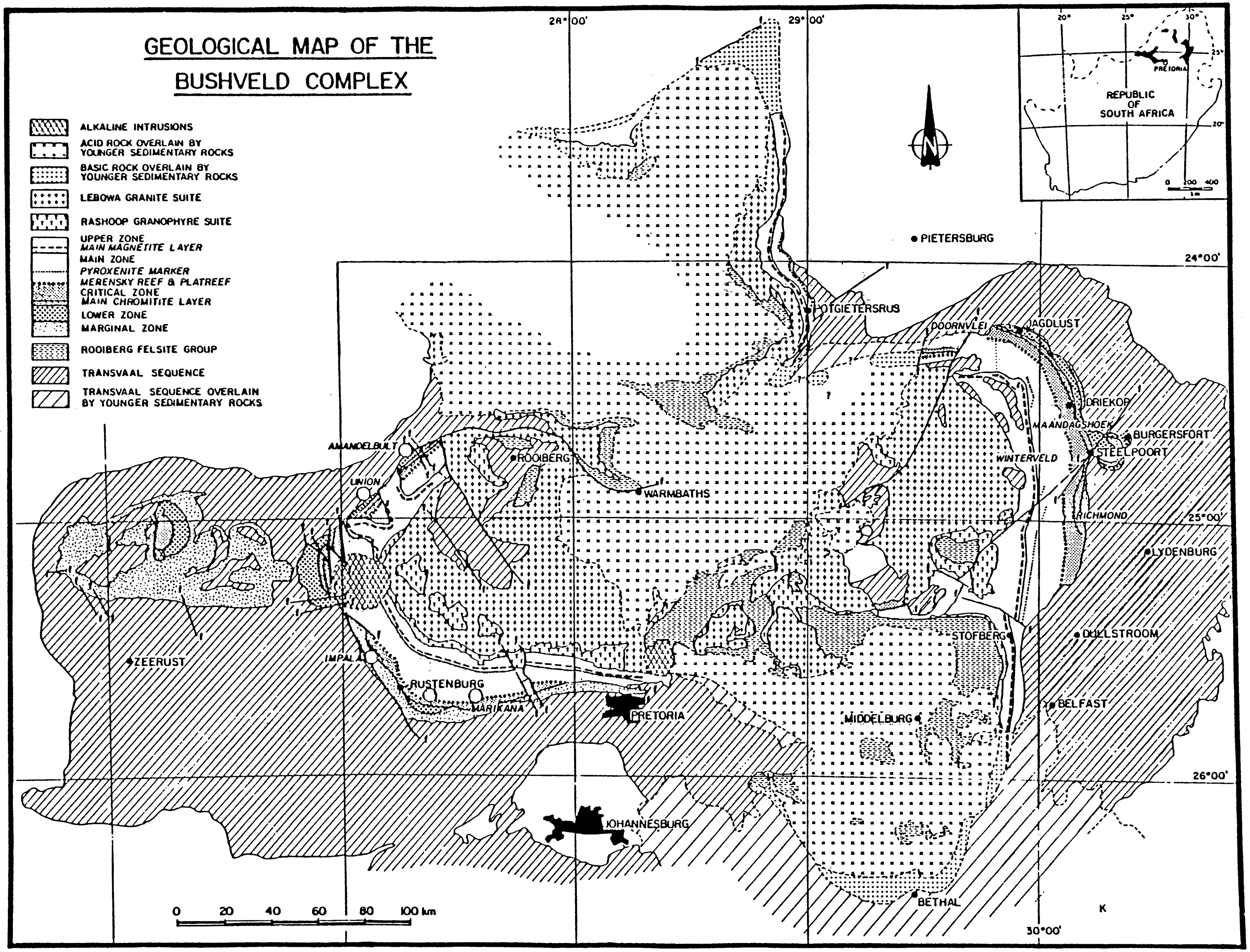

Fig. 2. Geology of the Bushveld Complex, South Africa. Reproduced, with permission, from *Economic Geology, 1985, Vol. 80, 804.*

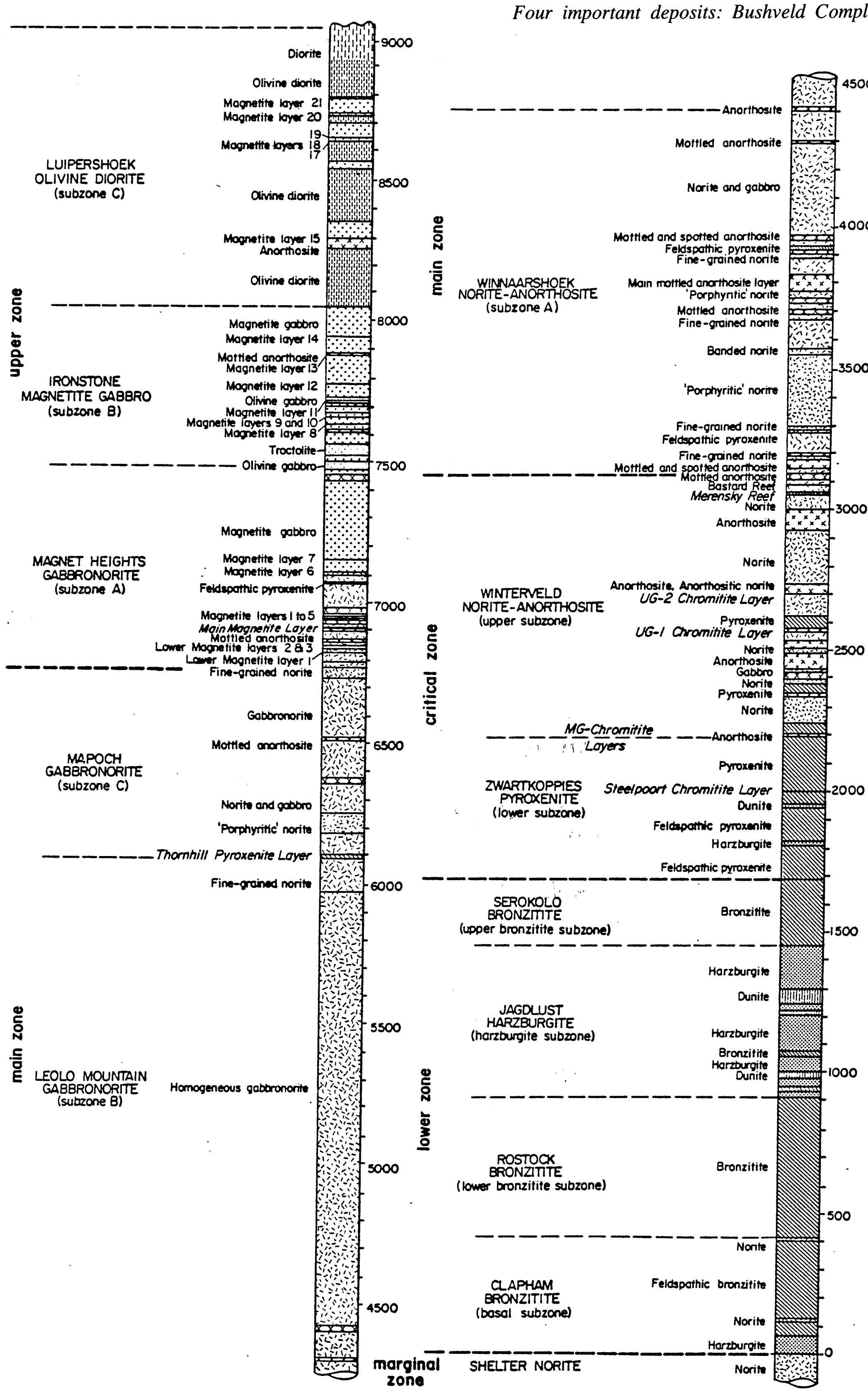

Fig. 3. Stratigraphic column of the Rustenburg Layered Suite, eastern Bushveld Complex. Economically important horizons and prominent stratigraphic markers are in italics. Reproduced, with permission, from *Economic Geology, 1985, Vol. 80, 808.*

were responsible for the pyroxene- and plagioclase-rich rocks of the layered succession, respectively. Both magmas were generated in different environments, and consequently have contrasting geochemical features. The U liquids were olivine-boninitic in composition, with relatively high SiO_2 levels (52–56%), MgO (12–16%), Cr (800–2000 ppm), and incompatible elements Rb (20–50 ppm) and Zr (150–400 ppm), and low $^{87}Sr/^{86}Sr$ ratios (0.703–0.705). The A derivatives have tholeiitic basaltic compositions, with SiO_2 (48–50%), MgO (8–10%) and low incompatible elements and Cr, and higher $^{87}Sr/^{86}Sr$ ratios (0.707–0.708). A

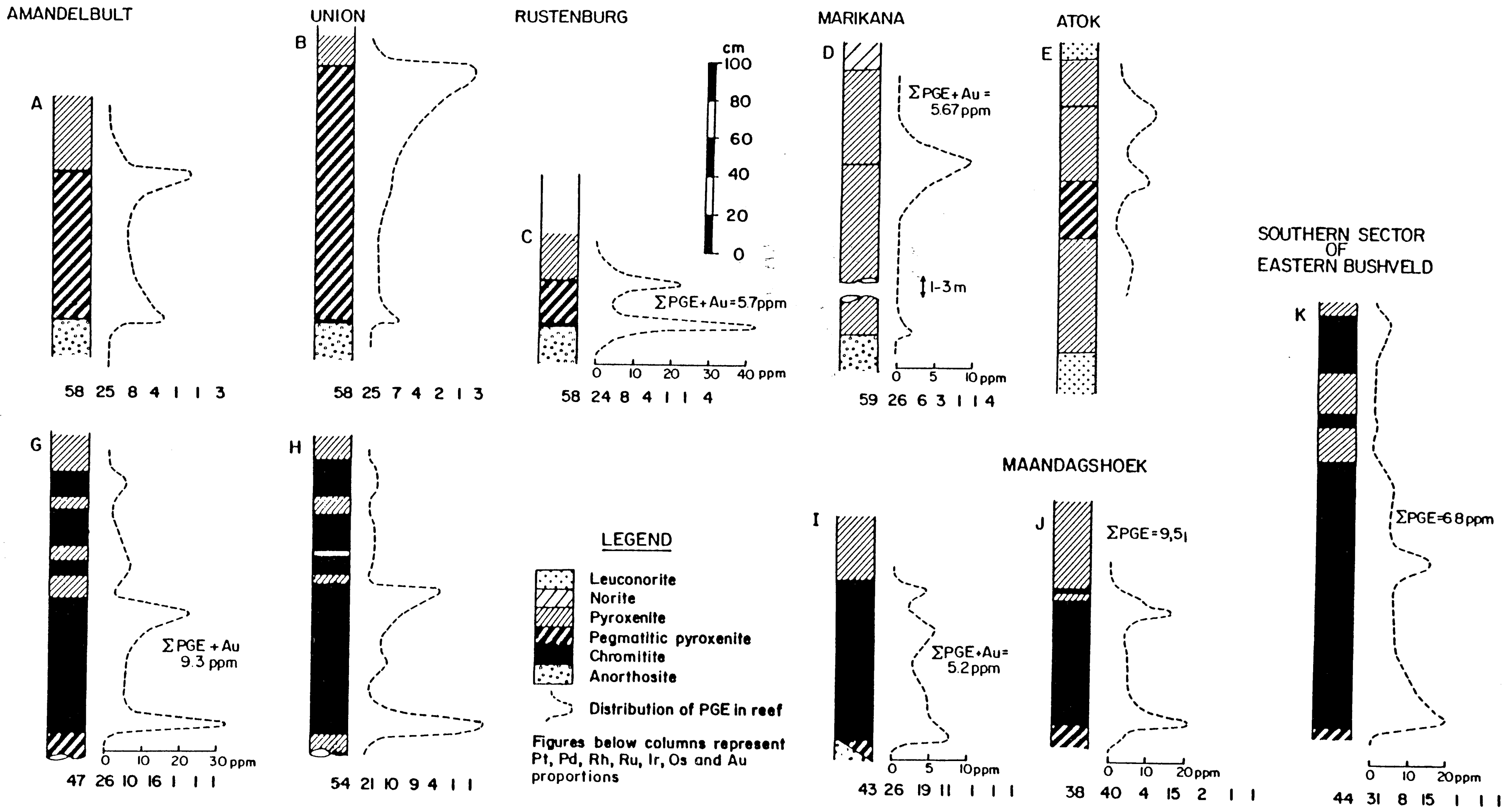

Fig. 4. Distribution of PGMs and Au in the Merensky Reef (sections A to E) and UG 2 Chromitite Layer (sections G to K) at various localities in the Bushveld Complex. The relative proportions of the PGMs are also shown at the base of each stratigraphic column. Reproduced, with permission, from Von Gruenewaldt & others (1986).

general enrichment of the albite component of plagioclase and of iron in pyroxene and olivine occurs upward through the complex, but there are numerous disruptions to these trends. The disruptions and reversals of the chemical trends are believed to reflect influxes of fresh magma, or are a part of a more complex irregular variation in mineral composition. Additional evidence pointing to influxes of new magma are (1) abrupt changes in initial $^{87}Sr/^{86}Sr$ ratios coinciding with both PGM-bearing layers, and (2) breaks in cumulus mineral compositions in the region of the UG 2 and Merensky reefs. It is believed that mixing of magma types was important in the development of the PGM and chromite horizons of the complex.

PGM mineralisation

Platinum mineralisation was first discovered by Adolf Erasmus in 1923 near Naboomspruit in the central Transvaal. The mineralisation was in quartz veins that infilled a brecciated fault zone within felsites near the roof portion of the Bushveld Complex. The veins were exploited during 1924–26, and created new interest in the PGM potential of the Transvaal. In 1924, a farmer, Andries Lombaard, found what he believed to be platinum while panning for gold in a stream on his farm, Maandagshoek, in the Lydenburg district of the eastern Bushveld. A grey-white concentrate was submitted to a consulting geologist, Dr. Hans Merensky, the son of a German medical missionary to the Transvaal. The concentrate was identified as ferroplatinum, and later led to the discovery of the PGM-rich Driekop, Mooihoek, and Onverwacht dunite pipes. Later in the 1920s, the PGM potential of the Rustenburg layered sequences of the Bushveld Complex was recognised, and a 250 km strike length of mineralised horizon was identified. The Rustenburg Platinum Mine was founded in 1931 to exploit this vast PGM resource.

Platinum-group mineralisation has four major settings in the Bushveld Complex: (1 and 2) the stratabound horizons of the Merensky Reef and the UG 2 Chromitite Layer, in the Critical Zone of the western and eastern Bushveld, (3) the Platreef of the Potgietersrus area, northeast Bushveld, and (4) the transgressive dunite pipes of the western and eastern Bushveld. Platinum-group mineralisation is also reported from a number of other environments, including chromitite layers, nickeliferous bronzitite pipes, disseminated sulphides in the Lower Zone at Volspruit, south of Potgietersrus, and between anorthosite and magnetite layers in the Upper Zone, but these occurrences are of minor economic significance relative to the four major PGM settings summarised below.

(1) Merensky Reef. The Merensky Reef, which occurs in the upper part of the Critical Zone, is a pegmatoidal feldspathic pyroxenite that underlies a porphyritic feldspathic pyroxenite unit. The two units grade upwards through norite, leuconorite, or spotted anorthosite to mottled anorthosite, and collectively form the Merensky cyclic unit. The Bastard cyclic unit overlies the Merensky cyclic unit and is also characterised by a basal feldspathic pyroxenite member. Anorthosites commonly form the footwall rocks to the Merensky Reef. The Reef varies considerably in thickness and texture throughout the Bushveld Complex, with its thickness ranging from a few centimetres to several metres, and averaging 0.8 m. Chromite layers 1–2 cm thick commonly define the top and bottom of the reef, particularly in the western Bushveld. Pegmatoidal textures are prominent in the western Bushveld, whereas equigranular pyroxenites are more typical of host-rock textures in the eastern sectors of the complex. Bronzite, minor sulphides (< 2.0 volume-%), and spinel are associated with intercumulus plagioclase, augite, and minor quartz, apatite, biotite, and hornblende in the reef. Only at the Union section where PGM mineralisation is associated with chromite-rich layers in an olivine-rich pegmatoid, is olivine an important component of the Merensky Reef. The Merensky Reef contains about 52% SiO_2, 10% Al_2O_3, and 21% MgO. Figure 4 shows the distribution of PGM levels in the vicinity of the Merensky Reef and the UG 2 chromitite horizon for various localities. Base-metal sulphides and associated PGM levels are not restricted to the Merensky Reef, but also occur in footwall anorthosite and hangingwall pyroxenite. However, highest PGM levels occur within the reef, and these levels commonly vary with the thickness of the pegmatoidal pyroxenite. Where the reef is more than 1.5 m thick (sections B and D), the highest PGM levels generally occur in or near the uppermost chromitite horizon; where the reef is thin, the PGM levels occur over the entire width of the reef; and for intermediate reef thicknesses the highest PGM levels are associated with the upper and lower chromitite layer (sections A and C). Figure 4 also shows that the relative proportions of the PGMs in the Merensky Reef are remarkably constant from different parts of the complex, a feature which negates a hydrothermal origin for the mineralisation. However, the PGM mineralogy changes considerably along strike. Major minerals include Pt-Fe alloys, Pt-Pd tellurides, sperrylite, braggite, cooperite, stibiopalladinite, moncheite, kotulskite, and laurite. Associated base-metal sulphides are chalcopyrite, pyrrhotite, pentlandite, nickeliferous pyrite, cubanite, millerite, and violarite. The platinum-group minerals occur with Ni-Cu sulphides as solid solutions, or as submicroscopic particles within the Ni-Cu sulphides, or more rarely enclosed by silicates. Platinum-Fe alloys generally occur as intergrowths with base-metal sulphides. The Pt : Pd ratio is higher in the Merensky Reef than in other PGM environments in the Bushveld (Table 6).

(2) UG 2 Chromitite layer. This horizon is 20 to 400 m below the Merensky Reef in the upper Critical Zone, and represents the largest single concentration of PGMs known in the world, almost twice that of the Merensky Reef (PGMs + Au reserves of 1041 million oz (32 300 t), Table 6). The UG 2 grade of 8.7 ppm PGM + Au is similar to the grade of the Merensky Reef (8.1 ppm); the Pt content relative to Pd is lower, but this is offset by the higher proportion of the most valuable PGM, Rh. The UG 2 has the added disadvantages of much lower Cu and Ni contents compared to the Merensky Reef, but the potential recovery of by-product Cr could enhance the value of the ore. Several companies in the eastern and western Bushveld are now mining UG 2 ore. Layers of cumulus chromite, designated UG 1, UG 2, and UG 3, occur at or near the base of various cyclic units ranging upward from porphyritic pyroxenite or melanorite through norite to anorthosite. Lenses and disseminations of chromite are commonly associated with melanorite and porphyritic pyroxenite in the UG 2 cyclic unit. The principal chromitite horizon however is the UG 2, which ranges in thickness from 0.15 to 2.55 m, and has an average thickness of 0.6 m. Dip attitudes are between 5° to 70° toward the centre of the complex, with the steeper dips commonly near dunite pipes. The UG 2 consists of 60 to 90 volume-% chromite, with minor bronzite and plagioclase, and accessory interstitial clinopyroxene and biotite. Porphyritic feldspathic pyroxenite containing thin chromitite leader seams similar to the Merensky Reef commonly forms the hangingwall sequence, while the footwall is represented by either anorthosite, leuconorite, or pegmatitic pyroxenite. Figure 4 shows that the maximum PGM values are at the base of the chromitite with a smaller peak 0.6 to 1.0 m above the basal concentration of PGMs, often near the upper contact of the UG 2 with the hangingwall rocks. The relative proportions of the PGMs vary slightly more along strike than in the Merensky Reef. The UG 2 and UG 3 layers contain trace amounts of pentlandite, pyrrhotite, chalcopyrite, pyrite, bornite, millerite, galena, chalcocite, covellite, and arsenopyrite, and the platinum-group minerals generally occur in or attached to the sulphides, along chromite grain boundaries or in gangue minerals. With the exception of laurite, few platinum-group minerals form inclusions in the cumulus chromite. Laurite, braggite, cooperite, vysotskite, sperrylite, and Pt-Fe alloys are the principal phases.

(3) Platreef. Platinum-group-metal, Ni, Cu, and Co mineralisation on the Potgietersrus limb (northern extension of the Rustenburg Layered Suite that intrudes country rocks downwards towards the Archaean granitic basement) occurs in a zone of sulphide blebs and rarer massive stringers within feldspathic pyroxenite, norite, and harzburgite over a strike length of 60 km and a thickness of up to 200 m. The Platreef is situated between the Main Zone and the Archaean granites in the northern part of the Potgietersrus compartment, and the Transvaal sedimentary sequence in the central and southern parts. The Platreef varies from a lower feldspathic pyroxenite that has variable feldspar content and grainsize (reef A), to a coarse-grained pyroxenite with minor chromitite (reef B), and the upper levels are characterised by a fine-grained feldspathic pyroxenite (reef C). Mineralisation is close to the base of the intrusion, with significant sulphide development resulting from the interaction of the magma with underlying ironstone and dolomite of the Transvaal Sequence. There are numerous inclusions of altered carbonate rocks up to 90 m in size in the Platreef, and sulphides are present in the dolomites, 30 m below the basal contact of the intrusion. Sulphides in the ore zone rarely attain more than 5 volume-%, and are dominantly pyrrhotite, pentlandite, chalcopyrite, and pyrite, with lesser galena, bornite, chalcocite, covellite, sphalerite, cubanite, tetrahedrite, millerite, cuprite, and molybdenite. The sulphides are heterogeneously distributed and form microscopic disseminations or coarser blebs up to 2 cm, and occur as intergrowths, inclusions, or interstitial grains with respect to the primary silicates. Sulphide concentrations occur along the floor as disseminations in unaltered igneous rocks, as enrichments in reaction aureoles in dolomitic xenoliths and in regions of serpentine alteration. Localised massive sulphides up to 2 m in thickness occur close to the basal contact and in brecciated contact rocks. Platinum-group levels and mineralogy vary erratically, with the former generally greatest in the upper levels of the Platreef. The platinum-group minerals are mainly sulphides, tellurides, and arsenides, and include cooperite, braggite, vysotskite, merenskyite, michenerite, moncheite, sperrylite, and Fe-Pt alloy. Significant amounts of Pd occur in solid solution in pentlandite. There is a broad vertical zonation of the platinum-group minerals from sulphide-associated minerals near the base of the Platreef; isoferroplatinum and electrum when present occur in the upper levels. Platinum-group levels of up to 68 ppm have been reported from the Platreef. The Platreef contains slightly higher Pd relative to Pt, and similar Cu and Ni levels to the Merensky Reef. In contrast to the Merensky Reef and UG 2, the Platreef mineralisation is generally diffuse and erratic, but may extend over greater widths.

(4) Dunite pipes. Transgressive dunite pipes and associated envelopes of olivine-bronzite-plagioclase pegmatoid occur in rocks of the Critical Zone in both the western and eastern parts of the complex. The best documented pipes, which were mined in the 1920s and 1950s, include the Onverwacht, Mooihoek, and Driekop. The pipes generally consist of a 10–20 m-diameter central zone of hortonolite dunite (olivine composition around Fo_{40-55}), which tapers downward and is encased within a 40–200 m wide zone of olivine dunite and wehrlite (olivine at Fo_{75-90}). The Onverwacht pipe cuts across the LG 6 chromitite layer (Steelpoort layer) and occupies the lowest stratigraphic level of the three major pipes, followed by the Mooihoek pipe 200 m higher, and the Driekop pipe 700 m higher than the Onverwacht pipe. It was originally thought that the pipes were genetically linked to the Merensky Reef and the UG 2, but they have different PGM ratios and mineralogy, and are now believed to be metasomatic. They have been interpreted as resulting from the replacement of bronzitite by hot chlorine-rich aqueous fluids which leached out SiO_2, Al_2O_3, and Na_2O and introduced FeO, TiO_2, V, and the PGMs. It is believed that all the constituents required in the replacement reactions are available in the Critical Zone rocks through which the fluids must have passed. Some pipes have produced the highest grades of up to 2000 ppm total PGMs for the complex. On the 20 m level of the Onverwacht pipe, the central 8 m core averaged 31 ppm and the outer 1 m shell had a grade of between 15 and 30 ppm PGMs. For the Mooihoek pipe the Pt content increases from the margin towards the core of the hortonolite dunite, where maximum grades of 80 ppm were reported. In the Driekop pipe there is no obvious relationship between the Pt content of the ore and the composition of the olivine. The average Pt grade for the Onverwacht, Mooihoek, and Driekop Pipes was about 10, 13, and 6 ppm, respectively. The platinum-group mineralogy of the pipes differs from that of the Merensky Reef and UG 2 in that Bi-tellurides are absent, and platinum-group sulphide minerals are rare. Platinum-Fe alloys, sperrylite, geversite, hollingworthite, and irarsite are the main minerals reported in the Driekop Pipe.

Relative proportions, grades, and reserves of the various styles of PGM mineralisation in the Bushveld Complex and other major overseas deposits are summarised in Table 6. The Bushveld Complex reserves do not include the resources for several proposed mines that are shortly to come on stream. These are described in the platinum-group-metal-supply section of the economic part of this report. Another recent development has been the recognition by the Botswana Geological Survey of a possible arm of the Bushveld Complex extending to a region north of the Molopo River, the boundary with South Africa. Von Gruenewaldt & others (1987b) believe the Molopo Farms Complex which covers an area in excess of 10 000 km^2 is of Bushveld age, but preliminary drilling has defined some marked differences to the Bushveld. Nickel-copper sulphides have been intersected at four

Table 6. Relative proportions (%), reserves (millions of oz.), and grades (ppm) of platinum-group metals in major world deposits

	Bushveld (a)											
	Merensky Reef		*UG2*		*Platreef*		*Sudbury*		*Stillwater*		*Noril'sk*	
	%	*Res.(a)*	*%*	*Res.(a)*	*%*	*Res.(a)*	*%*	*Res.*	*%*	*Res.(a)*	*%*	*Res.*
Pt	59	333	42	437	42	160	38	3.4	19	7	25	50
Pd	25	141	35	365	46	175	38	3.4	66.5	23	71	142
Ru	8	45	12	125	4	15	2.9	<1	4.0	1.4	1	2
Rh	3	17	8	83	3	12	3.3	<1	7.6	2.7	3	6
Ir	1	6	2.3	24	0.8	3	1.2	<1	2.4	<1	—	—
Os	0.8	5	—	—	0.6	2	1.2	<1	—	—	—	—
Au	3.2	18	0.7	7	3.4	13	13.5	<1.2	0.5	<1	—	—
Total		565		1 041		380		9		35		200
Grade		8.1		8.7		7–27		0.9		22.3		3.8

(a) Calculated to 1200 m vertical depth.
Source: Johnson Matthey's *Platinum 1985*.

levels in an ultramafic sequence and at three levels in gabbroic rocks. Maximum Pt + Pd levels of 1 ppm have been reported in the lowermost mineralised layer, near the base of the ultramafic sequence. These new mining developments throughout the Bushveld Complex indicate the immense PGM potential of the region, and during favourable economic times many deposits can be quickly brought on stream to the disadvantage of overseas competitors.

Stillwater Complex

(Conn, 1979; Naldrett, 1981a; Campbell & others, 1983; Boudreau & McCallum, 1985; Zientek & others, 1985; Hulbert & others, 1988)

Geological setting

The Stillwater Complex, in the Beartooth Mountains of southwestern Montana, is a differentiated, layered, Archaean mafic-ultramafic sequence (2701 ± 8 Ma, Sm-Nd age, De Paolo & Wasserburg, 1979), which intrudes a metamorphic terrane and has subsequently been faulted, uplifted and tilted (Fig. 5). As presently exposed, the complex is believed to represent the edge of a large saucer-shaped body, dipping steeply to the northeast. It extends for 48 km along strike and has an exposed thickness of 7.4 km. Considerable thinning has occurred during erosion. The southern contact is intrusive, but Phanerozoic sedimentary rocks unconformably overlie the highest stratigraphic levels of the complex to the north. The complex is locally intruded by quartz monzonite, diabase, and Tertiary granitic rocks, and has been extensively dislocated by strike and dip displacement faults in the middle and eastern portion of the intrusion.

The Stillwater Complex has been subdivided into five major series, in ascending order, the Basal, Ultramafic, Lower Banded, Middle Banded, and Upper Banded Series. The **Basal Series** (20 to 400 m thick) is a laterally continuous but varying unit, consisting of chilled gabbro, contaminated norite, and cumulate bronzitite. Metasedimentary xenoliths and disseminated and massive pyrrhotite, pentlandite, and chalcopyrite occur locally near the floor of the intrusion. Low-grade Cu + Ni resources have been delineated for the basal contact setting, but PGM levels rarely attain more than 0.1 ppm PGMs. The **Ultramafic Series** generally overlies the Basal Series, but in places lies directly on basement rocks, and has been subdivided into the Peridotite and Bronzitite zones. The Peridotite Zone (920 m thick) comprises the lower 75% of the Ultramafic Series and contains 15 cyclical units of dunite, harzburgite, and bronzitite, the majority having basal chromitite layers. The cyclical units are characterised by basal concentrations of cumulus olivine and chromite, which pass upward into cumulus bronzite with intercumulus plagioclase and augite. The cyclic units reflect the crystallisation order of olivine + chromite, bronzite, plagioclase and augite. The contact between the Peridotite Zone and the overlying Bronzitite Zone is sharp, and is defined by the disppearance of cumulus olivine. The Bronzitite Zone (300 m thick) is a succession of laminated and size-graded bronzite cumulates, which locally contain thin discontinuous layers of cumulus olivine and chromite.

The three **Banded Series,** which collectively make up more than 75% of the exposed thickness of the Stillwater Complex, have been subdivided on the basis of changes in the crystallisation order, and cryptic variation in cumulus-mineral compositions. The base of the Lower Banded Series is characterised by the first appearance of cumulus plagioclase. The Lower and Middle Banded Series in particular have significant economic potential since they host the two major PGM-enriched horizons, the J-M Reef and Picket Pin Zone. The **Lower Banded Series** (1600 m thick) consists of a complex succession of mainly norite and gabbronorite, with minor anorthosite, troctolite, and gabbro, while anorthosite with two olivine-bearing subzones characterises the

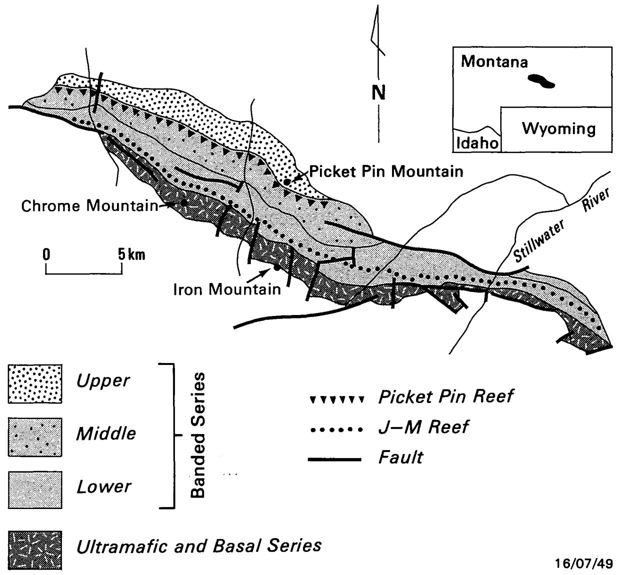

Fig. 5. Geology of the Stillwater Complex, Montana, USA. Modified from Barnes & Naldrett (1986).

Middle Banded Series (1750 m thick). A lower olivine-bearing subzone with a thick upper subzone of gabbronorite comprises the **Upper Banded Series** (1130 m thick).

PGM mineralisation

Sulphide-bearing rocks were discovered in the Stillwater Complex in 1883, but it was not until 1936 that Howland & others (1936) reported the first occurrence of PGMs, notably sperrylite and stibiopalladinite. These investigators also highlighted the similar features of the Stillwater and Bushveld complexes. Despite these important early observations, little exploration was conducted until the 1960s. In 1967, the Johns-Manville Corporation initiated a soil sampling and reconnaissance mapping program. Results were generally disappointing, and it was only one group of samples giving weak Pt, Pd, Cu, and Ni values that gave any incentive to carry on. After implementing several phases of multidisciplinary studies during the following years, the J-M Reef was finally discovered in 1973. The extensive geochemical programs were greatly assisted in 1968 by the development of the combined fire assay-atomic absorption procedure, which provided a practical, sensitive, and relatively economical analytical technique for the analysis of Pt and Pd.

Stratabound PGM mineralisation in the Stillwater Complex exists at a number of stratigraphic levels, indicating that, in the investigation of any layered intrusion, it is important to evaluate the PGM potential of the total stratigraphy. Initially, the chromitite horizons of the Ultramafic Series attracted PGM interest, but this direction rapidly changed with the more recent discovery of the J-M Reef and the Picket Pin Zone, much higher in the stratigraphy. These three major PGM settings are discussed below. PGM mineralisation is also associated with granitic intrusives containing selvages of chromite and sulphide-rich rocks, coarse-grained bronzitite lenses at the top of the Ultramafic Series, and bronzitite cognate xenoliths in the Banded Series, but these occurrences appear to have little potential for a major PGM resource.

(1) Chromitite layers. Platinum-group concentrations are associated with the chromitite cyclic layers in the Peridotite Subzone of the Ultramafic Series. The chromitites, which are hosted by harzburgite, are designated A to K from the lowest horizon upwards, and range from a couple of centimetres to several metres in thickness. The A chromitite horizon has the highest PGM levels: up to 20.5 ppm Pt + Pd + Rh, but averaging 3.4 ppm. The tenor of PGM mineralisation decreases upwards through the chromitite horizons, so that the thickest chromitites, G and H, have the lowest PGM grades. Small massive sulphide pods at the base of the G chromitite have PGM levels less than 0.5 ppm. Thus, it would appear that the PGMs are strongly partitioned with respect to early-crystallising chromite, and their distribution is not controlled by the abundance of chromite or later sulphides. Discordant dunite and chromitite bodies between the C and E chromitite horizons also have enriched Pt + Pd levels up to 5 ppm. Stibiopalladinite, sperrylite, cooperite, Pt-Fe alloys, and laurite occur as inclusions in chromite, and in interstitial sulphides. Chromium shows the strongest correlation with the PGMs, V a moderate correlation, and Ni, Cu, Co a lower correlation.

(2) J-M Reef. Production from the the J-M Reef, 335 to 425 m above the contact between the Bronzitite Subzone of the Ultramafic Series and the Lower Banded Series (Fig. 5), commenced in March 1987. The reef is continuous over a strike length of 39 km, ranges from 1 to 3 m in thickness, and is commonly transgressive. The PGM mineralisation occurs in discrete zones up to 3 m above and 10 m below the contact between an olivine-bearing unit (OB 1) and a gabbronorite unit (Gabbronorite 1). The OB 1 unit, which contains a stacked sequence of 5 to 15 laterally impersistent olivine-bearing cumulates, represents the reappearance of cumulus olivine that interrrupts the crystallisation sequence of the fractionating gabbroic magma forming the lower rock types. The olivine in the OB 1 unit occurs as either laterally discontinuous olivine cumulate layers that are bounded by anorthositic selvages; or in a mixed rock that contains plagioclase cumulates, olivine cumulates, and a distinctive coarse-grained olivine-rich rock referred to as 'ameboidal troctolite'; or in broadly stratiform bodies of plagioclase-olivine cumulates. Sulphides ranging from 0.5 to 1.5 volume-% are dominated by pentlandite, chalcopyrite, and pyrrhotite, with minor pyrite, sphalerite, galena, millerite, and marcasite, and trace covellite, native copper, stibnite, magnetite, graphite, and gold. The principal platinum-group minerals are braggite, vysotskite, moncheite, and Pt-Fe alloy, with lesser cooperite, stillwaterite, arsenopalladinite, Pd-tellurides, merenskyite, kotulskite, and sperrylite. Palladium also occurs in solid solution in pentlandite. Detailed drilling has delineated a 5.5 km segment of the J-M Reef to have 22.3 ppm PGMs over 2.1 m, and a Pd to Pt ratio of 3.5. The base of the stacked sequence of olivine cumulates is discordant with the underlying rocks. This has been used as evidence to indicate that magmatic erosion and mixing occurred between a resident magma and a new magma pulse, thus setting up a mechanisn for PGM mineralisation. Other genetic models suggest that hydrothermal fluids, or the filter pressing of the cumulus pile with subsequent migration of fluids upwards, played important roles in the precipitation of sulphides and the concentration of the PGMs.

(3) Picket Pin Zone. Unlike the J-M Reef, the Picket Pin mineralised zone has only recently been investigated for its PGM potential. The Picket Pin Zone is 3 km stratigraphically above the J-M Reef, immediately below the contact between the Upper and Middle Banded Series (Fig. 5). The PGM-sulphide mineralisation occurs in a narrow zone directly below the interface of coarse-grained anorthosite and a 10 m thick overlying medium-grained, monomineralic anorthosite. The bulk of the sulphides occur below this contact, but some sulphides are locally present up to the base of the overlying Upper Banded Series. The PGM-enriched sulphides have a podiform distribution over the 22 km strike length of the mineralised zone. The mineralisation consists of lenticular concentrations of 1 to 5 volume-% sulphide, which are conformable with the regional layering, and have a maximum thickness of 1.5 m and a lateral extent of 30 m. For 150 m below the main stratabound zone, PGM-bearing pipes that contain 1 to 5 volume-% sulphides may cut across the stratigraphy for over 50 m. The PGM-bearing sulphides of the stratabound zone are preferentially associated with pyroxene-poor, and quartz and apatite-bearing anorthosites. The sulphides are primarily pyrrhotite, chalcopyrite, and pentlandite; arsenides and antimonides are the main hosts for the PGMs. The Pt + Pd content of the coarse-grained anorthosite ore varies with the sulphide content, but ranges from 0.8 to 4 ppm, and averages 1.4 ppm. Platinum is marginally subordinate to Pd, with the Pt/Pd ratio about 0.8. A strong correlation exists between Pt + Pd and S for sulphides associated with the coarse-grained anorthosites, but no such correlation occurs for the medium-grained anorthosites. The occurrence of transgressive zones of sulphide leading up to conformable sulphide-rich zones, the association of sulphide with late-crystallising minerals, and the Cu-rich nature of the sulphide assemblage are consistent with a model in which mineralising solutions enriched in incompatible elements migrated upwards during the crystallisation of the interstitial melt of the coarse-grained anorthosites. The overlying medium-grained, adcumulate anorthosites acted as an impermeable zone that trapped the solutions.

New Rambler

(McCallum & others, 1976; Cabri, 1981)

Geological setting

The New Rambler Mine, in the Douglas Creek mining district of the Medicine Bow Mountains in southeastern Wyoming, is in a hydrothermal deposit where the host rock of the PGM minerals was also probably their source. It is believed the transportation and concentration of the PGMs resulted from hydrothermal processes acting on a disseminated PGM source, rather than the in-situ hydrothermal reworking of a pre-existing sulphide orebody.

The New Rambler orebody is near the intersection of a major east-trending branch of the Mullen Creek–Nash Fork shear zone with a set of closely spaced northwest-trending fractures, and a poorly defined northeast-trending mylonite zone (Fig. 6). This Mullen Creek–Nash Fork shear zone is a major late Precambrian lineament that divides the Medicine Bow Mountains into two distinct geologic provinces, both of which have had a complex tectonic history. The mineralised host rocks belong to a large layered tholeiitic intrusive complex, the Mullen Creek mafic complex, and include metadiorite and metagabbro that consist of saussuritised plagioclase, chloritised hornblende, uralitised pyroxene, with accessory magnetite, ilmenite, epidote, biotite, sphene, apatite, and olivine. The orebodies consisted of massive sulphides, nodules of massive and disseminated sulphide in a jasperoid matrix, and less abundant jasperoid disseminations in a sulphide matrix (matrix ore). All the ores displayed varying intensities of supergene alteration.

PGM mineralisation

The New Rambler Mine was closed by fire in 1918, after having produced about 7000 t of Cu-Ni concentrate, 14 kg of Pd, and 5 kg of Pt. The entire mine production came from three irregular ore pods. The economic potential of the associated PGMs was only recognised during the later stages of mining. Mineralisation occurs as lenses and irregular pods in a shear zone transgressive to the mafic rocks, which have been silicifed, sericitised, chloritised, and saussuritised to varying degrees. The primary sulphides have been subdivided into three major associations: (1) pyrite-magnetite, with trace chalcopyrite, pyrrhotite, and pentlandite, occurring as disseminations and massive concentrations in the quartz-sericite-altered wall rocks; (2) chalcopyrite-pyrrhotite-pyrite, with trace sphalerite, mackinawite, pentlandite, electrum, and Pd-Pt minerals, occurring massive and as disseminations in the metagabbroic rocks and forming the dominant association; and (3) an association similar in major ore and matrix mineralogy to association (2), but with a distinctive assemblage of sphalerite, magnetite, pentlandite, electrum and platinum-group minerals. Thermochemical data suggest that the mineralisation of association (1) was deposited at temperatures of at least 335°C, whereas the Cu-PGM mineralisation of associations (2) and (3) involved temperatures below 335°C.

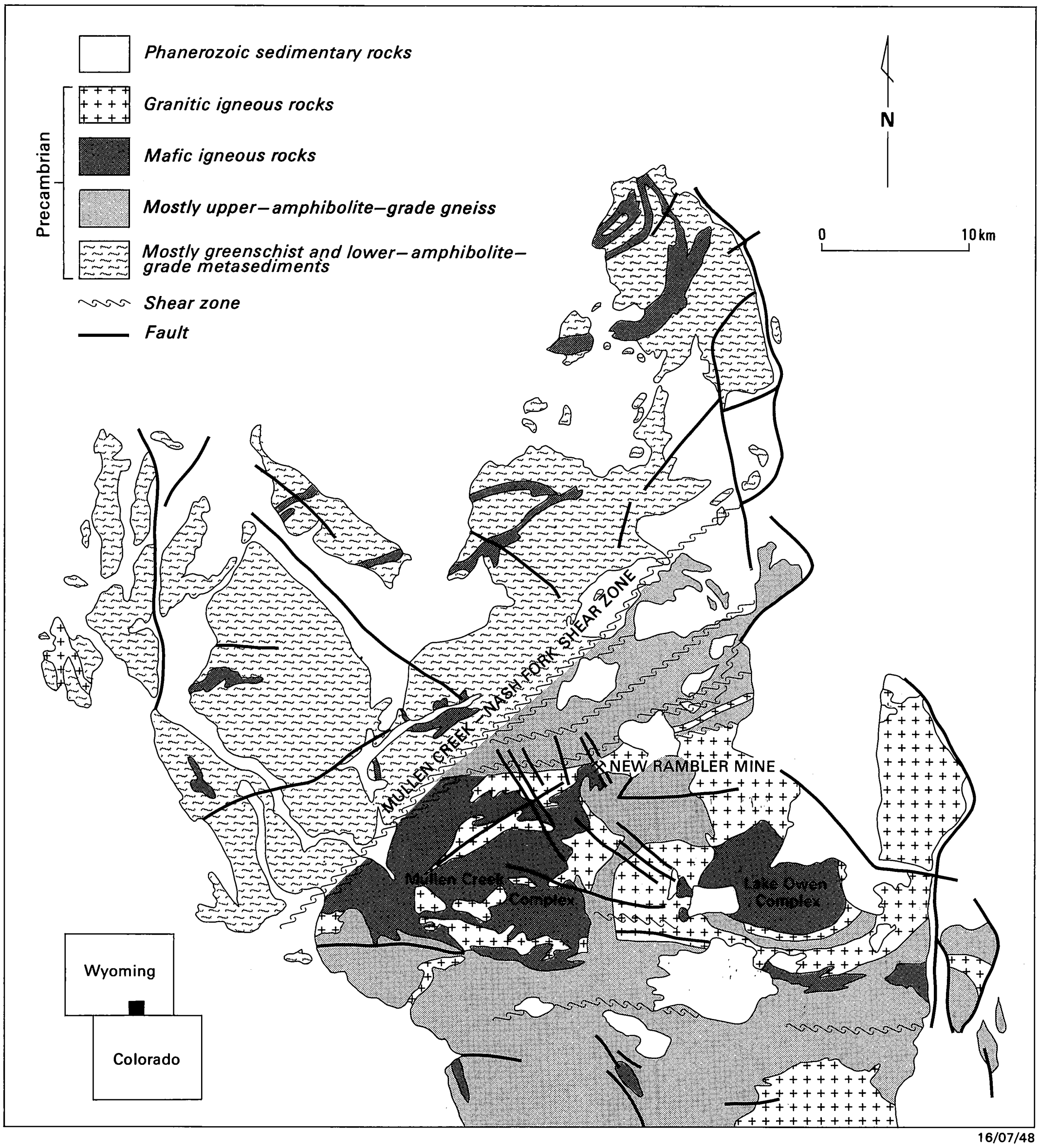

Fig. 6. Geological setting of the New Rambler Mine, Medicine Bow Mountains, Wyoming, USA. Modified from McCallum & others (1976).

The ratio of Pd:Pt in the unmineralised mafic rocks is approximately 1:1, but in the sulphide ore the ratio is nearly 18:1, with Pd enriched by a factor of about 7500, and Pt by about 400. The Pd:Pt:total Ru, Rh, Ir, Os is approximately 1800:100:1. The significant enrichment in Pd (the most soluble of the PGMs) relative to the other PGMs is similar to the Noril'sk, Messina, and Rathbun Lake hydrothermal deposits, and is taken as indicating a hydrothermal origin for the mineralisation. Bismuthotellurides and tellurides dominate the platinum-group minerals in the sulphide ores, and include merenskyite, kotulskite, michenerite, sperrylite, and native Pt. A significant proportion of the Pt occurs in solid solution in merenskyite and michenerite, and pyrite contains about 60 ppm Pd in solid solution. Ru, Rh, Ir, and Os probably occur as trace substituents in the Pd and Pt minerals. The general tendency of Pd and Pt to form compounds with Te, Bi, and Sb is believed to be consistent with a hydrothermal origin.

The structural setting, the spatial association of Cu-Ni-PGM mineralisation and hydrothermal alteration, the textures of ore and silicate matrix intergrowths, and the predominance of the most soluble PGMs, Pd and Pt, compared to the chemically more refractory elements Ir, Os, Ru, and Rh, support a hydrothermal origin for the New Rambler deposit. It is believed that the precious metals were derived by base cation leaching of a large volume of tectonised mafic rock during hydration resulting from an enhanced permeability of the rocks. The mineralising solutions deposited the PGM-enriched sulphides as fissure fillings and metasomatic replacements of mafic rock within dilatant shear zones, or at the intersection of various shear systems.

Coronation Hill

(Noranda Pacific Ltd, 1985, 1986; Needham & Stuart-Smith, 1987; S. Needham, personal communication, 1987; Battey & others, 1987)

Geological setting

The Coronation Hill Au-PGM deposit, about 220 km southeast of Darwin in the South Alligator River Valley, NT, in a district of mainly uranium and gold mineralisation, is an unusual PGM occurrence in that the mineralisation shows no clear association with, or derivation from, mafic-ultramafic rocks. Research on this unusual style of PGM mineralisation is expected to shed new light on the physico-chemical conditions of ore formation, including the chemical mobility, transport, and deposition of the PGMs and Au.

The South Alligator River region is underlain by an Early Proterozoic sequence of folded arenaceous, calcareous, and carbonaceous metasediments, with minor basic volcanics. This South Alligator Group, which forms part of the Pine Creek Geosyncline sequence, is unconformably overlain by the late Early Proterozoic El Sherana Group and Edith River Group felsic volcanics and related volcaniclastics, which in turn are unconformably overlain by fluviatile sandstone of the Middle Proterozoic Kombolgie Formation (Fig. 7). The major mafic igneous events in the region are represented by the pre-tectonic, pre-metamorphic Zamu Dolerite, which forms extensive sills of differentiated quartz dolerite mainly in the Koolpin Formation (South Alligator Group), and the post-tectonic Oenpelli Dolerite, which was probably the last igneous event in the Early Proterozoic. Faulting throughout the phases of geosynclinal development, igneous activity, and platform sedimentation, resulted in a graben-type structure for the volcanic and volcaniclastic sediments.

Fourteen U-Au mines were worked in the South Alligator River region, in the 1950s and 1960s. Production at ten of them amounted to 874 t U_3O_8 at grades from 0.2 to 2.5% U_3O_8. The larger mines include El Sherana (226 t @ 0.55% U_3O_8, 0.33 t Au), Rockhole Group (152 t @ 1.1% U_3O_8, minor Au), and Palette (124 t @ 2.5% U_3O_8, Au included in El Sherana Au figure). The Coronation Hill U-Au deposit was one of the smaller deposits worked. The U-Au mineralisation is generally stratigraphically and structurally controlled, occurring within 100 m of the Early/Middle Proterozoic unconformity, and near faulted contacts between the Koolpin Formation (mid Early Proterozoic) and the Coronation Sandstone or Pul Pul Rhyolite of the El Sherana Group

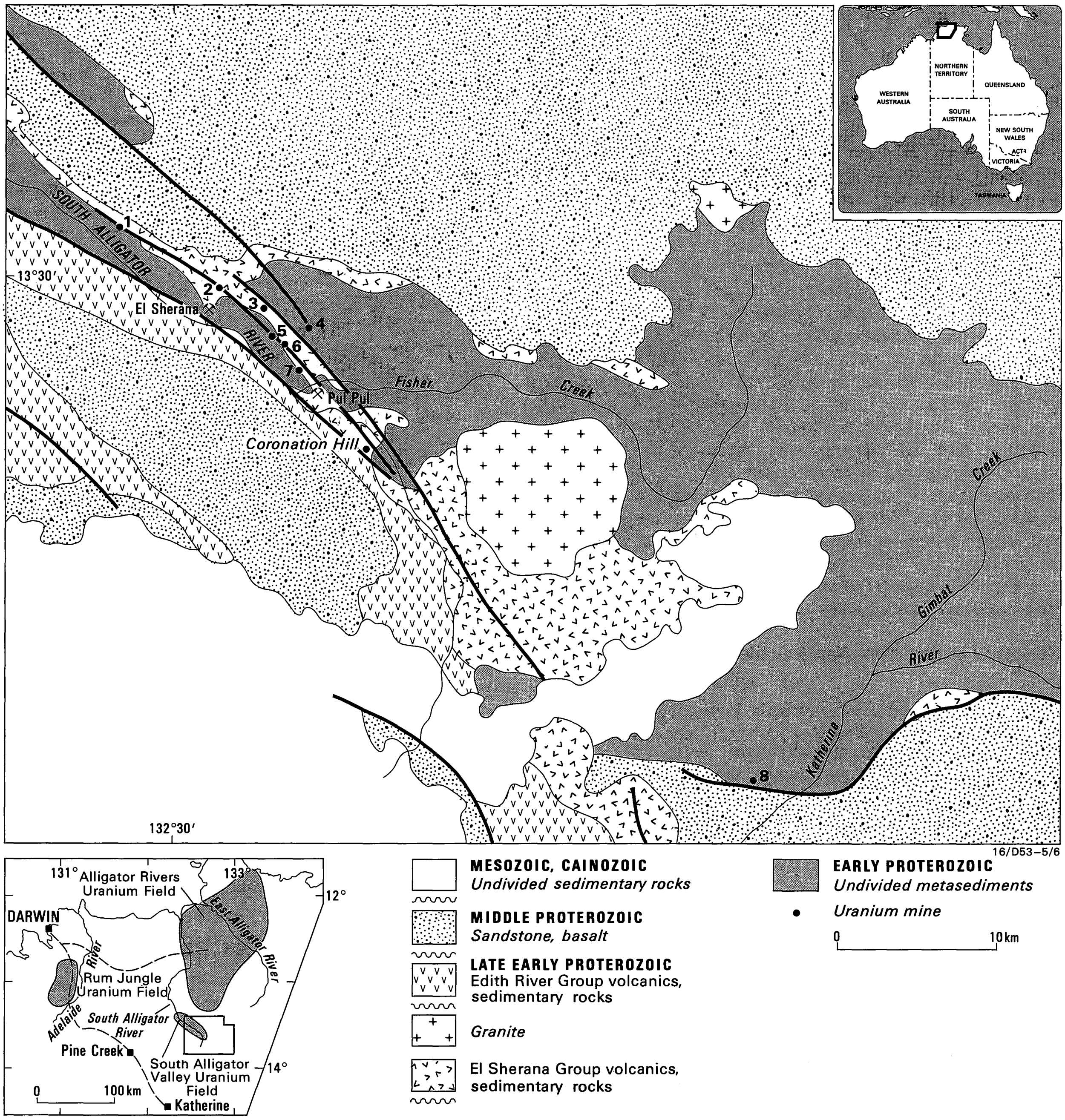

Fig. 7. Geology and mine localities, Coronation Hill region, South Alligator River Valley district, NT. 1 — Rockhole mine; 2 — El Sherana, El Sherana West mines; 3 — Koolpin mine; 4 — Scinto VI mine; 5 — Scinto V mine; 6 — Palette, Skull mines; 7 — Saddlle Ridge mine; 8 — Sleisbeck mine. From Needham & Stuart-Smith (1987).

(late Early Proterozoic). However, the Coronation Hill U-Au deposit has a different setting.

It is generally believed that the South Alligator River U-Au deposits have resulted from the leaching of U from the felsic volcanics; the mineralising solutions migrated along faults that cut the Early/Middle Proterozoic unconformity, and precipitated the U in carbonaceous and/or pyritic shale.

The Coronation Hill mine area is underlain by a gently folded basinal sequence of interbedded tuff, rhyolite, argillite, and shale of the Coronation Sandstone that unconformably overlies tightly folded carbonaceous shale, schist, and ferruginous siltstone of the Koolpin Formation (Fig. 8). A hematitic siliceous regolithic breccia (Scinto Breccia) that forms the top of Coronation Hill defines the unconformity between these two major sequences. Within and to the west of the Coronation Hill U-Au mine pit, the volcanic-sedimentary rocks are overlain by polymictic conglomerate and poorly sorted sandstone (also part of the Coronation Sandstone). The polymictic rock has been variously interpreted as a vent breccia, an agglomerate, or a debris-flow conglomerate. The mine area is transected by a north and west trending series of faults that strike at 45° to the northwesterly trending Pallette and Clear Springs faults. These latter faults define part of the regional graben structure of the South Alligator River Valley.

PGM mineralisation

The Au and PGM mineralisation is in altered volcanics and clastics east and southeast of the old Coronation Hill U-Au open cut mine. The mineralisation is distinct from the other South Alligator deposits, in that the Au is associated with Pd and Pt, and U of very low tenor. The mineralised zone contains altered felsic volcanics, tuff, sandstone, and felsic porphyry of the Coronation Sandstone, carbonaceous shale of the Koolpin Formation, and altered mafic rocks possibly belonging to the Zamu Dolerite. The

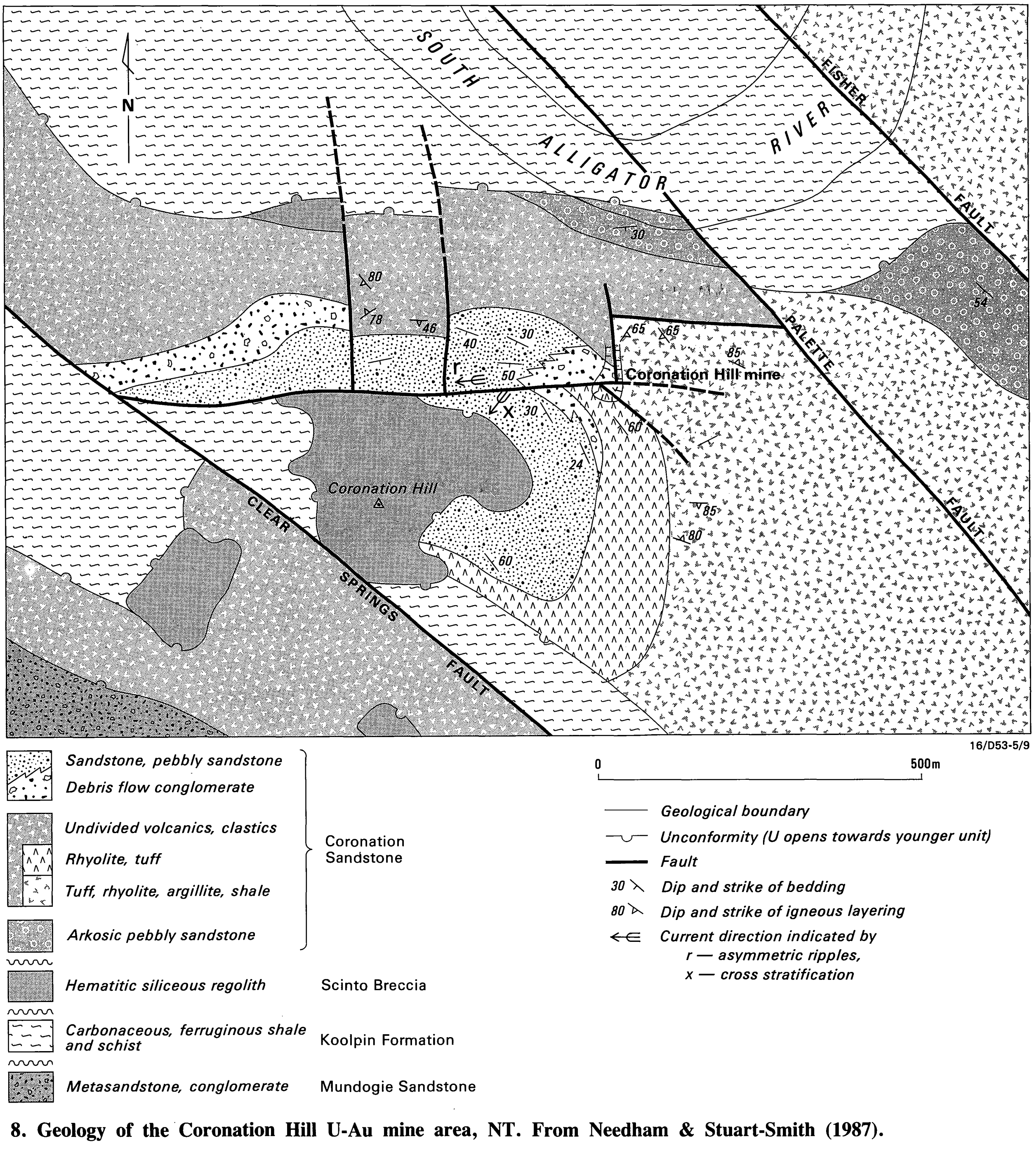

Fig. 8. Geology of the Coronation Hill U-Au mine area, NT. From Needham & Stuart-Smith (1987).

dominant styles of alteration associated with the fine-grained disseminated Au-PGM mineralisation (invisible to the naked eye) are sericitisation and silicification, with minor hematite, chlorite, and pyrite present. Drill intersections at Coronation Hill represent some of the best Au intervals recently reported in Australia, e.g. DDH 6: 78.4 m @ 12.3 ppm Au. In 1986 the Coronation Hill Joint Venture (BHP Minerals, Noranda, and Norgold) announced that the prospect has inferred resources of more than 34 t Au, and about 2.5 t Pt and 5.3 t Pd. The mineralisation is open to the south, east, and at depth. Mineralisation persists to at least 300 m vertical depth.

There is a positive correlation between Au and the dominant PGMs, Pt, and Pd, with the latter metals contributing 10–20% of the precious-metal gross value of the deposit. The average grade of 163 samples with > 1 ppm Au is 0.61 ppm Pt, 1.15 ppm Pd, and 7.72 ppm Au. The Pt/Pd ratios for high Au samples range from 0.30 to 0.88, with nearly 50% of the samples falling in the range 0.5 to 0.65. Preliminary metallurgical studies from a mineralised surface sample have identified native platinum, native palladium, stibiopalladinite, and possible porpezite (a variety of gold which contains up to 10% Pd) in gravity concentrates.

The Au-PGM mineralisation at Coronation Hill is still being studied, and so far one can only speculate about the ore genesis. One enigmatic feature in particular that stands out is the absence of an apparent source rock for the PGMs. No substantial bodies of mafic-ultramafic rocks crop out in the region to indicate an obvious mafic igneous derivation or association. Possible sources include:

- hydrothermal remobilisation of a fossil PGM placer that could occur at a Proterozoic unconformity, or be related to the high-energy clastic sedimentary units;
- an epithermal origin related to felsic volcanism, as suggested by the close spatial association of the disseminated Au–PGM mineralisation with alteration and felsic volcanics;
- hydrothermal remobilisation of a PGM-enriched phase of the Zamu Dolerite (e.g. similar to the mineralised differentiated picritic dolerites of the Noril'sk area, western Siberia), or a subsurface mafic-ultramafic igneous body;
- leaching from country rocks by sedimentary brines; and
- carbonaceous shales which are prominent in the Early Proterozoic Masson and Koolpin Formations.

Anomalous PGM concentrations have been documented in Permian carbonaceous Kupferschiefer shales at Zechstein, Poland (Kucha, 1975, 1982; Banas & others, 1978), in bituminous coal in Kentucky (Chyi, 1982), and in base-metal deposits of the central African Copper Belt in Zambia and Zaire, which are associated with organic C and U in black shale and dolomitic siltstone (Mertie, 1969; Freeman, 1983). In Australia, Valdora Minerals Ltd is investigating the Proterozoic Marimo Slate in the Cloncurry district of Queensland for a Kupferschiefer-type polymetallic deposit. The Marimo Slate, which contains carbonaceous shale units, is reported to have low, but geochemically significant Pd and Pt concentrations (Louthean & Seidel, 1988). The Cu-rich Zechstein rocks include thucholites (a carbonaceous clastic rock with an anomalously high U content) containing electrum and various Pd arsenides. Similarly, the South Alligator River mineralisation is associated with black shale containing unusually high U, Au, Pd, and Pt. Moreover, the Pd-enriched character of the mineralisation at Coronation Hill–El Sherana–Palette is consistent with the dominance of Pd over the other PGMs in the thucholites. The occurrence of Pd in the Jabiluka U-Au-graphitic metasedimentary deposits, 225 km east of Darwin (Hegge, 1977), may also support a genetic link of PGMs with carbonaceous metasediments in the South Alligator River region.

The Polish Kupferschiefer is one of the few stratabound ore environments in the world which show no evidence of igneous activity, i.e. no intrusions, dykes, or volcanic rocks. Hydrological processes acting at redox barriers and the catalytic activity of organic matter appear to be important mineralising mechanisms. Stumpfl (1986) notes that PGM values of more than 10 ppm in a cm-thick precious-metal-shale horizon at the contact of sandstone (oxidising conditions) and black shale (reducing conditions), extend over tens of thousands of square metres. Values exceeding 200 ppm Pt do occur over limited areas. The Pd and Pt in the thucholites are believed by Kucha (1975) to have been derived by the decomposition of Pd- and Pt-bearing organic compounds during diagenesis, and remobilised by circulating brines enriched in dissolved organic complexes and redeposited as arsenides, sulpharsenides, and bismuthides in the shales, or rocks directly below the shales. A later theory by Kucha & Pawlikowski (1986) involved brines which percolated downward from overlying anhydrites into underlying redbeds where, upon heating, they leached the PGMs from interbedded volcanics. The hotter metalliferous brines interacted with descending colder brines in shallower parts of the basin and deposition of the base and precious metals resulted.

GEOLOGY OF PLATINUM-GROUP METALS IN AUSTRALIA

(D. M. Hoatson)

HISTORICAL BACKGROUND

Australia's PGM production has been dominated by the alluvial deposits of Fifield, NSW (640 kg Pt), and western Tasmania (970 kg Os), and the hardrock nickel-sulphide deposits of the Kambalda district, WA (6050 kg Pd, Pt, Ru). These three provinces have accounted for more than 99% of mine production of approximately 1885 kg Pt, 4820 kg Pd, 970 kg Os, 5 kg Ru (total, 7680 kg) for the period 1894–1987. Figure 9 shows the history of Australia's Pt, Pd, and Os mine production, with the sequential contributions from the Fifield (Pt), western Tasmanian (Os), and Kambalda (Pd, Pt) provinces. The mining statistics of the major PGM deposits/ provinces are summarised in Table 7, and annual output statistics since the start of production in 1894 are shown in Appendix 2.

Many PGM occurrences were reported in Australia during the latter half of the 19th century. However, it was not until 1893 that Australia's first PGM production commenced from the Fifield district of central New South Wales. The first documentation of PGMs in Australia was by Stutchbury in a report dated 9 June 1851, in which, referring to the Macquarie and Turon Rivers, near Orange, New South Wales, he says 'I have seen a few grains of platina, but it appears to be rare' (Flack, 1967). W. B. Clarke reported in 1860 the occurrence of platinum grains in the goldfields of New South Wales, and alluvial platinum nuggets of up to 12 g were found in 1869 at Brickfield Gully on the Gympie Goldfield, Queensland (Dunstan, 1913).

Surveyor-General Sprent in 1875 is credited with the first discovery of osmiridium in Tasmania (Reid, 1921). During one of his early expeditions to the Wilson River of western Tasmania he incorrectly identified the osmiridium as palladium. In the late 1870s prospectors working in the Whyte and Savage River areas of the Corinna goldfield found abundant osmiridium in association with gold in the alluvial deposits. At that time there was no demand for the mineral and the prospectors considered it as an obnoxious impurity since it was difficult to separate from the gold and a penalty of 7s. 6d. per oz was imposed by the Mint for its removal. Most osmiridium in the sluicing operations was discarded. It was not until the turn of the century that small quantities of osmiridium filtered through to foreign investors, who appreciated the good quality and coarse grainsize of the material. Reid (1921) noted that although the price offered (25s. per troy oz) was very small, it gave the diggers some incentive to continue their prospecting and mining. With the rising metal price, production also increased and the osmiridium mining industry of western Tasmania became established. Production increased erratically during the early 1900s, and culminated in 1925 when the Adamsfield alluvial deposits were exploited and 104 kg of osmiridium was mined. During this period, Tasmania was the largest producer of osmiridium in the world (Geary & others, 1956).

Platinum, gold, and tin were found in beach sands in the Richmond River district, northern New South Wales in 1878. The deposits were mined for gold for many years, but a small quantity of platinum was recovered as a by-product. Platinum was first found at Fifield in 1887, but there was little production from the field until the discovery of the Platina Lead in 1893 (Geary & others, 1956). Production from the Fifield region peaked in 1896 when 75.6 kg Pt was recovered, but mining operations in subsequent years were often hampered by the lack of a regular water supply and by the thick clay that covered the flat countryside. The discovery of the nearby Gillenbine Tank Lead in 1917 provided minor impetus to the declining production rate from Fifield. Platinum from the Broken Hill district was first detected in 1889 in samples of nickel-copper ore submitted to the Department of Mines for assay (Mingaye, 1892). A field survey undertaken in 1892 showed that PGM mineralisation occurred throughout the eastern parts of the Broken Hill district, notably at Little Darling Creek, Mulga Springs, and Round Hill (Jaquet, 1893). One of the first examples of hardrock PGM production in Australia, albeit as a by-product of Cu-Ni-Au mining, was from the Thomson River copper mine, near Walhalla, Victoria. Intermittent mining since its discovery in 1864 produced about 10 kg Pt, most of which was obtained in 1911 and 1913.

Table 7. Platinum-group metal mining centres in Australia: production history, etc.

	Mine production (kg)	*Discovered*	*Main producing period(s)*	*Style of mineralisation*	*Reference*
Kambalda, WA	6 050 (Pd 4 820, Pt 1 225, Ru 5)	1966	1974–	Hard-rock	Hudson (1986) Hudson & Donaldson (1984)
Fifield, NSW	640 (Pt)	1887	1893–99	Alluvial	Flack (1967) Suppel & Barron (1986a)
Wilson River, Mt Stewart, Savage River, Tas.	490 (Os, Ir)	1875	1913–14 1918–23	Alluvial	Reid (1921) Geary & others (1956)
Adamsfield, Tas.	480 (Os, Ir)	1925	1925–34	Alluvial	Geary & others (1956) Varne & Brown (1978)
Thomson River, Vic.	10 (Pt)	1864	1911–13	Hard-rock	Cochrane (1982) Cozens & Rangott (1972)
Macquarie River, NSW	6 (Pt)	1851	1950–54	Alluvial	Geary & others (1956) Barrie (1965)
Ballina district, NSW	4 (Pt)	1878	1936–38	Beach-sand	Flack (1967)

Source: Geary & others (1956); Kalix & others (1966); Department of Mines, Western Australia, Annual Reports; *Australian Mineral Industry Annual Review*.

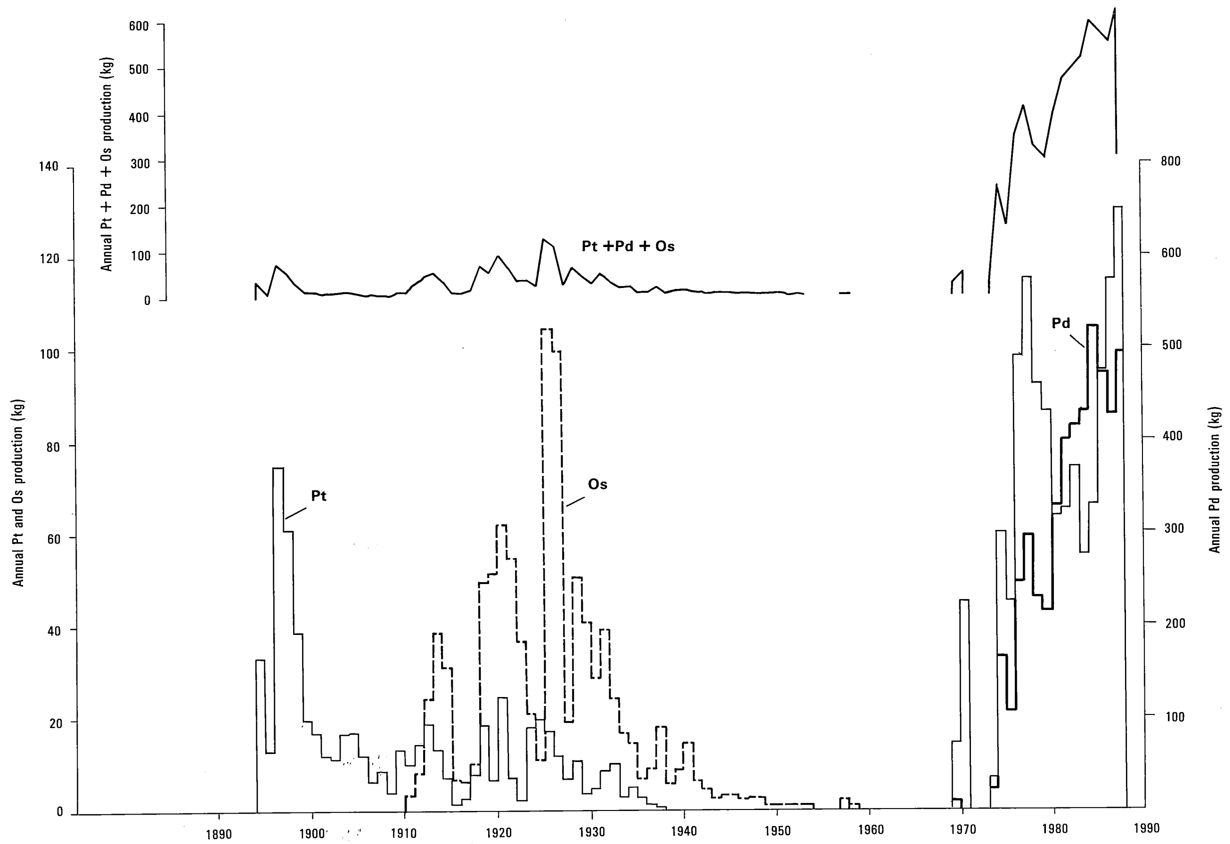

Fig. 9. History of Australia's Pt, Pd, and Os production (years with production of less than 1 kg not shown). Sources: Geary & others (1956); Kalix & others (1966); *Department of Mines, Western Australia, Annual Report; Australian Mineral Industry Annual Review.*

GEOLOGICAL SETTING

Platinum-group mineralisation is widespread in the Precambrian and Palaeozoic terranes of Australia, but so far no major economic resource has been found. The komatiite Ni-Cu sulphide deposits at Kambalda, WA from which PGMs are currently a by-product, is the only proved current economic resource. The prospects or deposits that appear at present to have the greatest economic potential are at Munni Munni, WA (Archaean layered mafic-ultramafic complex), Fifield, NSW (early Palaeozoic concentrically zoned complexes), Adamsfield and Heazlewood, Tasmania (early Palaeozoic alpine-ophiolite intrusions and alluvials), and Coronation Hill, NT (Proterozoic hydrothermal-remobilised). There are numerous PGM occurrences, many of which have a common age, style, and tectonic setting. These features are summarised in Table 8, and Figures 10, 11, and 12. Most Australian PGM occurrences can be related to the following six geological settings:

- **Alpine serpentinite intrusions and associated placer or laterite deposits**
- **Ophiolite complexes**
- **Concentrically zoned mafic-ultramafic complexes**
- **Layered mafic-ultramafic complexes**
- **Fe-Ni-Cu sulphide deposits associated with komatiitic volcanism**
- **Remobilised platinum-group metal mineralisation (hydrothermal)**

Alpine serpentinite intrusions and associated placer or laterite deposits

Placer deposits of Os, Ir, and Ru alloys are associated with tectonically emplaced alpine serpentinites that occur sporadically in belts in Tasmania, New South Wales, and Queensland in the Tasman Fold Belt System of eastern Australia. These generally linear chromiferous intrusions range in age from Cambrian in Tasmania and Devonian in central New South Wales to Permian in northern New South Wales and Queensland, indicating a regional younging in age towards the north. Notable intrusions of alpine serpentinite affinity occur in the Adamsfield, Montague Swamp, and Beaconsfield areas of Tasmania (Brown & others, 1979), the Gundagai–Coolac, Nundle–Bingara, and Copmanhurst–Gordonbrook Belts of New South Wales (MacNevin, 1975a, 1975b; Leitch, 1979), and the Rockhampton district of southern-central Queensland (I.N.A.L. Staff, 1975).

The distribution of the alpine serpentinite bodies in eastern Australia is commonly strongly controlled by steeply dipping northwest to northeast trending fault systems; hence they represent fault bounded intrusive blocks that form well-defined belts. Dunite, orthopyroxenite, and harzburgite are the dominant rock types, with syn-emplacement deformation fabrics and serpentine alteration commonly overprinting primary igneous textures. Massive podiform chromitite horizons appear to be more prominent in the Devonian and Permian complexes, whereas disseminated chromite is more typical of the Cambrian Tasmanian occurrences. Contact metamorphism is weak to absent since emplacement is generally via faults. The heterogeneous distribution of the Os-Ir-Ru alloys in these intrusions largely reflects the erratic nature of the chromite mineralisation associated with the serpentinites. Iridosmine and rutheniridosmine minerals dominate the Tasmanian placer deposits, osmiridium and Pt-rich alloys being rare (Ford, 1981). Alpine-type intrusions are believed to hold little promise for a major undiscovered resource of PGMs, since they are confined to well-defined belts, form hills, and are often associated with earlier discovered placer deposits. The hard-rock PGM mineralisation is also of low tonnage status and has an erratic distribution (Hoatson, 1984).

The Adamsfield alpine serpentinite complex in southern Tasmania has attracted considerable interest since its PGM potential was first realised in 1925. The Adamsfield district has produced approximately 480 kg of alluvial Os-Ir-Ru in the period 1925 to 1959, i.e. about 50% of Australia's total recorded production (Table 7). The Adamsfield Complex is one of several Cambrian ophiolite-alpine intrusions in the Adamsfield and Dundas troughs. It is a north-south trending arcuate body, some 15 km along strike and less than 1 km wide, that intrudes Upper Cambrian and Ordovician flysch and molasse-type sediments. Serpentinised dunite, olivine orthopyroxenite, and orthopyroxenite form an anticlinal structure, with well-developed layering of all rocks in the northern part of the complex, whereas the southern part consists of massive dunite and orthopyroxenite. The transition from massive to layered rocks is defined by a zone of intense, high temperature deformation. Varne & Brown (1978) document the olivine compositions in the layered rocks as Fo_{93-84}, orthopyroxene as En_{94-87}, and spinel, which forms a minor but widely disseminated phase, as having $Mg/(Mg+Fe^{+2}) = 0.57$ to 0.24, and $Cr/(Al+Cr+Fe^{+3}) = 0.95$ to 0.56. Varne & Brown (1978) believe the Adamsfield complex crystallised at low pressures from highly magnesian, titania-poor tholeiitic or andesitic magmas. The alluvial platinum-group minerals and chromite occur in Late Cambrian sedimentary rocks unconformably overlying the ultramafics, and in Holocene alluvial sand and gravel (Cabri & Harris, 1975). The Os, which is strictly hexagonal rutheniridosmine or iridosmine, generally forms irregular grains 0.5 to 1.5 mm across, but nuggets up to 50 g have been found; it has also been reported as occurring rarely in serpentinite but no occurrence has been documented in unaltered peridotite. The hardrock, and in particular the alluvial mineralisation potential of the Adamsfield region is currently being intensively evaluated.

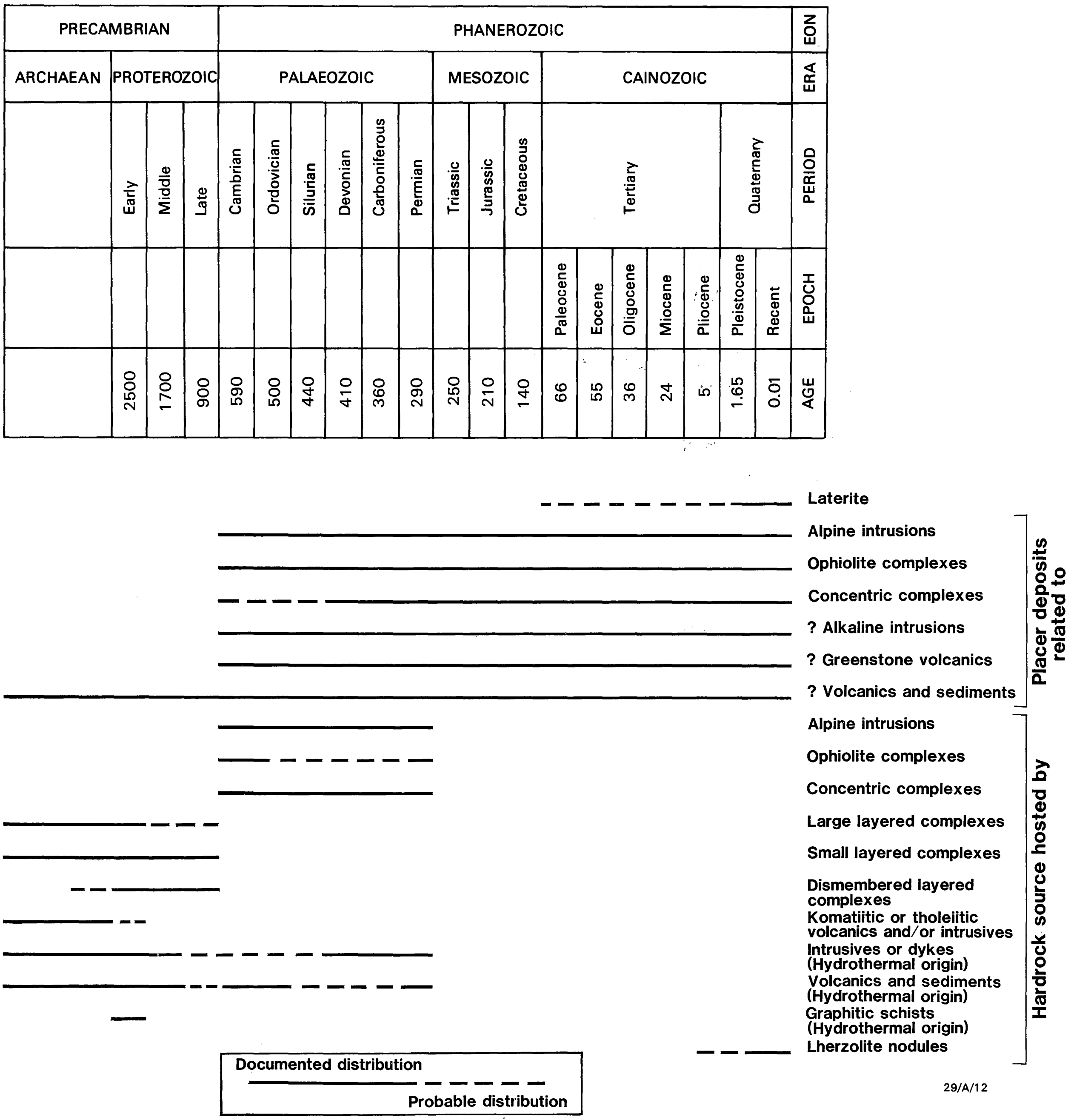

Fig. 10. Variation of PGM mineralisation styles with time. Geological time scale denotes age of base of periods, eras, etc. in millions of years (ages from Haq & van Eysinga, 1987).

Harzburgite and serpentinised dunite are the dominant rock types along the 100 km strike length of the Coolac serpentinite belt, near Tumut, New South Wales. The linear alpine-type intrusion was actively explored in 1894–1904 when approximately 30 000 t of chromitite was mined from 40 podiform chromitite deposits (Ashley, 1975). In recent years companies have focused their interest on PGM mineralisation related to the intrusions, and have reported Pt in stream sediment samples and tentatively identified it as inclusions in magnetite grains and in sulphide ore from the Bogong copper mine at the southern end of the Coolac belt (Helix Resources NL 1986 Prospectus).

Nickel-cobalt-bearing laterites are associated with alpine serpentinite in the Beaconsfield area of Tasmania, and the Rockhampton and Greenvale areas of Queensland; however, it is not known whether there has been any remobilisation and concentration of PGMs during lateritisation. Recent evidence suggests that the transport of the PGMs and Au in solution is aided by conditions prevalent in the development of laterite, particularly where humic or fulvic acids are present. Bowles (1985, 1986) has shown that PGMs are mobile in laterite under very acid, chloride-rich conditions with a high Eh. The PGMs may also be mobilised by thiosulphate and sulphite complexes in neutral to alkaline solutions or as chloro-complexes in acid solutions during oxidation of sulphides (Plimer & Williams, 1987). Bowles (1986) describes examples of Pt-Fe alloy nuggets in laterite associated with the zoned Yubdo ultramafic massif in western Ethiopia, and alluvial-eluvial PGM nuggets believed to be derived from laterite overlying anorthosite of the Freetown Peninsula layered complex in Sierra Leone. Davies & Bloxam (1979) noted Pt levels up to 100 ppb in the Freetown laterites. Derkmann & Jung (1986) have reported anomalous Pt and Pd levels in Ni-laterite in Burundi, and Ahmad & Morris (1978) reported PGM-enriched A and B horizons from lateritic profiles in New Caledonia, Guatemala, and Indonesia. Travis & others (1976) documented elevated Pd and Ir levels in

Table 8. Classification of Australian platinum-group metal occurrences (major published references for each deposit class are listed at the end of the table)

Association	*Age of host rocks*	*Tectonic setting*	*Dominant PGMs*	*Examples*
1. Laterite	Cainozoic	Orogenic and cratonic	Pd, Ir	Gilgarna Rocks[1], Carr Boyd, Youangarra, WA
2. Placer deposits related to:				
(a) Alpine intrusions	Cambrian to Cainozoic	Orogenic	Os, Ir	Adamsfield[2], Bald Hill, Tas.
(b) Ophiolite complexes	Cambrian to Cainozoic	Orogenic	Os, Ir, Ru	Nineteen Mile Creek[3], Wilson River, Tas.
(c) Concentrically zoned complexes	Devonian to Cainozoic	Orogenic	Pt	Fifield[4], NSW
(d) ? Alkaline mafic-ultramafic intrusions	Cambrian to Cainozoic	Orogenic	Pt	Murrumarang, Ulladulla, NSW
(e) ? Greenstone volcanics and associated sediments	Cambrian to Cainozoic	Orogenic	Pt, Os, Ir	Waratah Bay, Stockyard Creek, Turtons Creek[5], Vic.
(f) ? Volcanics and associated clastic sediments	Archaean to Cainozoic	Orogenic	Ir, Os, Ru	Karratha[6], WA
3. Alpine serpentinite intrusions	Palaeozoic	Early orogenic	Os, Ir	Adamsfield[2], Tas., Coolac[7], NSW, Rockhampton[8], Qld
4. Ophiolite complexes	Cambrian	Early orogenic	Os, Ir, Ru	Heazlewood[9], Tas.
5. Concentrically zoned complexes	Palaeozoic	Late orogenic	Pt, Pd	Fifield[4], NSW Wateranga, Qld
6. Layered mafic-ultramafic complexes				
(a) Large (more than 5 km thick)	Archaean to Early Proterozoic	Cratonic	Pt, Pd	Munni Munni[10], Windimurra[11], WA
(b) Small to moderate (less than 5 km thick)	Archaean to Proterozoic	Orogenic and cratonic	Pt, Pd	Jimberlana[12], Mt Thirsty, WA
7. Tectonically dismembered layered complexes of mobile zones	Proterozoic	Orogenic	Pt, Pd	Panton[13], Lamboo, Eastmans Bore, Plumridge Lakes, WA
8. Nickel-copper sulphide komatiitic or tholeiitic volcanic-intrusive association	Archaean	Orogenic and cratonic	Pt, Pd	Kambalda[14], Windarra[15], WA

Table 8 (continued)

Association	*Age of host rocks*	*Tectonic setting*	*Dominant PGMs*	*Examples*
9. Hydrothermal-remobilised				
(a) Spatial association with mafic-ultramafic intrusives or dykes	Proterozoic to Palaeozoic	Orogenic	Pt, Pd	Thomson River[16], Vic. Mulga Springs, NSW Westwood[17], Qld
(b) Spatial association with mafic-ultramafic intrusives	?Archaean	Cratonic	Pd, Pt	Yarawindah Brook[18], WA
(c) Spatial association with volcanics and sediments	Archaean to Palaeozoic	Orogenic	Pd, Pt	Kambalda[14], WA Coronation Hill[19], NT Gympie, Qld
(d) Spatial association with graphitic schists	Early Proterozoic	Orogenic	Pd	Jabiluka[20], NT
10. Sediments	Palaeozoic	Basinal	Pt, Pd	McWhae Ridge[21], WA
11. Lherzolite nodules	Cainozoic	Orogenic	Pt, Pd	Western Victoria[22]

1. Travis & others (1976); 2. Varne & Brown (1978); 3. Rubenach (1973); 4. Suppel & Barron (1986a, 1986b); 5. Ferguson (1936); 6. Hudson & Horwitz (1985); 7. Ashley (1975); 8. I.N.A.L. Staff (1975); 9. Cabri & Harris (1975); 10. Hoatson & Keays (1987); 11. Parks & Hill (1986); 12. Keays & Campbell (1981); 13. Hamlyn (1977, 1980); 14. Hudson & Donaldson (1984); 15. Roberts (1975); 16. Cochrane (1982); 17. Ostwald (1979); 18. Harrison (1986); 19. Needham & Stuart-Smith (1987); 20. Hegge (1977); 21. Playford & others (1984); 22. Keays & others (1981).

lateritised ultramafic rocks at Gilgarna Rocks, Carr Boyd, and Youangarra, WA. The similar chemical behaviour of gold and PGMs in the weathering cycle, and the recent recognition of one of Australia's largest gold mines, the laterite-hosted Boddington deposit (Davy & El-Ansary, 1986) 150 km south-southeast of Perth in the Archaean Saddleback greenstone belt, indicates that ferruginous layers overlying mafic igneous rocks should be investigated for lateritic, remobilised PGM-Au mineralisation.

Ophiolite complexes

Complete ophiolite sequences are rarely preserved in Australia. A typical ophiolite sequence comprises a basal zone of tectonised peridotite overlain by a cumulus sequence (ranging from peridotite to gabbro in composition), pillow lavas, feeder dykes, and cherts. The ophiolites have similar tectonic settings and geochemical features to the alpine serpentinite complexes, but the associated volcanics and chemical sediments are generally absent from the alpine intrusions. Due to their similar geological settings, alpine and ophiolitic intrusions could be classified into one group of tectonically emplaced Phanerozoic intrusions.

Tasmanian ophiolite complexes occur in Cambrian sedimentary troughs between regions of Precambrian basement. Brown & others (1979) believe they are slices of oceanic crust that were formed during the waning stage of igneous activity associated with abortive Cambrian rifting of continental lithosphere, and the formation of sedimentary troughs, i.e. a continental rift setting. Other theories invoke an active continental-margin origin (Berry & Crawford, 1988), with emplacement of the oceanic slices during plate collision. Intrusions resembling ophiolites include the Heazlewood River, Wilson River, Serpentine Hill, Anderson's Creek, Forth, and Cape Sorell complexes in northwest Tasmania. The largest of these, the Heazlewood Complex in the Dundas Trough, consists of a basal tectonised layered dunite sequence, overlain by a layered sequence of harzburgite, dunite, pyroxenite, and gabbro (Rubenach, 1973). The complex covers 30 km^2, and is about 6 km thick. Quartz-tholeiitic dolerites, pillow basalts, and high-magnesian andesite lavas accompany the intrusive rocks.

PGMs have been documented only rarely in Australian ophiolites, although precious metals occur in tectonised dunites and intensely serpentinised ultramafics of the Heazlewood Complex. Hardrock sources are of low grade, mining being largely restricted to eluvial deposits and stream placers buried by Tertiary lavas. Native Pt, laurite, and a possible Os-sulphide (? erlichmanite) have been documented with base-metal sulphides and Ni-Fe alloys in the Heazlewood chromitites, and native Pt or a Pt-sulphide in a dunitic pipe (D. Peck, personal communication, 1987). The chromitites form lenses associated with pegmatitic norite in a magma mixed zone. Localities for alluvial PGMs related to the Heazlewood Complex include Nineteen Mile Creek, Savage River, Whyte River, Long Plain, Brown Plain, Corinna, Mount Stewart, Wilson River, and Huskisson River (Ford, 1981). In the early 1900s, the Heazlewood area was a notable world producer of alluvial PGMs. Their compositions contrast to the native and S-bearing PGM assemblages of the hardrock source: dominant is rutheniridosmine with high Ru levels compared to the Adamsfield iridosmine grains (Ford, 1981). Osmiridium is also a rare alluvial mineral at Heazlewood. Cabri & Harris (1975) documented unusual compositional zoning trends in the Heazlewood Os-Ir alloys. From the centre of some grains to the margins, the Ru content remained constant and Ir increased with the antipathetic decrease in Os, while in other grains there were complex enrichment-depletion features of Ir and Os towards the margins, Ru again remaining uniform. Heavy minerals associated with the rutheniridosmine include gold, gold-platinum alloys, chromite, picotite, magnetite, pyrrhotite, and pyrite (Mertie, 1969).

Concentrically zoned mafic-ultramafic complexes

Alaskan-type intrusions appear to be rare in Australia, although this may be due in part to post-emplacement deformation and intrusion that has destroyed the concentric form and primary mineralogy of these small intrusions, thus making recognition difficult.

In the Girilambone Anticlinorial Zone of central New South Wales, several Early Devonian (405 Ma, Pogson & Hilyard, 1981) Alaskan-type intrusions form a north-northwest trending belt from Derriwong through Fifield to possibly as far north as Doradilla near Bourke. This regional province possibly extends over 320 km and coincides with the Parkes Terrace gravity high zone (Suppel & Barron, 1986a). The Gilgai, Honeybugle, Bulbodney Creek, Hylea, Owendale, Tout, Kars, Murga, Avondale, and Derriwong complexes, which intrude the Ordovician Girilambone Group, are composed of pyroxenite, peridotite, hornblendite, monzonite, meladiorite, and melasyenite. Their multiple and clustered distributions suggest further intrusions may occur along extensions of the presently defined province. Linear alpine serpentinites are commonly associated with the zoned intrusions. Anomalous PGM levels have been reported from many of the Alaskan-type intrusions; thus the Fifield–Doradilla region is a new PGM province of considerable interest.

There are three major settings for the PGMs in the Fifield area: (1) fresh bedrock, (2) alluvial deposits as buried leads and young gravels, and (3) the weathered zone above the intrusions.

(1) The Fifield district has been the largest producer of Pt from eastern Australia; thus it is surprising that the PGM potential of several intrusions in the region of the alluvial deposits appears only recently to have been realised. An important factor

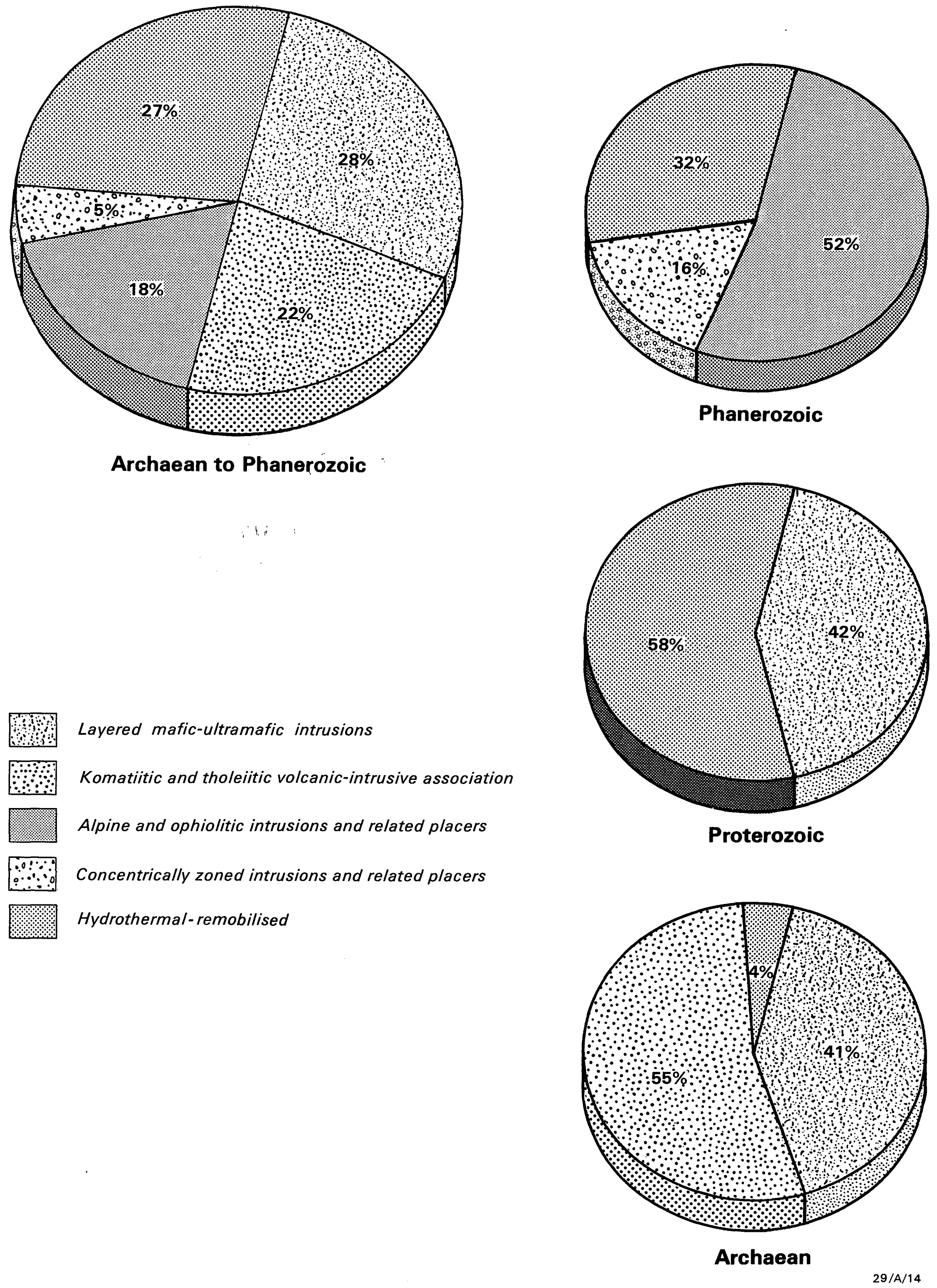

Fig. 11. Frequency distribution of the major PGM subclasses, from the Archaean to the Phanerozoic, based on the number of PGM occurrences.

contributing to the recent success in delineating PGM mineralisation at Fifield has been the philosophy of the companies concerned, leading them to consider other styles of PGM mineralisation, rather than the more conventional layered intrusive-type model. These include the possibilities of Alaskan-type intrusive and hydrothermal-remobilised mineralisation models. Resampling of old drill core by the Geological Survey of New South Wales from holes initially drilled in the 1960s for Ni-Cu sulphide mineralisation has returned narrow but significant PGM intersections. In the Owendale Complex, 10 km north of Fifield, anomalous Pt and Pd levels are associated with transgressive monomineralic clinopyroxenite (the 'p units' of Suppel & Barron, 1986b) in a biotite-hornblende clinopyroxenite. The best intersection was 1.57 m @ 13.19 ppm Pt, 0.90 ppm Pd, and 0.5 ppm Rh. Suppel & Barron (1986b) found that the mineralised clinopyroxenites are characterised by low levels of S ($< 0.04\%$), Se, Te, Sb, Bi, As, and Sn, but high Pt/Pd ratios $\geqslant 10$. Several platinum-group minerals have been tentatively identified by Suppel & others (1987), and these include platinum-isoferroplatinum, cooperite, geversite, platarsite, sperrylite, stibiopalladinite, and erlichmanite. Barron & others (1987) found that the platinum-group minerals occur as euhedral 15 to 30 μm grains of Fe-platinum coexisting with Rh-bearing erlichmanite, Al-F-sphene, and fluorite that were trapped in fractures in magnetite. Most rocks have variable amounts of Ti-poor magnetite ranging from 5 to 25 volume-%. Chromite forms a rare component of the Owendale mineralisation. The PGM mineralisation has no obvious geochemical signature, e.g. no changes in S, Cu, Ni, or Cr contents, except that high PGM levels are characterised by marked increases in the Pt/Pd ratio; thus tracing and delineating the remobilised mineralisation will be difficult.

A different style of hardrock PGM mineralisation has been recognised by Helix Resources NL at the Tout intrusion, 10 km southwest of the Owendale intrusion. Anomalous Pd and Pt levels are associated with elevated Cu, Ag, and Au concentrations in pyroxenitic rocks that are traversed by a pervasive fracture zone. The metal association and structural control may indicate that hydrothermal fluids were important in reworking and enhancing the PGM levels of disseminated sulphides of magmatic origin into areas with a favourable structural framework. It is probable that similar base metal sulphide-PGM associations of magmatic-hydrothermal origin will be defined in other intrusions of the Fifield region.

The small size, equidimensional form, and zoned nature (particularly evident from aeromagnetic trends) of the intrusions, their clustered distribution and alkaline compositions, paucity of orthopyroxene in the rocks, the Pt-dominance and localised irregular distribution of the primary mineralisation, and the association with Pt-bearing placers collectively indicate that the Fifield PGM occurrences have some affinities to the Alaskan-type deposits. However, Alaskan and Ural deposits are characterised by chrome-rich accessory minerals in dunite, which is in contrast to the setting at Fifield. Also some Fifield intrusions have a reverse zoning, with ultramafic rocks mantling an inner core of more fractionated rocks. Remobilisation of the PGMs in partly congealed magma-crystal mushes or hydrothermal-deuteric fluid systems may have played an important role in the distribution of the PGMs in the Fifield intrusions. Possible source rocks for this contribution of heat/volatiles are marginal dunites, or monzonitic rocks near the cores of the intrusions. Wyborn (1988) has suggested from trace-element geochemistry, that the Fifield intrusions have shoshonitic affinities, and possibly represent deep cumulate feeder zones to Ordovician volcanics and high-level sills that occur to the east and south of Fifield. Future geochemical and zircon age dating studies at BMR and ANU should provide more insight into the origin of the Fifield intrusions.

(2) The Fifield deep leads have been the most important source of Pt in eastern Australia, with alluvial Pt and Au occurring in Tertiary gravels, buried leads, and recent alluvium derived from both gravels and leads (Bowman & others, 1982). The most important palaeo-drainage system, the Platina Deep Lead, 5 km south of Fifield (S. Elliot, 1987, Helix Resources NL Technical Report 2011), produced approximately 474 kg of Pt at grades of 5–13 g/t and 124 kg of Au at grades of 1.5–4.6 g/t . The deep lead extended for approximately 3 km in a north–south direction, with the palaeo-drainage direction towards the south. After its apparent confluence with the Un-named Deep Lead from the west, the Platina Deep Lead changed direction towards the southeast. The Pt and gold-bearing gravels were less than 1 m thick and occurred in traps in the erosional surface of the basement Girilambone Group metasedimentary rocks. The gravels cropped out at the northern end of the lead, but towards the south they were covered by up to 22 m of Quaternary sands, clays and gravels. The distribution of the old workings indicates the deep lead varied from 20 to 30 m in width. The principal platinum-group mineral in the gravels is isoferroplatinum, but the source of the Pt-alloys and gold is unknown. It is likely the metals are derived from the nearby Alaskan-type intrusions and have experienced a complex history of multiple cycles of transport and deposition. Other platiniferous deep lead systems, such as the Gillenbine Tank Lead (3 km southeast of Fifield), and the Fifield Lead (1 km north of Fifield) also produced minor quantities of Pt and gold. Waterworn Pt and gold grains have also been found in the ferruginous cement of a quartz-bearing conglomerate of possible Tertiary age at Jacks Lookout, 3 km east of Fifield (Flack, 1967).

(3) Recent trenching and costeaning by a number of companies exploring in the district suggest that secondary enrichment in the weathered zone may hold potential for a bulk, low grade, surficial PGM deposit. The irregular distribution of Alaskan ores necessitates some transporting and concentrating mechanism if a large viable deposit is to be formed. At Fifield there has been secondary mobility of the PGMs in the weathered bedrock and overlying in situ soil profile. The soils, which are rarely more than 2 m thick, and the weathered bedrock have anomalous Pt levels over extensive widths. Companies have reported the following Pt intersections: (1) 58 m @ 0.44 ppm at the Derriwong Complex, south of Fifield (Platinum Search NL), (2) an 82 m wide zone grading 0.54 ppm at the Owendale Complex, Fifield (Helix Resources NL), (3) 2 m @ 17.5 ppm at the Honeybugle Complex (Helix Resources NL), and (4) at Bulbodney Creek, near Tottenham, a drill intersection in the oxidised zone above an Alaskan-type intrusion returned 16 m @ 3.4 ppm (Helix Resources NL 1987 Annual Report). The near-surface and laterally continuous character of the mineralisation indicates that the Fifield secondary Pt deposits may be amenable to blanket stripping mining techniques, and metallurgical extraction would be a cost efficient gravity separation process since the Pt is largely in the native or alloy form and coarse-grained.

Composite Palaeozoic–Mesozoic intrusions comprising norite, olivine gabbro, pyroxenite, and anorthosite of possible Alaskan type occur in the Wateranga district of southeastern Queensland. The four small intrusions of interest — Wateranga, Goondicum, Hawkwood, and Boyne — are near the intersection of the Darling River Lineament and the Yarrol and Perry fault systems, and are currently being evaluated for PGM mineralisation possibly associated with apatite-rich magnetite pyroxenite.

Layered mafic-ultramafic complexes (Appendix 3, Fig. 16)

Layered mafic-ultramafic complexes are prominent in the cratonic terranes of western and central Australia, e.g. the Archaean Yilgarn and Pilbara Blocks and Proterozoic Musgrave Block. Tectonically dismembered variants of the layered intrusions also occur in Proterozoic mobile zones, such as the Halls Creek and Albany-Fraser Mobile Zones. Phanerozoic layered intrusions in eastern Australia are not as prospective for Bushveld-Stillwater style PGM mineralisation because of their younger age and smaller size.

It is not coincidental that the major stratabound PGM-bearing sulphide horizons of the world occur in intrusions more than 5 km thick. The average Pt + Pd content of unmineralised mafic-ultramafic rocks ranges from 5 to 50 ppb; thus, if economic grades (> about 6 ppm Pt + Pd in Australia) are to be achieved for a Merensky Reef type deposit, a concentration factor of at least 100 to 1000 is required. This high concentration factor necessitates a large volume of PGM-bearing magma, and/or a very efficient concentrating mechanism. Thus, intrusions that exceed 5 km in thickness, are strongly fractionated, contain multiple magmatic pulses, and experienced late S-saturation, will be more favourable for stratabound-type PGM mineralisation than smaller homogeneous intrusions that have an early evolution of S-saturation.

Australian layered intrusions stratigraphically thicker than 5 km include the Windimurra Intrusion (Yilgarn Block; around 9 km thick; Parks & Hill, 1986), Narndee Complex (Yilgarn Block; 6 to 10 km; personal communication, C. Williams), Munni Munni Complex (Pilbara Block; 5.5+ km; Hoatson & Keays, 1987), intrusions of the Giles Complex (Musgrave Block; around 5 to 6 km; Nesbitt & others, 1970), and the McIntosh Sill (Halls Creek Mobile Zone; around 6 km; Mathison & Hamlyn, 1987). The Heazlewood Complex in Tasmania which has ophiolitic affinities is also reported to exceed 5 km in thickness (personal communication, D. Peck, 1987). These intrusions are currently being studied by various companies and universities and by BMR and CSIRO. In these larger intrusions the most commonly explored target has been stratabound sulphide-enriched horizons, similar to a Merensky or J-M Reef, which offer potential for uniformity of grades over long strike lengths, large tonnages, and open-cut or strip mining. Other potential styles of PGM mineralisation, e.g. pipe-like bodies, or podiform Picket Pin-type (Stillwater Complex) sulphide horizons high in the gabbroic stratigraphy, have unfortunately been largely ignored.

Exploration targets in layered intrusions of Proterozoic mobile zones are generally discontinuous chromite segregations that have been tectonically disrupted, e.g. chromitites of the Panton and Lamboo sills and the Louisa Downs Complex. Concentrations within these chromitites are generally < 3 ppm total PGMs; however, localised values up to 7.5 ppm over 0.1–0.5 m width have been documented in the Louisa Downs chromitites (Louthean, 1987). Various features of nearly 100 Australian Archaean and Proterozoic mafic-ultramafic intrusions are summarised in Appendix 3.

The Munni Munni mafic-ultramafic complex in the western Pilbara Block (Fig. 14) is Australia's most prospective PGM deposit that conforms to the layered-intrusive model. It is a good example where during the 1970–83 period, companies investigated along the basal contact of the ultramafic zone for Ni-Cu sulphide segregations, but did not evaluate the PGM potential of the intrusion at higher stratigraphic levels. In 1983, the BMR commenced a PGM-orientated study of Munni Munni as part of a regional evaluation of the PGM potential of intrusions in the Pilbara. It was believed that the intrusion was prospective for a chromite-PGM association in cyclic units of the ultramafic zone, or for sulphide-hosted PGM mineralisation near the interface of the ultramafic and gabbroic zones, similar to the major overseas PGM deposits (Hoatson, 1984). During 1984, Hunter Resources Ltd delineated by soil and rock geochemistry in the western half of the complex (Whim Creek Consolidated and Samim Australia Pty Ltd hold title over the eastern half of the complex), a persistent mineralised horizon at the ultramafic-gabbroic interface. Subsequent diamond drilling has shown the mineralised horizon extends for 7.5 km along strike, and has grades of 1.0–3.2 ppm Pt + Pd + Au over a 3.5 to 13.0 m thickness. Within this low grade layer there is a higher grade zone that averages 2.1–6.7 ppm Pt + Pd + Au over a 2.0 m width (Williams & Nisbet, 1987). The outcropping mineralised horizon has a strike length of 12+ km (including both the Hunter Resources and Whim Creek–Samim titled areas), and is stratigraphically within 400 m of where a Merensky or J-M Reef would be situated. Hoatson & Keays *in* Von Gruenewaldt & others (1987a) have described in detail the geological setting and PGM geochemistry of the complex.

Exposed over an area of 4 by 9 km, the 2800 Ma old Munni Munni Complex is composed of a lower 1850 m-thick ultramafic zone and an overlying gabbroic zone which has a minimum thickness of 3630 m (Fig. 14). The gabbroic zone of the complex is unconformably overlain to the southwest by shallow dipping Fortescue Group sedimentary rocks and volcanics, but aeromagnetics (Yarraloola 1: 250 000 BMR Total Magnetic Intensity Sheet F50/B1–7, 1963) and gravity (Yarraloola 1:250 000 BMR Bouguer Anomalies Sheet 21–1/F50–6, 1979) indicate the overall dimensions of the intrusion are closer to 9 by 25 km. The ultramafic zone contains rhythmically layered dunite, lherzolite, olivine websterite, clinopyroxenite, and websterite, with orthopyroxenite, norite, chromitite, and mineralised websterite occurring below the ultramafic-gabbroic zone interface. The gabbroic zone consists of gabbronorite and anorthositic gabbro, which display a pronounced tholeiitic fractionation trend. The cumulus mineral paragenesis of the complex is: olivine, olivine-clinopyroxene, clinopyroxene-olivine, clinopyroxene, orthopyroxene-chromite, and plagioclase. This sequence is at variance with other major PGM-hosting intrusions where crystallisation of orthopyroxene generally preceded that of clinopyroxene. This is significant since chromite mineralisation at Munni Munni is controlled by the appearance of cumulus orthopyroxene at the expense of cumulus clinopyroxene.

It is considered that the PGM and minor Cu-Ni-Au mineralisation that occurs in a porphyritic plagioclase websterite horizon along the ultramafic-gabbroic interface resulted from the combined magmatic processes of crystal fractionation and mixing of chemically distinct magma types. During the crystal fractionation of a S-undersaturated ultramafic magma, Pt, Pd, Au, Cu, and S behaved incompatibly by building up in concentration in the melt. A hotter, more buoyant S-saturated tholeiitic magma rose through the density-stratified PGM-enriched ultramafic magma before reaching its own density level near the top of the the chamber, where it spread out laterally for a distance of at least 12 km. Destabilisation along this interface resulted in overturning and mixing with the PGM-bearing ultramafic magma. The chalcophile platinum-group minerals, because of their high partition coefficients into the sulphide phase, were scavenged by immiscible sulphide droplets, and precipitated slowly in a porphyritic-plagioclase websterite in a zone up to 20 m below the ultramafic–gabbroic zone contact. The platinum-group minerals comprise arsenides, sulpharsenides, tellurides, native metals, and mercury-bearing phases that form small (generally < 10 μm) subhedral to anhedral grains spatially associated with chalcopyrite-pentlandite-pyrrhotite blebs (22% of occurrences), or enclosed within silicates or within actinolite-tremolite-carbonate alteration assemblages of the sulphides (78%). This alteration is attributed to the localised interaction of the sulphides with fluids that probably were derived from the mixing event, or filter pressing of the cumulus pile directly below the mineralised horizon (Hoatson & Keays *in* Von Gruenewaldt & others, 1987a).

Fe-Ni-Cu sulphide deposits associated with komatiitic volcanism

Naldrett & Cabri (1976) have subdivided mafic-ultramafic volcanic bodies into two distinct magma suites: (1) a highly magnesian komatiitic suite, characterised by the skeletal and spinifex-textured crystal growth of olivine and clinopyroxene in the upper parts of the flows, a low FeO/(FeO + MgO) ratio for a given Al_2O_3 content, and relatively low TiO_2 contents; and (2) a less magnesian, tholeiitic suite, lacking spinifex textures, and having a higher FeO/(FeO + MgO) ratio and TiO_2 content. A feature of the komatiitic magmas is their high extrusive temperatures relative to the tholeiitic magmas. Komatiitic flows with 23% MgO have liquidus temperatures around 1425°C, while magmas with up to 32% MgO would have been extruded at about 1650°C. Iron-Ni-Cu sulphide mineralisation is commonly associated with komatiitic and to a lesser degree tholeiitic bodies throughout the Archaean terranes of Western Australia, but only in the Kambalda district, south of Kalgoorlie, are the PGMs exploited as a by-product of the Ni-Cu mineralisation. Total recoverable PGM content from Ni concentrates, as reported by the Mines Department of Western Australia for 1969–87 was approximately 6050 kg, comprising 1225 kg Pt, 4820 kg Pd, and 5 kg Ru (Table 7). Some of these PGMs are recovered from the treatment of copper-sulphide residues from the Kwinana nickel refinery, Western Australia, and some overseas from the refining of exported Ni matte.

Marston & others (1981) and Marston (1984) have subdivided the major Ni-sulphide deposits of Western Australia into (1) Archaean extrusive-peridotite-associated, (2) Archaean intrusive-dunite-associated, (3) and the gabbroid-associated deposits of Archaean or Proterozoic age. The first two sub-groups have strong komatiitic affinities and appear to have greater PGM potential, especially as a by-product of Ni-Cu mining, than the more basalt-derived gabbroid-associated deposits. Using textural and geochemical evidence, Donaldson & others (1986) argue that the intrusive dunite bodies are slowly cooled end-members of a continuum from spinifex-textured komatiites (former liquids) through cumulate komatiites (40 to 90% olivine) to adcumulate komatiitic dunite (> 90% olivine). They consider that the dunites are probably lateral 'stratigraphic' equivalents of the volcanic komatiites, and therefore the past emphasis on their contrasting intrusive setting is unwarranted. Similarly, Barnes & others (1988a) postulate the nickel sulphide mineralisation at the Agnew deposit is hosted by komatiite flows older than the associated dunite body, which is also believed to be extrusive.

Nickel-sulphide deposits associated with komatiitic peridotites (type 1) in the Norseman–Wiluna belt of the Yilgarn Block have significant PGM levels. Marston & others (1981) note that deposits such as Kambalda–St Ives, Nepean, and Mount Windarra are characterised by altered flows, 25–200 m thick and several hundred metres long, of olivine peridotite-dunite (38–45% MgO) at or near the base of volcanic sequences up to 800 m thick. The ultramafic sequence often occurs close to major strike faults and on limbs of major plunging anticlines. Sulphide-bearing metasediments are intercalated with the ultramafic flows, and basalts commonly underlie and overlie the ultramafic units. The Ni-Cu-PGM mineralisation occurs in lenticular shoots of massive, matrix and disseminated ores at the base of the flows, commonly confined by embayments in the basal ultramafic-basalt contact. About 90% of the mineralisation occurs in the contact or massive ore. The major minerals are pyrrhotite, pentlandite, pyrite, chalcopyrite, magnetite, and chromite in the massive and disseminated ores, with rare millerite and heazlewoodite generally confined to disseminated ores.

The intrusive–dunite deposits (type 2) such as Agnew, Mount Keith, and Forrestania consist of subconcordant lenses, 500–10 000 m long, and 50–1100 m thick, of komatiitic dunite-olivinite (45–51% MgO). The intrusions are restricted to curvilinear ultramafic zones in proximity to major strike faults and at a high stratigraphic position within Archaean greenstone belts. Important deposits are largely confined to the northern third of the Norseman–Wiluna belt, and the southern part of the Southern Cross–Forrestania region of the eastern Yilgarn. Associated rocks include clastic sedimentary rocks and felsic volcanics in the footwall, and mafic volcanic and ultramafic units in the hanging-wall. Lenticular shoots of massive, matrix, and breccia ores occur near the margins, and disseminated ores above and in the cores of the lenses. Disseminated ores comprise the bulk of the Ni resources, some deposits, e.g. Mount Keith and Agnew, being some of the largest Ni deposits of their type in the world. Pyrrhotite, pentlandite, magnetite, pyrite, chalcopyrite, and chromite are the major phases in ores grading > 1% Ni, with millerite, heazlewoodite, godlevskite, and polydymite in ores < 1% Ni.

The gabbroid Ni-sulphide association (type 3), as typified by the Carr Boyd, Mount Sholl, and Sally Malay intrusions, generally has relatively low levels of associated PGMs (total PGMs < 1 ppm). In contrast to the extrusive-peridotite and intrusive-dunite Ni-Cu deposits, the gabbroid association shows greater variation in their tectonic settings, occurring in both stable Archaean cratons and Proterozoic mobile belts. Intrusions are composite and consist of gabbronorite, with lesser pyroxenite, peridotite, and anorthosite, which crystallised from basaltic magmas of uncertain affinity. Low-grade disseminated or blebby sulphides form basal layers or irregular bodies associated with lenses or veins of matrix, massive, or breccia sulphides. There is no lithological control of mineralisation, since gabbro, gabbronorite, pyroxenite, or peridotite may be the host rocks. Pyrrhotite dominates, with minor pentlandite, chalcopyrite, pyrite, and magnetite. Metamorphic intergrowth textures between silicates and sulphides are commom in intrusions of cratonic terranes, whereas disseminated remobilised sulphides in granoblastic-textured pyroxenites are typical of tectonised intrusions in the Proterozoic Halls Creek and Albany–Fraser Range mobile zones.

Lesher & Keays (1984) believe that the komatiitic peridotite-hosted mineralisation at Kambalda is magmatic, but that various postmagmatic processes have modified the distribution, structure, texture, mineralogy, and chemistry of the ores. These processes have resulted in a spectrum of sulphide mineralisation types, ranging from complete dislocation (faulted ores), and more localised mobilisation (stringer sulphides), through metamorphic replacement (interpillow-interbreccia sulphides), to hydrothermal dissolution and redeposition (vein-type sulphides). Ross & Keays (1979) and Keays & others (1981a) found that Pd is enriched in pentlandite relative to other sulphide phases, whereas Ir occurred in pentlandite, pyrrhotite, pyrite, and chalcopyrite, and Au was enriched in pyrite and chalcopyrite. These workers concluded that discrete PGMs were rare in the massive and matrix ores, and the chalcopyrite-rich footwall stringers were enriched in Pd and Au, owing to the remobilisation of these elements from the massive ores. Hudson & Donaldson (1984) noted that the Kambalda Ni ores contain (concentrations recalculated to 100% sulphides are shown in brackets) 2.96% Ni (14.45%), 0.22% Cu (1.10%), 8.09% S (39.95%), 326 ppb Pt (1630 ppb), 425 ppb Pd (2104 ppb), 110 ppb Os (537 ppb), 60 ppb Ir (293 ppb), 50 ppb Rh (240 ppb), 220 ppb Ru (1074 ppb), and 339 ppb Au (1721 ppb). The major platinum-group minerals are sperrylite, moncheite, sudburyite, stibiopalladinite, palladoarsenide, and some uncharacterised palladium antimonides and arsenides, and palladian melonites. Barnes & others (1988b) have documented the precious-metal levels of the nickel sulphide ore types for the Agnew deposit. For massive, matrix, and vein-filling ores, maximum concentrations (recalculated to 100 weight-% sulphides, and all units in ppb) were, 410, 210, 360, Pt; 830, 300, 1200, Pd; 260, 50, 32, Os; 210, 36, 28, Ir; 150, 20, 49 Rh; 590, 92, 110, Ru; and 110, 27, 23, Au, respectively.

Remobilised platinum-group metal mineralisation (hydrothermal)

Remobilised PGM mineralisation in Australia has been described at the Thomson River Cu-Ni mine in Victoria, and the Coronation Hill Au-PGM deposit in the Northern Terrritory (summarised previously), but there is increasing evidence to suggest that these deposits are more widespread than previously thought. Throughout Australia there are examples of remobilised PGMs, e.g. the Kambalda district and Yarawindah Brook–New Norcia (Yilgarn Block, WA); northern margin of the Munni Munni Complex (Pilbara Block, WA); Nairne (Kanmantoo Fold Belt, SA); Jabiluka (Pine Creek Geosyncline, NT); Gympie and Westwood (New England Fold Belt, Qld); Prospect Bore (Georgetown Block, Qld); Mulga Springs (Broken Hill Block, NSW); Fifield (Lachlan Fold Belt, NSW); and Errinundra (Lachlan Fold Belt, Vic.).

Remobilised (including hydrothermal) PGM mineralisation is diverse in its setting, and not bound by a specific time period, as the mineralising events in the above examples encompass the Archaean, Proterozoic, and Phanerozoic. The geological settings range from komatiitic volcanic-intrusive successions, layered mafic-ultramafic intrusions, Alaskan-type intrusions, serpentinite sills, to sedimentary and volcanic geosynclinal successions. Host rocks include peridotite and pyroxenite intrusives, ultramafic to felsic volcanics, porphyry, dioritic dykes, tuff, conglomerate, and various argillaceous and arenaceous sediments. In the Archaean, hydrothermal PGM occurrences generally have a major magmatic component, with the remobilised mineralisation still preserving various magmatic features and hosted by mafic to ultramafic rocks (Kambalda, Munni Munni in places), but in the Proterozoic and Phanerozoic there is often no obvious spatial or genetic association with these particular rock types. Thus there appears to be a broad transition from occurrences in the Archaean having a dominant magmatic-subordinate hydrothermal setting to deposits in the Proterozoic and Phanerozoic which have experienced more widescale and intensive hydrothermal mineralising systems. Within these younger terranes disseminated mineralisation is prominent in the Proterozoic, whereas quartz vein systems are more typical of the Phanerozoic. Hydrothermal PGM metal associations also appear to differ with time, with Cu and Ni common associated metals in the Archaean, and Au and/or U in the Proterozoic; Au, Ag, Cu, Ni, Pb, and As may occur with the more polymetallic Phanerozoic occurrences.

The Thomson River mineralisation is an example of hydrothermal remobilisation of Au, and to a lesser degree Pt and Pd, from an original magmatic setting. After being discovered in 1864, the Thomson River mine had several phases of mining activity, with production up to 1881 amounting to 10 000 t of Cu-rich ores (10%+ Cu). During 1911–13 the Pt potential of the ore was exploited and 2500 t of ore averaging 2.3 ppm Pt, 3.8 ppm Pd, 3.7% Cu, 0.3% Ni, 12.8 ppm Ag and 1.5 ppm Au was mined (Cozens & Rangott, 1972; Cochrane, 1982). The host rock for the Cu-Ni-Au mineralisation is a Devonian hornblendite dyke, faulted, sheared, and hydrothermally altered by carbonate-bearing solutions (Keays & Kirkland, 1972). Gold was remobilised from the magmatic Cu-Ni sulphides and redeposited in quartz-carbonate-chalcopyrite-pyrite stringers. Keays & Kirkland (1972) noted that the platinum-group minerals were less mobile than Au, with 1 to 10 μm sized sperrylite grains occurring along fissures in pyrite grains, and merenskyite situated in chalcopyrite. They believe the Au may have been transported as $(AuCl_4)^-$ in oxidising and chloride-bearing solutions, or as $(AuS)^-$ in slightly alkaline, sulphide-bearing (reducing) solutions.

SUMMARY OF THE DISTRIBUTION AND POTENTIAL OF PLATINUM-GROUP METALS IN AUSTRALIA

Although PGMs in Australia are diverse in their geological settings, there still exist parameters such as tectonic-structural constraints and metal associations with time, to assist the explorationist in forming a framework for the discovery of further deposits. Placer deposits of Os, Ir, and Ru alloys are spatially associated with tectonically emplaced Cambrian to Permian alpine-ophiolite serpentinite bodies that occur in north-south trending linear belts throughout the Tasman Fold Belt System. Platinum-group mineralisation related to Alaskan-type Palaeozoic mafic-ultramafic complexes is of restricted distribution, occurring in the Fifield–Bourke region of central New South Wales, and possibly in the Wateranga area of southern Queensland.

Platiniferous layered mafic-ultramafic complexes are most prominent in the Archaean Yilgarn and Pilbara cratonic terranes, and tectonically dismembered variants of the layered intrusions occur in Early Proterozoic mobile zones, such as the Halls Creek and Albany–Fraser mobile zones of Western Australia. Unlike the PGM-chromite association typical of the eastern Australian PGM deposits and Proterozoic mobile zones, PGMs in the large layered intrusions of tectonically stable terranes generally occur with Fe-Cu-Ni sulphides in thin horizons at particular stratigraphic levels in the fractionating mafic-ultramafic sequence. Komatiitic volcanic-hosted PGM mineralisation is largely restricted to the eastern parts of the Archaean Yilgarn Block, with several deposits in the Norseman–Wiluna belt having significant PGM levels associated with Fe-Ni-Cu sulphide mineralisation.

Australian PGM occurrences related to remobilised-hydrothermal systems cover a wide spectrum, ranging from deposits which are largely due to primary magmatic processes and having a minor hydrothermal overprinting, through those involving late-stage hydrothermal remobilisation of PGMs derived from a nearby mafic-ultramafic rock source, to deposits which are strictly hydrothermal in origin, i.e. the PGMs show no association with, or obvious derivation from mafic-ultramafic rocks, and fluid movement has been the dominant mechanism for PGM transport. In some of these deposits it is suggested that graphitic horizons may provide an important source of PGMs for subsequent remobilisation by magmatic-hydrothermal processes. The recent recognition of the importance of late and post-magmatic processes in the transport and concentration of PGMs has seriously questioned the conventional view that PGMs are exclusively associated with the early stages of mafic-ultramafic magma evolution. The time and frequency distributions of Australia's PGM occurrences are summarised in Figures 10 and 11.

The majority of PGM occurrences are associated with: (1) laterally continuous sulphide horizons at particular stratigraphic levels in large Archaean layered intrusions, or in komatiitic volcanic-intrusive sequences, (2) sulphide-bearing chromitite cycles in dismembered intrusions of Early Proterozoic mobile zones, and (3) chromite in Palaeozoic alpine peridotite or ophiolite and related placers in eastern Australia. This distribution reflects the secular variation of the PGMs associated with sulphur and chromium from the Archaean to the Proterozoic to the Phanerozoic. Platinum-group mineralisation associated with most Palaeozoic Alaskan-type intrusions does not appear to show any clear affinity with sulphides or chromite. However, PGMs in hydrothermal settings are commonly associated with Cu and Ni in the Archaean, Au and U in the Proterozoic, and with Au, Ag, Cu, Ni, Pb, and As in the Phanerozoic.

It is believed that two geological settings offer the greatest potential for a large-tonnage PGM deposit in Australia: (1) magmatic, or combined magmatic-hydrothermal mineralising systems in the variably deformed, large 2000 to 3000 Ma old layered mafic-ultramafic intrusions typical of the Yilgarn and Pilbara Blocks, and (2) hydrothermal-remobilised deposits within the Proterozoic of northern Australia and the Phanerozoic of northeastern Australia. The small intrusions representative of the Proterozoic mobile belts, such as in the Halls Creek Mobile Zone, have had a relatively long history of Cu-Ni-PGM exploration, and combined with their disrupted and dismembered character offer limited potential for a major hardrock resource. In eastern Australia, the hardrock deposits related to alpine and ophiolitic intrusions can be downgraded since they have been extensively explored by prospectors, are confined to well-defined belts, crop out well, are associated with earlier discovered placer deposits (thus making recognition easy), and have limited long-term economic significance. They offer more promise for small-scale placer deposits, where production can be quickly brought on stream during periods of favourable metal prices, and mining processes are cost-effective. The economic status of the Alaskan-type intrusions of the Fifield region is still largely unknown, but it is clear that a large PGM province has been defined that offers potential for hardrock (p-units, or PGM-base-metal-sulphide association of magmatic-hydrothermal origin), alluvial, and secondary-enrichment styles of mineralisation.

RECOMMENDED EXPLORATION STRATEGY FOR PLATINUM-GROUP METALS IN AUSTRALIA

Geological and geochemical processes and their relevance for PGM exploration

Large layered intrusions such as the Bushveld and Stillwater complexes dominate PGM reserves in the Western world. Although these intrusions differ considerably in detail, they have common features (age, tectonic setting, size, etc.) that together provide a useful framework for identifying prospective intrusions.

The major PGM-hosting intrusions are characterised by:

— thick cyclic sequences resulting from multiple magma pulses that differ in PGM-S chemistry;

— a strongly differentiated stratigraphic succession at least 5 km thick, with rocks ranging from dunite, harzburgite, orthopyroxenite, websterite, norite, gabbro, and anorthosite, to granophyre, diorite, and dolerite; complexes less than 5 km thick may also be prospective, provided the parent magma(s) are not depleted in PGMs (for example, by early S-saturation events), underwent late S-saturation, and there was an efficient and widespread mineralising mechanism;

— individual rock types and cumulus-layering textures displaying great lateral continuity;

— intrusions generally older than 2000 Ma and younger than 3000 Ma, emplaced into tectonically stable Early Proterozoic or Archaean terranes as lopoliths;

— associated diverse economic minerals, including nickel, copper, chromite, vanadiferous magnetite, vanadium, lead, zinc, tin, fluorite, and magnesite;

— PGMs generally associated with sulphides near the base of cyclic units, within 500 m of the interface between major magma pulses; and

— mineralised stratigraphic horizons resulting from magma mixing as indicated at Munni Munni by (1) the occurrence of hybrid rocks, and injection and assimilation features; (2) unconformities or structural disturbances in the footwall sequences that may have resulted from magmatic erosion cycles, or by the migration of intercumulus melt prior to solidification of the cumulus pile; (3) lateral variation of rock types near the interface of the magmas, expressed in interfingering, thinning, or thickening along strike; (4) marked changes in cumulus paragenesis (i.e. disappearance of olivine at the expense of plagioclase, or change over from cumulus clinopyroxene to cumulus orthpyroxene, or vice versa), volume of intercumulus minerals, hydrous phases, and sulphide content; (5) the presence of chromitites and/or graphite, reflecting changing fO_2 conditions; and (6) the development of porphyritic-pegmatoidal textures, which may reflect increased incompatible-element concentrations and the activity of volatile-rich magmatic fluids.

Numerous models have been proposed to account for PGM enrichment in layered intrusions. These have involved discussions on the relative importance of such factors as: the chemical heterogeneity of the mantle source (e.g. source enriched in PGMs?), magma type and magma generation processes (boninite-type, second-stage melting of refractory mantle, timing of S-saturation), magma chamber processes (crystal fractionation, crystallisation sequences, crustal contamination, magma mixing), and post-emplacement mechanisms (adcumulus growth, late magmatic fluids, hydrothermal remobilisation) in regard to the evolution of PGM-bearing intrusions (S. Sun, personal communication, BMR, May 1988). Important mineralising models have been described by Vermaak (1976), who proposed that sulphide immiscibility in the Merensky Reef was related to increases in S fugacity following the depletion of iron in the magma due to the settling of chromite, and Barnes & others (1985) emphasised the incompatible nature of Pt, Pd, and Rh during crystal fractionation, and the importance of late S-saturation in the development of a PGM-enriched horizon. Von Gruenewaldt (1979) demonstrated that the PGM tenor of the Merensky Reef sulphides was upgraded by ascending PGM-enriched, late magmatic intercumulus fluids that were expelled during the compaction of the underlying cumulus pile, and similarly, Boudreau & McCallum (1986) in their study of the Picket Pin deposit, Stillwater Complex, have used the presence of transgressive sulphide zones, and the Cu-rich nature of the sulphide assemblage, to suggest that ascending hydrothermal fluids that became trapped below impermeable anorthositic zones were responsible for the PGM enrichment of the ores. Gain (1985) has also used the filter-pressing model to explain the PGM-enrichment of the UG 2 chromitite layer from upward-migrating, highly-fractionated intercumulus fluids under highly reducing conditions. Sulphide precipitation and the interplay of contamination and mineralisation processes along the basal contact of the Bushveld Complex have been discussed by Liebenberg (1970), de Waal (1977), Von Gruenewaldt (1979), Grunshaw (1983), Buchanan & Rouse (1984), and Cawthorn & others (1985). Various contamination mechanisms have been proposed for the driving of mafic magmas towards S-saturation. These include the direct addition of S by assimilation of sulphides, H_2S, or SO_2-bearing material from the basement rocks, and the increase in fO_2 by addition of oxygen or water.

It is difficult to predict the stratigraphic level or type of PGM mineralisation that may occur in a layered intrusion. For example, in the Bushveld Complex, platinum-group enrichment occurs (1) in narrow sulphide-bearing pegmatoidal horizons 400–500 m above the appearance of cumulus plagioclase, and in the vicinity of cumulus augite joining cumulus orthopyroxene (Merensky Reef), (2) in chromitite horizons (UG 2 and UG 3 chromitites), (3) in cross-cutting dunite pipes (Onverwacht, Driekop pipes), and (4) in contaminated floor rocks (Platreef). In the Stillwater Complex, PGM enrichment occurs (1) as discontinuous layers above, along, and below the contact between an olivine cumulate zone and gabbronorites, and 400 m above the first cumulus plagioclase (J-M Reef), i.e. in a similar stratigraphic position to the Merensky Reef, (2) with chromitites in the ultramafic zone, and (3) in felsic rocks 3 km above the J-M Reef (Picket Pin Zone). The PGM mineralisation in the Munni Munni Complex and the Great Dyke of Zimbabwe occurs where cumulus bronzite joins cumulus augite, directly below the advent of cumulus plagioclase in the gabbros. Thus, 'stratabound' PGM mineralisation (i.e. Merensky Reef, J-M Reef, Munni Munni) is commonly located at, or up to 500 m above, the stratigraphic level of the introduction of cumulus plagioclase. These deposits are not strictly stratabound in all intrusions, since the mineralised horizons are commonly discordant to the underlying rocks, e.g. the J-M Reef, and the mineralised porphyritic websterites at Munni Munni.

The similar stratigraphic level, and structural discordance of these mineralised horizons is believed to be in many cases a result of the mixing of chemically distinctive magma types. Such mixing appears to have been an important mechanism in many PGM-bearing layered intrusions, such as the Bushveld, Stillwater and Munni Munni. Magma mixing offers scope for a large volume of PGM-bearing silicate melt to interact with an immiscible sulphide phase, an important requirement for the formation of economic 'stratabound' PGM horizons. The extremely high partition coefficients of the PGMs for S (i.e. D_{PGM} = ppm PGM in sulphide/ppm PGM in silicate), which are in the range of 1000 to 100 000, compared to Fe and Cu, which have partitioning values of approximately 15 and 25 respectively, indicate that the PGMs will be strongly associated with the development of any sulphide accumulations. In a fractionating S-poor magmatic environment, Pt and Pd will behave incompatibly (i.e. do not partition into any crystallising silicate phases), and subsequently these elements will increase in concentration in the residual melt. However, Ir and Os will largely partition with early crystallising olivine; hence, Ir and Os concentrations will generally decline with increasing fractionation (Hoatson & Keays *in* Von Gruenewaldt & others, 1987a). Thus, if the PGMs have been able to build up in concentration in the melt through fractional crystallisation, filter pressing, or by hydrothermal processes operating in a S-undersaturated cumulate sequence, and a newer S-saturated magma pulse intrudes and mixes with the PGM-enriched magma, the potential exists for a sulphide-mineralised horizon to form near the interface of both magmas. However, if the PGM-hosting magma (either the resident magma or the new magma pulse) is S-saturated early in its evolution, then, because of the high partition coefficients of the PGMs for S, the PGMs will be disseminated throughout the magmatic sequence and thus no potentially economic PGM-enriched horizon is likely to develop. Therefore it is critical to ascertain where S-saturation occurs in the stratigraphic succession of a layered intrusion.

In general, most mafic-ultramafic rocks are S-saturated, with S contents exceeding 1000 ppm. The most important variables that control the solubility of S in mafic magmas are temperature, pressure, FeO content, and fugacities of O_2 and S_2 (Haughton & others, 1974). Sulphur solubility in a silicate melt increases with increasing temperature, pressure, FeO content, and fS_2, and decreasing fO_2. Confirmation of whether S-saturation has occurred also requires a knowledge of the rock porosity, i.e. the proportion of intercumulus melt present in the cumulate rock. For example an adcumulate rock with 5 volume-% intercumulus melt, 95% cumulus phases, and 100 ppm S, would have formed from a S-saturated magma with $100 \div 0.05 = 2000$ ppm S, given that all the S in the rock was contributed by the intercumulus melt, whereas a chilled rock having no cumulus component and 500 ppm S would be unlikely to be S-saturated.

Historically, analyses of chilled contact rocks have been used to help determine the parental magma characteristics and PGM potential of layered intrusions. However, as seen with the numerous studies on the Bushveld's marginal rocks and sills, it has taken many years to ascertain the chemical characteristics of the parental magma(s). Various magma types have been proposed over the years for the Bushveld, including ultramafic magmas (MgO ~ 30%), magnesian basalt (MgO ~ 12%), tholeiitic basalt (MgO ~ 7%), and combinations of magmas having boninitic and anorthositic affinities. Even today there is considerable controversy about the nature of the parental magma(s) and their implications for PGM mineralisation. Thus, analysing a chilled margin will not provide a quick and definitive assessment of the PGM potential of a layered intrusion. Also, chilled margins may not always be reliable, since:

- true chilled melt rocks are rare; such rocks may vary along strike and have some cumulus character, thus not accurately reflecting the composition of the parental melt;
- contact rocks are commonly contaminated from partial melting of country rocks during intrusion or by post-intrusive metamorphism, magmatism, or shearing; and
- sulphur may be derived from the country rocks during intrusion, with sulphide precipitation being induced by rapid cooling or compositional changes (e.g. FeO and SiO_2) along the contacts.

Hoatson & Keays *in* Von Gruenewaldt & others (1987a) have shown that, for the Munni Munni Complex, variations in the ratios of the precious metals and in the trends of the incompatible lithophile and chalcophile elements are invaluable in understanding the S evolution, and therefore the PGM potential of layered intrusions. Marked disruptions in trends of Cs, Zr, Th, Y, Sr, Rb, S, Se, Cu, (Pt+Pd)/S, (Pt+Pd)/Cs, (Pt+Pd)/Zr, (Pt+Pd)/Ir, and Cu/Zr may indicate a potentially mineralised stratigraphic level represented by a new magma pulse that has different PGM-S characteristics from those of an older resident magma. Determination of the (Pt+Pd)/S and/or Cu/Zr ratios of a few samples through a layered intrusion would help to establish if and where S-saturation has occurred. In the Munni Munni Complex, the S-undersaturated ultramafic rocks have (Pt+Pd)/S x 10^6 ranging from 42 to 265, whereas the S-saturated gabbroic rocks have a range of 3 to 16. PGM mineralisation, related to the influx of a new magmatic pulse, occurs at the crossover point of these differing ratio trends, i.e. near the contact of the ultramafic and gabbroic zones. Similarly, the other ratios of the PGMs and the incompatible elements described above help to delineate the potentially mineralised stratigraphic level. Iridium and Ni partition largely with cumulus olivine, and Cr into clinopyroxene and olivine, which reduces the effectiveness of these elements as pathfinders at Munni Munni. However, if cumulus olivine and clinopyroxene are absent, or have a restricted distribution in a layered sequence, Ir, Ni, and/or Cr may be useful in delineating PGM-enriched horizons related to sulphides or chromite. Therefore a knowledge of the cumulus paragenesis in a layered intrusion is important.

Hulbert & others (1988) have noted that Se/S ratios of PGM-rich magmatic sulphide deposits such as the Merensky and J-M Reefs are generally greater than inferred mantle values (Se/S range of approximately 220–350 x 10^6). The significance of the Se enrichment for these deposits is not well understood, but this parameter appears to be a valuable geochemical discriminant. In contrast, magmatic sulphides with relatively low PGM levels have Se/S ratios less than the mantle range, and are usually indicative of a crustal source of S. Another observation by Hulbert & others (1988) is that chrome spinels from a number of magmatic PGM deposits have high TiO_2 concentrations, up to 12% or more. Examples include Noril'sk–USSR, Crystal Lake–Ontario, Fox River–Manitoba, and Wellgreen–Yukon. For focussing in on the mineralised horizon of a layered intrusion, the presence of graphite, and Cl-bearing phases such as apatite and mica, may be useful. These minerals are widely documented throughout the main mineralised horizons in the Bushveld and Stillwater complexes.

In contrast to the layered intrusions, there have been few detailed PGM studies relating to **Australian alpine serpentinite and ophiolite intrusions,** and thus the geological and geochemical controls on the distribution of the mineralisation in these intrusions are not well understood. This is further compounded by intense alteration and deformation. However, certain characteristics of these intrusions influence the exploration methods used in these orogenic terranes. These include: (1) the alpine and ophiolite intrusions are tectonically emplaced Palaeozoic fault-bounded bodies, commonly in well-defined linear belts, (2) the Os-Ir-Ru alloy mineralisation is generally associated with Cr rather than S, (3) the primary disseminated or podiform type PGM-Cr mineralisation is of small volume, and erratic in distribution, (4) syn- and post-emplacement fluids in some intrusions appear to have been important in the mobilisation of the PGMs, and (5) placer deposits are commonly associated with the hardrock source and are generally a more attractive target than the primary source.

The Fe-Ni-Cu sulphide deposits associated with **komatiitic volcanism** in the Yilgarn Block have been intensively explored since 1966, although initially for Ni. These deposits, as summarised by Marston & others (1981) and Marston (1984), are characterised by altered komatiitic flows 25–200 m thick and several hundred metres long of olivine peridotite-dunite at or near the base of ultramafic volcanic formations up to 800 m thick. Basalts and S-bearing metasediments generally comprise the remainder of the stratigraphy. The Fe-Ni-Cu ± PGM mineralisation occurs as lenticular shoots of massive, matrix, and disseminated ores near the base of the flows, in embayments along the basal ultramafic-basalt contact. Most ultramafic sequences are found on the limbs of plunging anticlines cored by granitoids, and in close association with major strike-slip faults.

Various processes, such as amphibolite-facies metamorphism, multiphase deformation, and hydrothermal action, have modified the original magmatic distribution and character of the platinum-group minerals in the komatiitic sulphide deposits. Hudson (1986) has found that sperrylite, the most abundant platinum-group mineral in the Kambalda deposits, occurs largely in chalcopyrite-rich massive ores, which may be a primary magmatic feature. However, many of the Pd-bearing minerals occur in veins in the massive and matrix ores, in stringers of sulphide in the footwall rocks, or in association with post-ore hydrothermal veins and porphyries. These settings indicate that the Pd phases largely formed post-magmatically, notably from the metamorphic segregation of sulphides and the interaction of Pd-bearing pentlandite with younger hydrothermal veins. Thus, for similar environments to Kambalda, the platinum-group minerals, and in particular the Pd minerals, may have been considerably mobilised and modified.

The recent recognition of the importance of **late- and post-magmatic processes** in the transport and concentration of the PGMs (Stumpfl, 1986, 1987; Stumpfl & Ballhaus, 1986), has superseded the traditional view that PGMs are exclusively associated with the early stages of mafic-ultramafic magmatic evolution. The evidence from the magmatic, metamorphic, and weathering environments suggests that PGMs are chemically mobile at low temperatures in aqueous solutions, and consequently a variety of rock types and environments may be mineralised, ranging from acid volcanics and mafic dykes to various sediments and laterites. It is apparent that Pt and Pd are the most commom PGMs in hydrothermal deposits, and that Au is a common component. This reflects the greater solubilities and tendencies of these metals to form aqueous complexes relative to the more refractory PGMs — Ir, Os, and Ru.

Stumpfl (1986, 1987) has noted that PGMs can be transported as chlorine complexes in sea water (anomalous levels of up to 1 ppm PGMs have been documented in Mn nodules from the Pacific Ocean) at temperatures of a few degrees celsius, from metalliferous sediments from the Red Sea and the East Pacific Rise, or in brines (Kupferschiefer black shales) at temperatures of about 150–300°C. Stumpfl (1986) argues that the most important factor favouring PGM concentration is not temperature but the availability of chlorine-rich fluids that permit the formation of chloride complexes. Mountain & Wood (1988), using thermodynamic and physical-chemical considerations, have shown that the PGMs may be mobile in hydrous fluids as a variety of complexes depending on the pH, fO_2, temperature and ligand concentrations. These include various hydroxide, amine, thiosulphate, polysulphide, and bisulphide complexes. Hulbert & others (1988) have recognised two major settings of hydrothermal Pt mineralisation. These are (1) at redox fronts, with Pt mobilised as chloride complexes by oxidised fluids or as thio-complexes by reduced fluids, and (2) in structurally controlled sites spatially associated with mafic-ultramafic rocks, where Pt precipitation is controlled by desulphidisation of pore fluids produced by the hydrothermal alteration of olivine-bearing rocks.

The combination of a potential source such as a fractionated mafic-ultramafic rock or a more unusual source (such as a carbonaceous shale, boninitic basalt, or fossil placer), with a hydrothermal-meteoric fluid system that remobilises and concentrates the PGMs from the source rock, transports them in an aqueous phase, and initiates a favourable structural plumbing system in the host rock, provides a basic framework for remobilised PGM mineralisation that could occur in a variety of geological environments. Structural elements, such as faults and shear zones appear to be particularly important where the PGMs are remobilised from magmatic sulphides and redeposited in fractured mafic rocks (e.g. New Rambler and Thomson River). For hydrothermal PGM deposits which show no obvious spatial association with mafic-ultramafic rocks (e.g. Coronation Hill and Jabiluka), redox fronts at the interface of oxidised and reduced rock sequences, or near fault zones that traverse unconformities between similar rock types, appear to be important for the localisation of mineralisation. Hematite alteration in the mineralised environment at both Nicholson Bay and Coronation Hill may also reflect redox processes. Hulbert & others (1988) have also noted that some hydrothermal PGM deposits are characterised by anomalous levels of Se and the presence of Se-bearing minerals. Detailed field and laboratory studies (similar to the research that has been done on Au) involving investigations into the thermodynamic properties of the PGMs, the role of various complexing agents, and the relationship of fluid movement and structural elements, etc., are required in order to better understand the chemical mobility of the PGMs in the hydrothermal and weathering environments.

Exploration techniques

Exploration methods for PGMs in Australia depend largely on the style of mineralisation being investigated and the terrain.

The Palaeozoic alpine serpentinite and ophiolite intrusions of eastern Australia generally form linear hills with deeply incised drainage systems. Consequently, stream-sediment sampling using panned concentrates is a useful reconnaissance technique, especially where the intrusions are extensively deformed and it is hard to recognise favourable stratigraphic horizons. The chemical and physical stability of the Os-Ir-Ru alloys during weathering and transport, their high specific gravities and common association with chromite and native Au, make stream sediment sampling the obvious approach in these environments. In hilly terrain, heavy-mineral stream geochemistry would also be useful in defining PGM mineralisation associated with Alaskan-type concentric intrusions. Unlike the alpine and ophiolite derived PGM placers, the placer PGMs related to intrusions such as the Tulameen Complex, British Columbia, are magnetic (Raicevic & Cabri, 1976), and thus both the magnetic and non-magnetic fractions of the heavy-mineral concentrate should be investigated. For Alaskan-type intrusions in shallow (< 2 m) soil-covered areas such as at Fifield, NSW, trenching and costeaning have been successful in delineating PGM mineralisation in the weathered bedrock and soil profiles.

The sporadic distribution of PGM mineralisation and small tonnage of the hardrock deposits make it difficult to delineate the mineralisation in alpine and ophiolite intrusions. Geochemical methods are of limited use, since these deposits have no geochemical halo. As evident from overseas alpine-ophiolite complexes, chromite-PGM mineralisation is associated with olivine- and orthopyroxene-rich rocks, but rarely with clinopyroxene-dominant rocks. Mineralisation in these intrusions, which can be broadly subdivided into a mantle sequence and an overlying crustal cumulate sequence, may occur in the lowest cumulate dunite, in the crustal-cumulate/mantle-harzburgite transition zone, or within about 1 km below this transition into the mantle sequence. Orebodies are clustered along small sections of the favourable zones, and large areas are barren. Surface prospecting, incorporating stream-sediment sampling, followed by development trenching and grid drilling are the most effective methods of locating shallow orebodies and their extensions.

In the low-relief terrain of western and central Australia, Archaean and Proterozoic layered mafic-ultramafic intrusives are more prospective than the Phanerozoic layered intrusions of eastern Australia. Exploration methods are largely governed by extent of exposure and depth of weathering. The mineralised layered intrusions are generally characterised by thin (1–3 m) PGM-enriched sulphide horizons at particular stratigraphic levels, which contrasts with the disseminated PGM-chromite mineralisation found in the tectonically emplaced intrusions of eastern Australia. In oxidising and alkaline conditions typical of semi-arid to arid environments, sulphides readily break down in the weathering zone, remobilising any associated PGMs. The chemical vulnerability of the PGM-S assemblage, the poorly developed drainage systems of the Precambrian regions, and the narrow widths of primary mineralisation all reduce the effectiveness of stream sediment sampling in these areas as a regional exploration tool.

The most important exploration technique for assessing layered intrusions is careful and detailed geological mapping, using good quality colour aerial photography at scales of 1: 10 000 to 1: 15 000. An understanding of the fractionation processes, of the distribution trends of the cumulus-intercumulus minerals, and chromite, and of evidence for magma mixing, hydrothermal activity, or determining the stratigraphic level of S-saturation etc., can only be achieved by detailed mapping and sampling through the total stratigraphic succession. Sampling at 20 to 50 m spacing is recommended in order to obtain the regional petrological and geochemical trends through a large intrusion, but since the mineralised horizons are generally less than 3 m wide, the sample spacing has to be significantly closed up in the mineralised environment. Detailed core drilling on a grid system (often less than 20 m spacing) is required to delineate the geometry and resources of the mineralised horizon(s).

A flexible exploration approach to the potential styles of mineralisation that may occur in an intrusion is also important. The Munni Munni Complex is an obvious example where companies in the 1970s and early 1980s investigated the basal contact of the ultramafic zone for Ni-Cu-PGM sulphide segregations, but did not consider the possibilities of PGM mineralisation at higher stratigraphic levels. The mineralised horizon at Munni Munni crops out over a strike length of 12 km, contains fresh sulphides or evidence of sulphides in places, and occurs at a similar stratigraphic level to the major overseas stratabound PGM horizons; thus it is surprising that the PGM potential of the intrusion was first recognised only in the mid 1980s. Another example is from the Fifield district, where the exploration success of the companies involved is largely attributable to the realisation that PGMs occur in a variety of geological environments, rather than being 'blinker-visioned' to a particular model, such as a Bushveld setting, which was partly the problem with previous investigations. Accordingly, companies at Fifield employed an exploration strategy that was relevant to various styles of mineralisation that may exist (e.g. hydrothermal remobilisation of PGMs related to an Alaskan-type setting, secondary enrichment in the weathered zone, and alluvials, etc.), and implemented exploration methods applicable to the physiography of the area, such as regional-scale trenching and costeaning.

Soil sampling has application in areas where shallow in-situ soil profiles are developed. The prospective horizons in most 'stratabound' deposits of layered intrusions are narrow, and so may be missed by rock chip sampling in poorly exposed areas. Recent evidence from laterite and hydrothermal deposits indicates that the PGMs are mobile under a variety of physico-chemical conditions, so that soil surveys may define the mineralised horizon because of the greater geochemical dispersion in the soil profile relative to the underlying rocks. Companies have successfully utilised soil geochemistry to define the mineralised region of various intrusions, such as the Munni Munni, Fifield, and Lamboo intrusions. At Munni Munni, a widely spaced (400 m) soil geochemical survey delineated PGM-Cu-Ni mineralisation near the ultramafic-gabbroic zone contact. Subtle anomalous geochemical signatures occurred on eight of the eleven soil profiles at the same stratigraphic position. Maximum soil geochemical results were 42 ppb Pt and 230 ppb Pd (Williams & others, in press).

However, in much arid terrain, a high aeolian component in the soil profile would hinder the effectiveness of soil geochemistry. Frick's (1985) geochemical study over the Platreef in the Bushveld Complex found that, in areas where transported soils are absent, Ni, Cu, and Co, which are adsorbed on iron oxides and can be transported in that form, may be successfully used to locate a sulphide body. In areas of thick transported soils, the volatile elements Hg and to a lesser degree As were useful, but Ni, Co, Cu, and Fe gave erratic and poor results. Mercury was successful in locating faults that intersected the orebody at depth. Gain & Mostert (1982) reported anomalous Ni and Cu levels in the A_2 black turf soil horizon over mineralised Platreef rocks in the Drenthe area. Fuchs & Rose (1974) documented Pd and Pt levels in soils above mineralised rocks of the Stillwater Complex. They concluded that Pd was mobile in acid soils, probably as a chloride complex, and consequently was depleted from the surface and enriched in deeper horizons, whereas Pt was only mobile in extremely acid or high-chloride waters. Conn (1979) noted that soil sampling was useful in delineating the J-M Reef.

Geobotanical studies have had limited application in the study of PGM deposits. Dunn (1986) found, in northern Saskatchewan, that twigs and trunks of black spruce, and jack pine, and stems of labrador tea are the most effective media for concentrating Pt and Pd around the Rottenstone Ni-Cu-PGM deposit. Ashed twigs of black spruce growing downstream from the tailings debris contained up to 880 ppb Pt and 1350 ppb Pd, compared to background levels of less than 10 ppb Pt and 2 ppb Pd. However, birch and willow twigs and conifer needles did not significantly concentrate the metals. Geobotanical techniques have been employed in reconnaissance surveys in outlining ultramafic rocks in the Eastern Goldfields area of the Yilgarn Block. Species which have been used include *Hybanthus floribunda, Eucalyptus torquata,* and *Melaleuca sheathiana* (Cole, 1973).

Remote sensing has considerable application in the evaluation of prospective PGM-bearing intrusions. Results from the Thermal Infrared Multispectral Scanner (TIMS) and Airborne Imaging Spectrometer (AIS) used in the NASA-BMR Thematic Mapper Simulator experiment (Simpson, 1986) on the Munni Munni Complex successfully differentiated rock types, structures, soil, and vegetation types (which were related to underlying rock types), and areas of alteration, throughout the ultramafic and gabbroic zones. These techniques can discriminate rock types based on the silicate content of the rock and the different reflectivities of the minerals that comprise the rock, and were particularly useful in defining the mineralised contact between the ultramafic and gabbroic zones. The information obtained from the Munni Munni area is computer-stored and can be extrapolated to other intrusions in the west Pilbara region, thus enabling interpretation to be carried out in the office.

Geophysical techniques have greatest application in outlining the macroscopic features of mafic-ultramafic bodies. Aeromagnetics and gravity are useful in defining the regional extent, geometry and major structures of intrusions, particularly in poorly-exposed areas, such as at Munni Munni, WA, and Fifield, NSW. It is possible to define by magnetics the upper stratigraphic levels of a fractionating body that contains titaniferous magnetite in the gabbroic-anorthositic zone. Magnetics may therefore provide younging directions for intrusions and define major faults in poorly exposed terrain. Magnetics and gravity over the Bushveld Complex were useful in delineating at least four or five intrusions that coalesced to form the composite body. However, magnetic surveys over many intrusions would not discriminate narrow magnetic pyrrhotite-bearing horizons, especially if serpentinised peridotites are close to the sulphide horizon (magnetite is released during serpentinisation of olivine). The high density of the host rocks would also reduce the effectiveness of gravity techniques in defining a prospective horizon. In areas of deep cover and weathering, IP and other electrical techniques have limited application, because of the disseminated nature and low sulphide content (generally $<$ than 2 volume-% sulphides) of the mineralised horizon. Electrically conductive overburdens and fluctuating water table levels would also reduce the effectiveness of EM techniques. Radiometrics have greatest application for hydrothermal PGM mineralisation that is associated with U (e.g. Nicholson Bay, Jabiluka). Radiometric anomalies associated with shear zones and/or unconformities in close proximity to or within mafic-ultramafic bodies should be investigated. The Stillwater Complex is a good example where in well-exposed terrain, a combination of mapping, soil and silt geochemistry, magnetics, IP, low-frequency EM surveys, trenching, and diamond drilling successfully delineated a major PGM resource. Delineation of reserves over a 1 km strike length of J-M Reef required a grid drillhole spacing of less than 15 m, and at least 575 holes. Despite the success of these techniques, it has taken 20 years of exploration and evaluation to bring the Stillwater deposit into production.

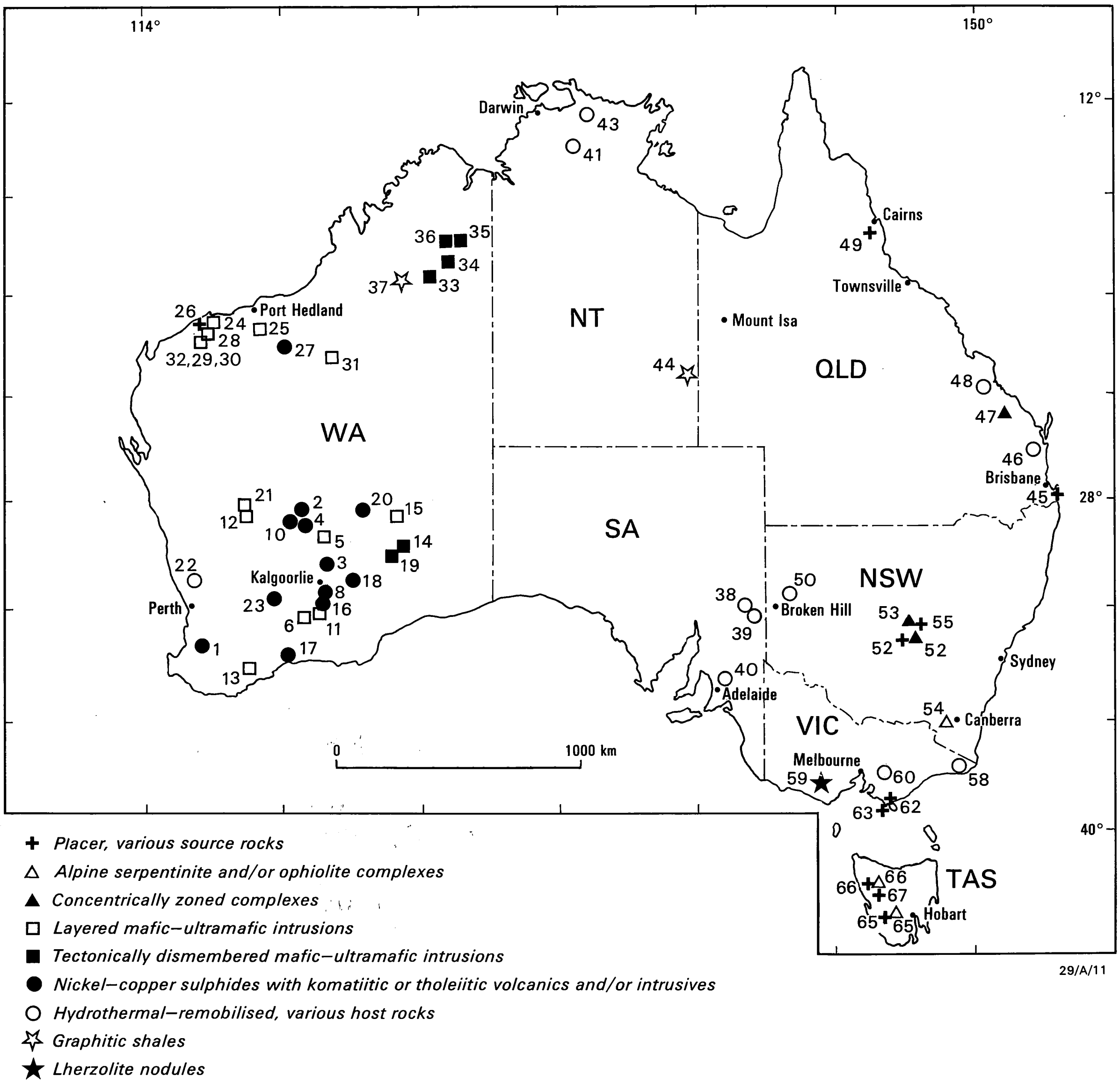

Fig. 12. Occurrences of platinum-group metals in Australia. (1) Darkan–Boddington South, (2) Camel Bore, (3) Carr Boyd, (4) Fly Bore, (5) Heron Well, (6) Jimberlana, (7) Kalgoorlie region laterites, (8) Kambalda, (9) Kambalda and Leonora region, (10) Marshall Creek, (11) Mount Thirsty, (12) Narndee, (13) Netty, (14) Plumridge Lakes, (15) Point Salvation, (16) Polar Bear, (17) Ravensthorpe, (18) Round Hill, (19) Salt Creek, (20) Windarra, (21) Wondinong, (22) Yarawindah Brook–New Norcia, (23) Yellowdine, (24) Andover, Balla, and Mount Dove, (25) Dead Bullock Well, (26) Karratha, (27) Lionel, (28) Mount Sholl, (29) Munni Munni, (30) Munni Munni South, (31) Rudall River, (32) Toorare Pool, (33) Eastmans Bore–Louisa Downs, (34) Lamboo–Loadstone Hill, (35) Panton, (36) Springvale, (37) McWhae Ridge and other Western Australian occurrences, (38) Boolcoomata, (39) Mingary, (40) Nairne, (41) Coronation Hill, (42) Coronation Hill area, (43) Jabiluka, (44) Desert Syncline, (45) Coolangatta, (46) Gympie and Widgee Mountain, (47) Wateranga, (48) Westwood, (49) Russell and Laura Rivers and other Queensland occurrences, (50) Mulga Springs, (51) Mulga Springs area, (52) Fifield, (53) Fifield–Bourke region, (54) Coolac–Goobarragandra belt, (55) Wellington, (56) New South Wales coast, (57) other New South Wales occurrences, (58) Errinundra, (59) Mount Leura, (60) Thomson River, (61) Thomson River area, (62) Turtons Creek, (63) Waratah Bay, (64) other Victorian occurrences, (65) Adamsfield, (66) Heazlewood, (67) Serpentine Ridge, and (68) other Tasmanian occurrences. 'Localities' 7, 9, 42, 51, 56, 57, 61, 64, and 68, being multiple, are not shown.

SUMMARY LISTING OF AUSTRALIAN PLATINUM-GROUP METAL OCCURRENCES

(D. M. Hoatson)

Reported occurrences of anomalous PGM concentrations, or platinum-group minerals, for each Australian State are summarised below. The occurrences range from grains in lherzolite nodules from Mount Leura in western Victoria, which obviously have little economic importance, to potential economic resources such as Coronation Hill and Munni Munni. The numbering refers to the locality map, Figure 12, opposite.

Western Australia has been subdivided into four major tectonic provinces: the Yilgarn Block (including the Albany–Fraser Mobile Zone), Pilbara Block, Halls Creek Mobile Zone, and Canning Basin. In central and northern Australia, PGM occurrences are documented for the Broken Hill Block, Kanmantoo Fold Belt, Georgina Basin, Pine Creek Geosyncline, and Murphy Inlier provinces, whereas those in the east are in various tectonic subprovinces of the Tasman Fold Belt System, according to the scheme outlined in Palfreyman (1984).

The classification of each occurrence refers to the scheme used in Table 8.

WESTERN AUSTRALIA

Yilgarn Block (including Albany–Fraser Mobile Zone)

(1) Darkan–Boddington South

Location: 30 km south of the Worsley gold joint venture at Boddington, which is 150 km south-southeast of Perth.

Title holders: Mawson Pacific Ltd and Tectonic Systems Pty Ltd.

Classification: ?8.

Geology and PGMs: The tenements are in the Archaean Saddleback Greenstone Belt, which is a north-northwest-trending zone that extends from Mount Wells southeast to Mount Saddleback. The Saddleback Belt includes rocks similar to the Eastern Goldfields region, which hosts Au, Au-Cu, Cu-Zn, and Ni-Cu deposits. The Boddington South greenstone sequence contains basalt, gabbro, andesite, and associated sedimentary units permeated by quartz vein stockworks. Field work has identified seven major areas of mineralisation, and limited rock chip sampling has defined anomalous Au, PGM, and base-metal concentrations.

Status: Continuing evaluation of grass roots prospect.

Source: Davy & El-Ansary (1986); Louthean (1987).

(2) Camel Bore

Location: 20 km southeast of Lawlers, in the East Murchison Goldfield.

Title holder: Forsayth NL, with a possible ownership component by Pancontinental Mining Ltd.

Classification: 8.

Geology and PGMs: Anomalous Cu, Pb, Zn, and PGM levels are associated with Archaean mafic-ultramafics with carbonaceous shale and exhalative chert horizons. Drilling in 1970 by Mines Administration Pty Ltd reported anomalous Pt (up to 3.4 ppm) and Pd levels (3 ppm) in four holes north of Camel Bore. Outside Kambalda, these are some of the best PGM intersections reported for the Yilgarn Block. Composite bulk samples of chrome-rich zones for the best two holes are:

Interval(m)	*Cr(%)*	*Ni(%)*	*Pt(ppm)*	*Pd(ppm)*
CBP 5				
0.0–7.6	0.44	0.42	1.7	3.0
7.6–15.2	0.40	0.27	3.0	2.0
15.2–22.9	1.72	0.40	3.4	0.9
22.9–30.5	1.03	0.52	0.5	0.3
30.5–38.1	0.49	0.22	0.3	0.5
T3				
0.0–7.6	0.80	0.91	2.2	0.02
7.6–15.2	1.32	0.70	1.3	0.02
15.2–22.9	1.04	0.57	0.5	0.02
22.9–30.5	0.39	0.59	1.8	0.03

Status: Evaluation continuing.

Source: Louthean (1987); Louthean & Seidel (1988); Pact Resources Quarterly Report for the period ending 30 June 1986.

(3) Carr Boyd

Location: Carr Boyd mining centre, 80 km north-northeast of Kalgoorlie (excludes WMC's Carr-Boyd Ni-Cu mine).

Title holder: Defiance Mining NL, with possible ownership components by Austplat Minerals NL and Western Reefs Ltd.

Classification: 8.

Geology and PGMs: In mafic-ultramafic extrusives and intrusives and associated sedimentary rocks of the Archaean Morelands Formation. Magmatic cycles consist of basal dunite, passing upwards through harzburgite, peridotite, and metagabbro, the layered sequence forming a broad concentric belt parallel to the margins of the complex. Bronzite pegmatoids and sulphide-bearing pegmatoids in the Carr Boyd mine environment may be prospective for PGM-sulphide and/or Pt-Fe alloy mineralisation. Anomalous Pt and Pd levels have been detected from a pyroxenite unit near the base of a differentiated magmatic cycle, and also in stream sediments distant from the mine.

Status: Grass roots prospect.

Source: Louthean (1987); Louthean & Seidel (1988); Hoatson (1984).

(4) Fly Bore

Location: 80 km north-northwest of Leonora.

Classification: 8.

Title holders: Miralga Mining NL (80%), The Union Gold Mining Co. NL (20%).

Geology and PGMs: In a north-south trending greenstone belt that traverses the eastern flank of the Wildara Dome, between the Wildara Fault and the Mount Keith–Kilkenny Lineament. Mafic and ultramafic lavas, peridotite-dunite intrusives, and talc-chlorite rocks comprise the greenstone sequence, which may attain 4 km in thickness. Laterite covers large parts of the sequence. Minor Pd values with anomalous Ni, Cu, and Zn levels were reported in gossans sampled during the Ni-boom years.

Status: Grass roots prospect.

Source: Louthean (1987).

(5) Heron Well

Location: 24 km south of Leonora.

Title holder: Mount Isa Mines Ltd.

Classification: ?6(b).

Geology and PGMs: In a north–south trending greenstone belt, which contains pillowed tholeiitic basalts, acid volcanics, and shale horizons. Two large gabbroic bodies intrude the greenstone sequence: the western Boxies Bore complex, and an eastern gabbro body. A differentiated peridotite sequence defines the western margin of the Boxies Bore gabbro and has a strike length of about 1500 m. Massive and disseminated Ni-Cu sulphide mineralisation containing PGM concentrations occurs along the basal contact of the peridotites with the underlying felsic volcanics. The mineralisation consists of chalcopyrite, pentlandite, chromite, cobaltite, and michenerite. The most encouraging intersections have been: HWDD-2, 2.1 m @ 6.51 ppm Pd, 1.55 ppm Pt, 0.44 ppm Au, 0.79% Cu, and 1.14% Ni; HWP-9, 2.0 m @ 0.63 ppm Pd, 0.45 ppm Pt, 0.99% Cu, and 0.65% Ni. Minor Pd and Pt enrichment also occurs in the oxidised zone of the peridotite, with Pd+Pt around 0.5 ppm.

Status: Continuing evaluation of mineralised basal peridotite zone.

Source: Helix Resources NL 1986 Prospectus.

(6) Jimberlana

Location: Extending from Norseman to Lake Johnston.

Title holders: Ajax Mining Nominees Pty Ltd and Aztec Exploration Ltd, with a possible ownership component by Austplat Minerals NL.

Classification: 6(b).

Geology and PGMs: The Jimberlana Intrusion is a layered, horizontal pipelike body 180 km long, 5.5 km deep, and 1.5 km wide. Macrorhythmic units comprise dunite, harzburgite, norite, norite-gabbro, and gabbro rock types, and rare chromitites at the base of dunite-pyroxenite cycles. Similarities have been drawn with the Great Dyke of Zimbabwe, although recent exploration programs have also focussed on a Platreef-type setting, as seen in the Bushveld Complex. Drilling has defined PGM values up to 0.8 ppm over 0.5 m, with anomalous Cu and Ni up to 0.5% in upper pyroxenite units. It is believed that the sulphides in parts of the Jimberlana Intrusion equilibrated with a restricted amount of magma; hence the sulphides generally have low PGM contents.

Status: Advanced prospect.

Source: Keays & Campbell (1981); Hoatson (1984); Louthean & Seidel (1988).

(7) Kalgoorlie region laterites

Location: Gilgarna Rocks, Carr Boyd, Youangarra: all in the north Kalgoorlie-west Leonora region.

Title holders: Various.

Classification: 1.

Geology and PGMs: Precious-metal enrichment (relative to background levels) occurs in some lateritised barren ultramafic rock in the eastern Yilgarn Block. Indurated ferruginous products, developed above magnesium-rich rocks, have elevated Pd (up to 48 ppb) and Ir (up to 32 ppb) concentrations. Background level for both Pd and Ir is about 2 ppb. Palladium generally follows the trend of Mn, Cu, and to a lesser degree Ni, Co, and Zn, but Ir correlates with Fe and Al oxides. This suggests that Ir is largely residual in the upper sections of the laterite profile, while Pd appears to have been mobilised from other parts of the profile.

Status: No economic significance where the laterite profile is developed over barren bedrock; however, lateritisation may be an important concentrating mechanism for the PGMs where the basement rocks have some PGM content.

Source: Travis & others (1976).

(8) Kambalda

Location: Kambalda.

Title holder: Western Mining Corporation Ltd.

Classification: 8.

Geology and PGMs: The Kambalda Ni-Cu-Au-PGM deposits are elongate, high-grade sulphide bodies that are contained in a thick sequence of metamorphosed komatiitic flows, tholeiitic basalts, and carbonaceous and pyritic sediments. Most are at or near the basal contact of metaperidotite with underlying tholeiitic metabasalt. Ni-Cu ores (2.96% Ni, 0.22% Cu) have PGM concentrations of approximately 325 ppb Pt, 425 ppb Pd, 110 ppb Os, 60 ppb Ir, 50 ppb Rh, 220 ppb Ru. The major platinum-group minerals are sperrylite, moncheite, sudburyite, stibiopalladinite, and palladoarsenide. The nickel-copper matte (73% Ni, 5.5% Cu) produced in treating the ore contains about 4.2 ppm Pt, 10.9 ppm Pd, 1.2 ppm Rh and 4.1 ppm Ru.

Status: Mines.

Source: Hudson & Donaldson (1984).

(9) Kambalda–Leonora region

Location: Various.

Title holders: Various.

Classification: 8.

Geology and PGMs: Several Ni-Cu deposits in the Kambalda–Leonora region are reported to contain moderate to high PGM levels associated with massive and disseminated ores. They have similar settings to the Kambalda deposits, the Ni-Cu mineralisation being generally associated with komatiitic and tholeiitic mafic-ultramafic flows. Maximum PGM levels reported are: Nepean 31.30 ppm Pd (with 19.8% Ni, 0.16% Cu); Scotia 2.35 ppm Pd, 1.09 ppm Ir (19.0% Ni, 0.81% Cu); Carnilya Hill 1.50 ppm Pd (10.4% Ni, 1.22% Cu); and Redross 1.99 ppm Pd (17.6% Ni, 0.08% Cu). Nickel gossans in the region have anomalous PGM levels, and include, Carnilya 1.50 ppm Pd (0.35% Ni, 0.27% Cu); Mount Clifford 1.70 ppm Pd (2.52% Ni, 1.40% Cu); Kurnalpi 3.63 ppm Pd (2.70% Ni, 5.05% Cu), and Bronzite Ridge 2.49 ppm Pd (1.25% Ni, 0.35% Cu).

Status: Various.

Source: Keays & Davison (1976); Travis & others (1976).

(10) Marshall Creek

Location: Near the old Bannockburn Au mine, between Leonora and Agnew.

Title holder: Noble Resources NL.

Classification: 8.

Geology and PGMs: The prospect is traversed by lineaments associated with the Mount Keith–Kilkenny Lineament. Host rocks are an Archaean greenstone sequence of mafic-ultramafic extrusives and intrusives, with minor sedimentary outcrops in the central section of the prospect. The mineralisation has formed three gossans along a basalt-ultramafic contact for a distance of over 1 km; the prospective contact region extends for 4 km before being covered by alluvium. The gossans locally grade along strike into black shale and chert. Surface bulk chip sampling has returned anomalous PGM values up to 3.37 ppm.

Status: Continuing evaluation of gossan areas and Heron Well area to the south.

Source: Louthean (1987); *Mining Monthly*, December–January, 1986–87, 24.

(11) Mount Thirsty

Location: 20 km northwest of Norseman.

Title holder: Separate titled areas held by Australian Tin & Tantalite Ltd and Helix Resources NL.

Classification: 6(b).

Geology and PGMs: The Mount Thirsty Sill is an extensive differentiated mafic-ultramafic complex, which intrudes metasediments and mafic volcanics. It consists of basal dunite, clinopyroxenite, and peridotite, with higher units of orthopyroxenite, harzburgite, hornblende gabbro, hornblende diorite, and quartz diorite. Granite occurs in the western part of the prospect. Magnetics indicate the sill forms an anticlinal structure, at least 30 km long and 5 km wide. Nickel-Cu pyrrhotite mineralisation occurs in the mafic-ultramafic rocks. A zone of anomalous Cr, Cu, Ni, Pt, and Pd values was outlined in soils on three adjacent traverses, suggesting bedrock PGM mineralisation may extend over a 1 km strike length. Helix Resources NL have noted that previous explorers at Mount Thirsty delineated Pt concentrations of up to 120 ppb in soil programs.

Status: Evaluation continuing of contact area of ultramafics and gabbros, and mineralised soil and rock zones.

Source: Helix Resources NL Quarterly Report for the period ending 31 March 1988; Louthean (1987).

(12) Narndee

Location: Approximately 100 km south-southeast of Mount Magnet.

Title holders: BHP Minerals (60%), Hunter Resources Ltd (40%).

Classification: 6(a).

Geology and PGMs: The Narndee Complex is one of the thickest intrusions in Australia (6–10 km stratigraphic thickness), and consists of interlayered peridotite and pyroxenite overlain by gabbro and norite. Platinum has been reported in association with Ni-Cu sulphides, and anomalous Pt, Pd, and Au levels have been detected in trenching and stream sediment samples. The mineralisation appears to be related to chromitite cycles at various stratigraphic levels in the intrusion. BHP have located four narrow chromitites associated with orthopyroxenites, norites, and pegmatoidal norites. Platinum up to 0.21 ppm, and Pd up to 0.19 ppm in rock chip samples have been reported from the lowermost chromitite layer. Mineralogically the chromite consists of a Cr-rich magnetite with associated pentlandite and lesser chalcopyrite grains. Trenching of chromitites associated with laterites in the Milgoo Peak area has defined wide PGM intersections, notably, in Trench 192, 32 m @ 0.06 ppm Pt, and 0.42 ppm Pd. About 500 m stratigraphically below this level, another level of chromitites has returned up to 0.54 ppm Pt, 0.13 ppm Pd, and 16.8% Cr_2O_3.

Status: Horizons within the cyclically layered mafic-ultramafic sequence and in the vicinity of the laterite cover are being drilled.

Source: Louthean (1987); Hunter Resources Quarterly Reports for the periods ending 30 September 1987, 31 December 1987.

(13) Netty

Location: 8 km northeast of Jerramungup, in the Southwest Mining Field.

Title holder: AuDax Resources NL, covering the old Netty Cu mining centre.

Classification: 6(b).

Geology and PGMs: In the Western Gneiss Terrane of the Yilgarn Block, foliated granitoid and gneissic rocks have been intruded by the mafic Netty Dyke, which is probably part of the Widgiemooltha Dyke Swarm (includes the Jimberlana Intrusion, near Norseman). The Netty Dyke consists of a leucogabbro core and marginal dolerite, and can be traced for 18 km. Sampling of the mullock heaps at the Netty mine revealed anomalous levels of Au, Ag, and PGMs associated with the Cu-Ni mineralisation. Surface samples of gabbroic rocks with disseminated sulphides have averaged 1.5 ppm Au.

Status: Continued evaluation for PGM-enriched sulphides in the mafic intrusive.

Source: Louthean (1987); Louthean & Seidel (1988).

(14) Plumridge Lakes

Location: 360 km northeast of Kalgoorlie, in the Great Victoria Desert.

Title holder: ELA by New Holland Mining NL, with a possible ownership component by Hampton Australia Ltd.

Classification: 7.

Geology and PGMs: Tectonised intrusion occurs in the northeastern limits of the Albany–Fraser Range Complex, which contains mafic–felsic granulite and gneiss. Wind-blown sand, silcrete, and calcrete cover most of the bedrock. Silicified ultramafic rocks occur along low ridges. Chromitite layers in a layered mafic-ultramafic complex, 30 km west of Plumridge Lakes have Cr contents of 46% and 28%, and traces of Pt.

Status: Grass roots prospect.

Source: Louthean (1987).

(15) Point Salvation

Location: 140 km east of Laverton.

Title holders: Delta Gold NL (40%), Mumbil Mines NL (40%), Anglo Australian Resources NL (20%).

Classification: 6(b).

Geology and PGMs: A prospective isolated greenstone belt near the eastern margin of the Yilgarn Block is being explored for PGMs and Au. The layered mafic-ultramafic body that extends for about 1.5 km and has a maximum thickness of 300 m consists of an olivine-cumulate zone, and a larger plagioclase cumulate unit of gabbroic composition. The olivine-cumulate zone is intensely serpentinised, and hosts up to six chromitite horizons. Other rock types in the poorly exposed sequence include felsic volcanics with interbedded basalt and thin banded iron formation (BIF), and younger granitic rocks. Surface chromitite samples from a gabbro-anorthosite body from the western part of the tenement have returned up to 36.5% Cr_2O_3, 0.19 ppm Pt, and 0.10 ppm Pd. Minor PGM levels were reported in DDH YAD-1: 0.15 ppm Pt and 0.32 ppm Pd over 18 cm.

Status: Evaluation continuing of prospective 10 km strike length of mafic-ultramafic rocks.

Source: Louthean (1987); Mumbil Mines NL Quarterly Report for the period ending 31 December 1985.

(16) Polar Bear

Location: 40 km north of Norseman, east of the Polar Bear Peninsula, Lake Cowan.

Title holders: Croesus Mining NL (66.6%), Thames Mining NL (33.3%).

Classification: 8.

Geology and PGMs: Mafic-ultramafic rock types of the Archaean Mulgabbie Formation and various sedimentary units of the Gundockerta Formation comprise the greenstone sequence in the Halls Knoll area of the prospect. These rocks form small isolated outcrops in Lake Cowan, east of Polar Bear Peninsula. The Hall's Knoll prospect is in a sequence of basal dolerite and basalt, overlain by high-magnesium mafic-ultramafic flows and high-level sills, with interlayered silicified black shale, and fine grained quartzite. The serpentinites contain minor sulphide minerals, and there are gossans up to 30 m long and 2 m wide over silicified black shales between ultramafic extrusives. Drilling has obtained Pt values of up to 0.58 ppm, and Pd varies from trace amounts to 1.83 ppm. Sulphide-bearing gossans are enriched in Pt (5.18 ppm), Pd (3.40 ppm), Au (0.1 ppm), Ag (15 ppm), Cu (1.57%), and Ni (1.32%). The sediments associated with the gossans also have anomalous PGM levels.

Status: Grass roots prospect.

Source: Croesus Mining NL Prospectus, 1986.

(17) Ravensthorpe

Location: 30 km south of Ravensthorpe.

Title holder: Pancontinental Mining Ltd.

Classification: ?8.

Geology and PGMs: The prospect encompasses Archaean ultramafic sills that have intruded metasediments near the boundary between the Yilgarn Block and the Albany-Fraser Province. Surface sampling has defined two lenticular sill-like structures, with Pt levels of up to 1 ppm associated with Cu and As.

Resolute Resources Ltd (50%) and Pact Resources NL (50%) are also investigating the Jerdacuttup and Bandalup Rivers, southeast of Ravensthorpe for placer-type Au-PGM mineralisation. The rivers drain a major zone of ultramafics and volcanic basement rocks. The region contains numerous Tertiary gold placer deposits consisting of partly eroded sequences of fine to coarse-grained polymictic gravels. Previous investigators have noted the presence of PGMs with the gold.

Status: Grass roots prospect.

Source: Louthean (1986); Louthean & Seidel (1988).

(18) Round Hill

Location: On the western side of Lake Rebecca, 130 km east of Kalgoorlie.

Title holder: Defiance Mining NL.

Classification: ?8.

Geology and PGMs: Massive BIF on Round Hill, occurs at the contact betweeen rhyolite of the Upper Gindalbie Formation and the overlying sedimentary rocks and mafic volcanics of the Mulgabbie Formation to the east. Rock chip and drainage samples have returned anomalous Pt and Pd values.

Status: Grass roots prospect.

Source: Louthean (1987).

(19) Salt Creek

Location: 360 km east-northeast of Kalgoorlie.

Title holders: Australian Pacific NL (90%), Dale & Leahy (10%), with a possible ownership component by Toledo Minerals.

Classification: 7.

Geology and PGMs: Prospect covers large areas of tectonised mafic-ultramafic layered intrusive rocks, in the Albany–Fraser Mobile Zone that borders the southeastern flank of the Yilgarn Block. Chromite mineralisation was discovered in the 1970s during Ni exploration. PGM values of up to 0.4 ppm were reported from the chromites.

Status: Grass roots prospect.

Source: Louthean (1987).

(20) Windarra

Location: 25 km northwest of Laverton.

Title holder: Western Mining Corporation Ltd.

Classification: 8.

Geology and PGMs: The Windarra Ni deposits are in a northwesterly trending, wedge-shaped greenstone belt comprising metabasalt, altered dunite, peridotite, pyroxenite, and BIF. Mineralisation occurs in partly folded sheets or near-vertical lenses above the contact of BIF and ultramafic rock. The distribution of ore is largely controlled by the Mount Windarra dragfold structure. The stratiform geometry and general disseminated nature of the Ni-Cu ores suggest a magmatic origin for the sulphide mineralisation, but breccia and BIF hosted ores are believed to have formed from the remobilisation of magmatic ore components into adjacent sulphide-rich sedimentary units during deformation and/or metamorphism. Platinum (0.15–0.17 ppm) and Pd (0.77–2.3 ppm) are associated with the Ni-sulphide ore.

Status: Mine.

Source: Roberts (1975).

(21) Wondinong

Location: Near the northern margin of the Windimurra Intrusion, 100 km south-southeast of Mount Magnet.

Title holders: The Windimurra Intrusion is under title to various companies including BHP Minerals, Pancontinental Mining Ltd, Degussa AG, Yinnex NL, and AuDax Resources NL.

Classification: 6(a).

Geology and PGMs: The Windimurrra Intrusion is the largest mafic-ultramafic complex in Australia, with a total stratigraphic thickness of about 9 km. Ultramafic rock types are rare: anorthosite, troctolite, gabbronorite, and gabbro are the major rock types. Subeconomic vanadiferous Ti-magnetite horizons have been delineated in the upper levels of the intrusion, chromitites being restricted to the ultramafics. Minor sulphides occur in the Wondinong area (northern margin of complex) and Wagoo area (north of Windimurra Hills on eastern side of complex). Anomalous PGM levels have been reported from the Wondinong area.

Status: Continuing evaluation.

Source: Parks & Hill (1986); Hoatson (1984).

(22) Yarawindah Brook–New Norcia

Location: 100 km north of Perth.

Title holder: AuDax Resources NL, and an ownership component by Reynolds Australia.

Classification: ?9(b).

Geology and PGMs: A differentiated layered mafic-ultramafic complex has intruded gneiss of the Jimperding Metamorphic Belt. The complex has been interpreted as a composite body comprising several smaller intrusions, some of which also form concordant satellite bodies in the country rocks and along the eastern margin of the main complex. Drilling in 1976 delineated values of up to 3 ppm Pd, 0.4 ppm Pt, and 1.0 ppm Au in sulphide-rich plagioclase cumulate amphibolites and hangingwall metaquartzite. Recent resampling of the drill core confirmed anomalous PGMs, e.g. 0.5 m @ 2.6 ppm Pt, 0.36 ppm Pd, and an extended wide zone of 28 m @ 0.35 ppm Pd in the intrusive rocks.

Based on aeromagnetics, the Geological Survey of Western Australia recognised several Archaean mafic intrusive complexes in the Yarawindah Brook region of the Western Gneiss Terrane. Common rock types include meta-anorthosite, metagabbro, metapyroxenite, metaperidotite, and younger intrusions of granophyre and dolerite. The complexes are believed to be derived from magmas of tholeiitic composition, and consequently have potential for vanadiferous, titaniferous, chromiferous, and PGM-enhanced nickel-sulphide mineralisation.

Status: Continuing prospect, with exploration directed at PGM-Au-enriched stratiform Cu-Ni type mineralisation, and/or precious metals in structurally controlled hydrothermal alteration zones.

Source: Louthean (1987); Louthean & Seidel (1988); Harrison (1986).

(23) Yellowdine

Location: 34 km east-southeast of Southern Cross.

Title holder: Mannkal Mining Pty Ltd.

Classification: ?8.

Geology and PGMs: The Yellowdine prospect encompasses a Cu-Ni-bearing metaperidotitic segment of a large ultramafic complex along the eastern margin of a granite dome. The layered mafic complex also has potential for by-product Pt, Pd, and Au. Deeply weathered serpentinite, mafic volcanics, tremolite-chlorite schist, BIF, and metasediments are the major rock types. Minor Au production has been derived from ferruginised serpentinite and quartz veining at the southern end of the prospect. Exceptionally high Pt values, up to 200 ppm, have been reported at depths of 30 m, near the base of a 1.5 km long ultramafic unit.

Status: Continuing evaluation of the basal section of the ultramafic body.

Source: Mining Monthly, November 1983; Mannwest Internal Consulting Geological Reports.

Pilbara Block

(24) Andover, Balla Balla, Mount Dove, Sherlock River–Mount Fraser

Locations: In the Roebourne and Port Hedland district of the west Pilbara Block: Andover 5 km south of Roebourne, Balla Balla 10 km northwest of Creek, Mount Dove 65 km southwest of Port Hedland, and Sherlock River–Mount Fraser 45 km east of Roebourne.

Title holders: Andover — Greater Pacific Investments Ltd (52%), Gold & Mineral Exploration NL (24%), Newmex Exploration NL (24%); Balla Balla — Australia Pacific Resources Ltd, with a possible ownership component by Westfield Oil & Gas; Mount Dove — Australia Pacific Resources Ltd, with a possible ownership component by Hunter Resources Ltd; Sherlock River–Mount Fraser — Hunter Resources Ltd.

Classification: 6(b).

Geology and PGMs: The Andover Complex (also called Roebourne, or Mount Hall–Carlow Castle Complex), is one of several differentiated Archaean intrusions in the Karratha–Roebourne–Port Hedland region that are being intensively explored for PGMs and base-metal sulphides. Areally Andover is a large mafic-ultramafic intrusion, cropping out over 150 square kilometres; however, the stratigraphic thickness is probably less than 2 km. The complex consists of cycles of dunite-peridotite-pyroxenite-gabbro-anorthosite, and is intruded by gabbro, dolerite, aplite, and pegmatite. Layering is poorly developed and the intrusion is extensively faulted and dislocated, making reconstruction of the geometry of the body difficult. Serpentinisation of ultramafics is intense and widespread. Disseminated chromite is associated with orthopyroxene and olivine cumulates. The Andover Complex is possibly genetically related to the Munni Munni, Radio Hill, and Maitland complexes nearby to the southwest. As with Munni Munni, there is a progression from an ultramafic zone at the northeastern corner, through a transitional zone of hybrid ultramafic and gabbroic rocks, to a gabbroic zone at the southwestern end of the complex. It is therefore important when delineating a potential PGM-enriched horizon, to ascertain where in the sequence S-saturation and cumulus chromite occur. Anomalous PGM levels have been reported during early exploration, near a contact between ultramafic and gabbroic rocks.

The Balla Balla Complex, extending over 15 km strike length and 1–2 km in thickness, consists of lower norite, anorthosite, and minor pyroxenite units, overlain by gabbro, granophyre, and vanadiferous-titanomagnetite units. Anomalous PGM and gold values have been delineated in a reconnaissance rock sampling program from the poorly-exposed intrusion. The precious metals coincide with anomalous Cu and Ni concentrations in soil samples along a geologically favourable horizon within the lower half of the stratigraphy.

Preliminary drilling at Mount Dove to test low-order PGM soil anomalies has delineated minor PGM levels of 1 m @ 0.25 ppm Pt+Pd+Au. The mafic-ultramafic intrusion, which was recognised during Cu-Ni orientated exploration by Utah in 1972–74, consists of a deformed sill-like body strongly differentiated from dunite, peridotite, pyroxenite, to gabbro and granophyre. Further investigations will test a series of stratigraphically controlled PGM anomalies.

Anomalous PGM levels have been defined in a copper-nickel sulphide gossan at the base of the Sherlock River–Mount Fraser mafic intrusion. Rock–chip samples range up to 0.32 ppm Pt, 1.30 ppm Pd, and 0.51 ppm Au, and are associated with Cu, Ni, and As anomalism. The Pt : Pd : Au and Cu : Ni ratios are highly variable. The PGM potential of the primary sulphide zone has not been evaluated.

Status: Evaluation continuing.

Source: D. M. Hoatson, also D. A. Wallace (personal communication), arising from BMR Project on the PGM potential of layered intrusions in the west Pilbara Block; Louthean & Seidel (1988); Hunter Resources Quarterly Reports for the periods ending 30 June 1987 and 30 September 1988.

(25) Dead Bullock Well

Location: 90 km southwest of Marble Bar, in the east Pilbara Block.

Title holder: Pilbara Resources Ltd.

Classification: 6(b).

Geology and PGMs: The rock types in the tenement include interbedded mafic-ultramafics, metasediments, BIFs, and amphibolite schists flanked to the southwest by gneiss, granite, and pegmatite dykes. The amphibolite schists are believed to be metamorphosed gabbroic rocks, forming the major part of a layered complex up to 330 m wide, while the ultramafics represent a differentiated portion of the complex. Intruding the complex is a coarse-grained altered chrysotile pyroxenite body, which has a circular outcrop and has been interpreted as a pipe. Drilling 4 km southeast of the pipe in the layered complex delineated anomalous Pd values in chromiferous ultramafic.

Status: Grass roots prospect.

Source: Pilbara Gold Trust (managed by Pilbara Resources Ltd) Interim Report, March 1986.

(26) Karratha

Location: Midway between Karratha and Roebourne, in the west Pilbara Block.

Title holder: Unknown.

Classification: 2(f).

Geology and PGMs: Ir, Os, Ru, and Pt alloys and Au have been recovered from stream sediment samples derived from clastic sedimentary rocks, acid and mafic volcanics, and chert from a 10 km strike length of the Archaean Nickol River Formation. The platinum-group minerals form both flattened and irregular to subhedral grains that vary in diameter from 0.1 to 0.4 mm. Associated heavy minerals include gold, ilmenite, chromite, magnetite, rutile, spinel, sphene, garnet, zircon, tourmaline, and epidote. The compositional spread of the platinum-group minerals may indicate multiple sources, possibly related to layered mafic-ultramafic intrusions in the area, e.g. the Andover, Sherlock River, and Munni Munni complexes near Roebourne. Archaean palaeoplacers are favoured to account for the present distribution of the mineralisation, although Jurassic or Tertiary alluvial sediments may be potential host rocks.

Status: Grass roots prospect, minor economic interest.

Source: Hudson & Horwitz (1985).

(27) Lionel

Location: 25 km north of Nullagine in the east Pilbara Block.

Title holder: Monarch Resources NL is earning 75% equity from tenement holders.

Classification: 8.

Geology and PGMs: Serpentinite alteration is intense and widespread in the Lionel Archaean sequence, which consists of dunite, peridotite, pyroxenite, and gabbro. Banded chert, BIF, felsic agglomerate, tuff, andesite, and basalt are associated with the sill-like intrusive rocks. Copper-sulphide vein mineralisation occurs in gabbro and the ultramafics. Copper was mined before World War 2. Drilling in mid 1987 delineated anomalous PGM levels near a contact between gabbro and peridotite.

Status: Grass roots prospect.

Source: Louthean (1987); Louthean & Seidel (1988).

(28) Mount Sholl

Location: 30 km south of Karratha.

Title holders: Whim Creek Consolidated, Samim Australia Pty Ltd.

Classification: 6(b).

Geology and PGMs: Metagabbro and metaclinopyroxenite, with minor serpentinised metaperidotite and dunite, constitute the poorly layered units in the Mount Sholl mafic-ultramafic intrusion (Fig. 13). Disseminated and minor massive Ni-Cu mineralisation occurs above the basal contact of the intrusive rocks with the volcanic units of the Warrawoona Group. Weakly anomalous PGM levels of up to 0.18 ppm Pt, 0.35 ppm Pd, and 0.04 ppm Ir are associated with the basal sulphide mineralisation, which grades 1.0% Ni+Cu. The Mount Sholl Intrusion contrasts with the nearby Munni Munni Complex in the higher proportion of gabbroic rocks relative to ultramafic rocks, and the Mount Sholl rocks were more widely and intensely altered during greenschist metamorphism. Significantly the Mount Sholl magma was S-saturated before or during its emplacement; thus the PGMs did not build up during fractional crystallisation (unlike at Munni Munni), or filter pressing of the cumulus pile, and consequently the basal sulphides are only weakly enriched in PGMs. The basal stratigraphic level of the mineralisation may also suggest that the sulphides did not come into contact with a large volume of PGM-bearing magma which would also hinder PGM enrichment. These situations may also apply to the other Ni-Cu rich deposits in the district such as in the Radio Hill and Dingo complexes.

Status: Advanced prospect.

Source: From joint BMR–Melbourne University studies by D. Hoatson, with assistance from Whim Creek Consolidated NL, and Samim Australia Pty Ltd.

(29) Munni Munni

Location: 45 km south of Karratha, western Pilbara Block.

Title holders: Hunter Resources Ltd (western sector); Whim Creek Consolidated and Samim Australia Pty Ltd (eastern sector).

Classification: 6(a) and 9(b).

Geology and PGMs: The 2800 Ma old layered Munni Munni Complex (Fig. 14) is currently the most prospective layered-intrusive-type PGM deposit in Australia. The complex is composed of an underlying 1.85 km thick ultramafic zone that contains cyclic sequences of dunite, lherzolite, olivine websterite, and clinopyroxenite. Gabbronorite and anorthositic gabbro are the main rock types in the 3.6+ km thick gabbroic zone. Orthopyroxenite, chromitite, and norite are restricted to the highest stratigraphic levels of the ultramafic zone.

Mineralised porphyritic plagioclase websterite occurs for 12 km along strike within a zone up to 20 m directly below the interface of the ultramafics and gabbros. The mineralisation is dominantly disseminated chalcopyrite-pentlandite-pyrrhotite; the platinum-group minerals, cooperite, braggite, vysotskite, moncheite, potarite, atheneite, temagamite, michenerite, sperrylite, platarsite, native Pt, and native Pd generally occur as 2 to 20 μm grains in silicates, or associated with, or near chalcopyrite or pentlandite, or alteration silicate products of the sulphides. The precious-metal mineralisation is dominated by Pd, with lesser amounts of Pt, Au, and Rh. It is considered that the Pd and Pt were progressively enriched in the melt during the fractional crystallisation of the S-poor ultramafic magma, and were precipitated in a hybrid magma (involving the fractionated ultramafic melt and a new S-saturated gabbroic magma pulse) at the interface of the two zones (Hoatson & Keays *in* Von Gruenewaldt & others, 1987a). The sulphide content of the mineralised websterite varies along strike, with some mineralogical evidence of local hydrothermal remobilisation of the sulphides, but the PGM levels generally are consistent along strike. By mid 1988, 56 diamond drill holes had been completed along 7.5 km of the strike length of the mineralised horizon, with 53 of these intersecting PGM mineralisation at the same stratigraphic level. The best intersection to date is in DDH MMD 34: 5.5 m @ 4.3 ppm PGMs+Au. The mineralised horizon averages 2.5 m true thickness and typically grades 2.9 ppm Pt+Pd+Au, 0.2% Ni, and 0.3% Cu. A potential resource of 20 to 30 Mt of PGM mineralisation is inferred by drilling to a depth of 500 m, and higher-grade zones are present within this resource. The deposit is open along strike and at depth. Future drilling will further evaluate the central region of the complex, where early drilling has indicated an apparent increase in grade and width of the mineralised horizon with depth, and the possibilities of other mineralised horizons occurring at higher stratigraphic levels. Metallurgical testing of the Munni Munni material is being carried out in Canada. Precious-metal content of selected drill intersections are listed below: (Note: recent analytical check assays by Hunter Resources have shown that the Pt levels reported after the first five holes were 29% to 54% too low, but Pd and Au showed good correlation; the following Pt data have not been corrected for this underestimation.)

Hole/interval(m)	*Pt(ppm)*	*Pd(ppm)*	*Au(ppm)*	*Pt+Pd+Au(ppm)*
MMD 1 64.0–66.5	1.28	2.03	0.15	3.46
MMD 3 76.0–79.0	0.98	1.74	0.13	2.85
MMD 5 42.0–45.0	0.69	1.20	0.09	1.98
MMD 7 236.0–241.0	0.62	1.11	0.15	1.88
MMD 11 109.0–118.5	0.63	1.06	0.20	1.89
MMD 15 87.0–92.0	0.81	1.47	0.54	2.82
MMD 28 231.0–232.5	2.25	3.77	0.71	6.73
MMD 34 543.0–548.5	1.2	2.6	0.5	4.3
MMD 38 224.0–229.0	0.6	1.1	0.1	1.8
MMD 42 384.5–387.5	0.7	1.3	0.1	2.1
MMD 47A 202.5–205.5	0.4	1.6	0.2	2.2
MMD 52 30.5–32.0	0.8	1.7	0.3	2.8

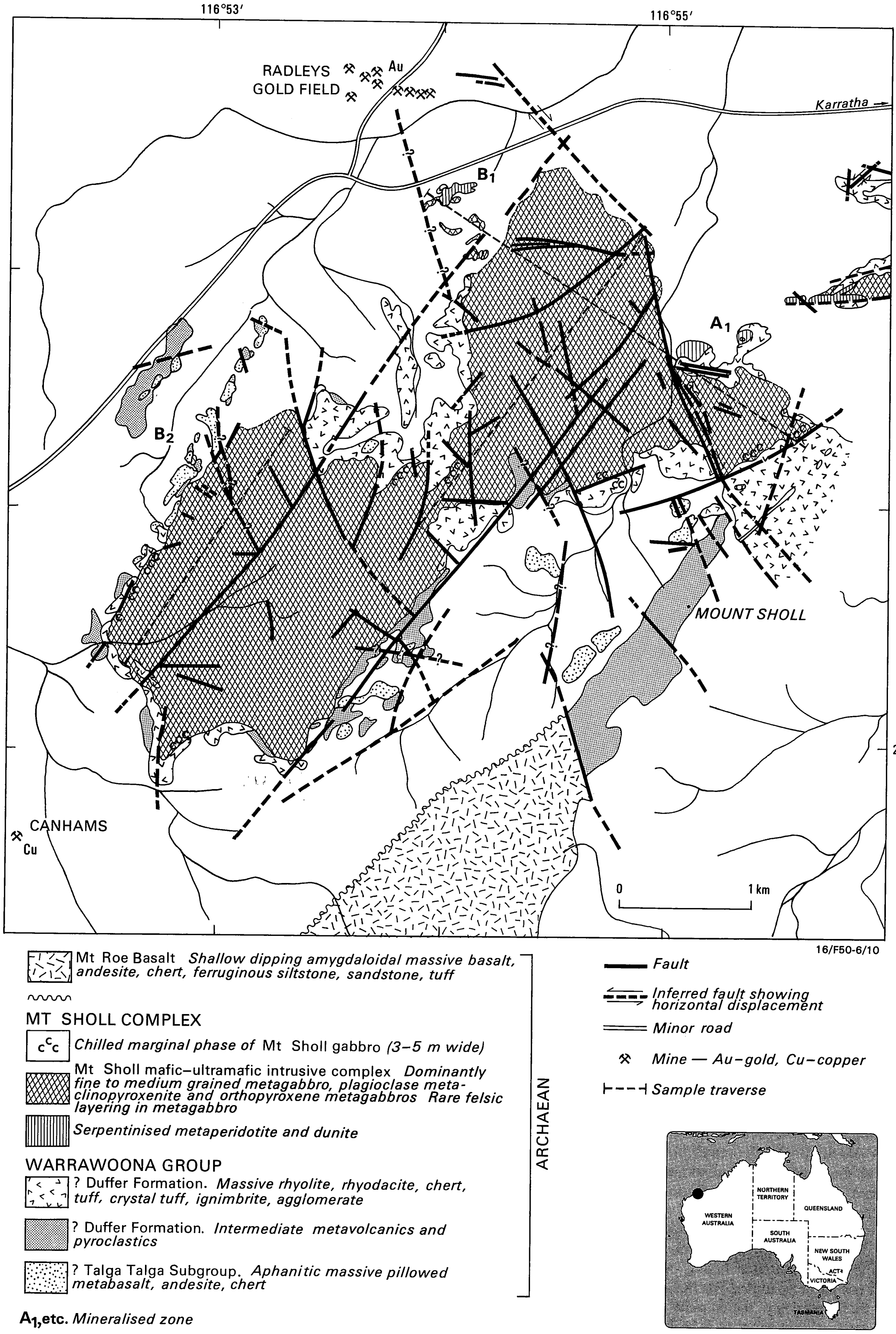

Fig. 13. Geology of the Mount Sholl Intrusion, west Pilbara Block, WA.

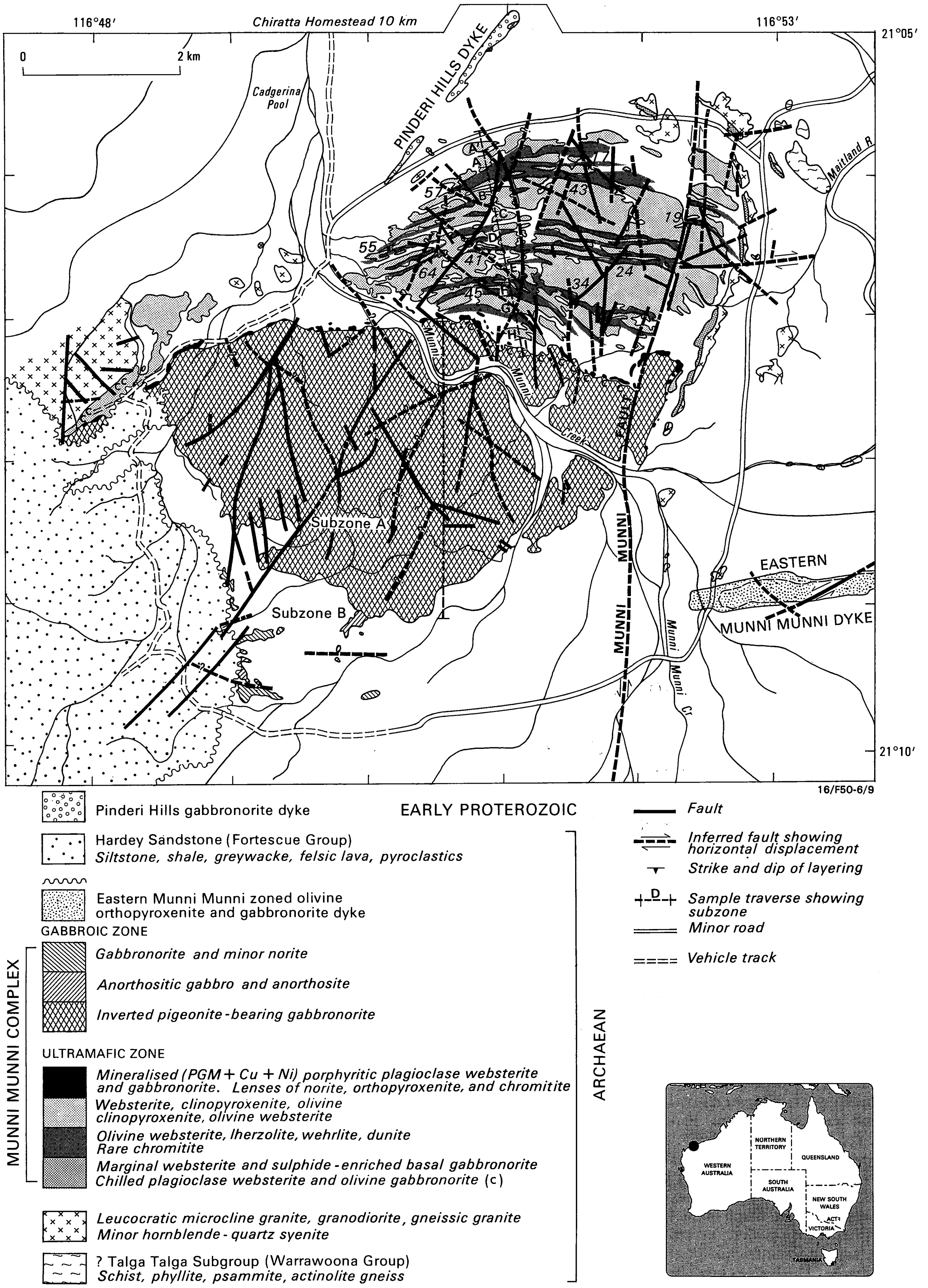

Fig. 14. Geology of the Munni Munni layered mafic-ultramafic intrusion, west Pilbara Block, WA.

Samim Australia, in their investigations for structurally controlled precious metal mineralisation at the Munni Munni Complex, delineated strong hydrothermal silver mineralisation along the Munni Munni Fault (Fig. 14) on the northern margin of the complex. Spectacular assays of 6 m @ 3478 ppm Ag have been obtained, with associated peak values of 6450 ppm Cu, 3130 ppm Ti, 2180 ppm Ni, 1580 ppm Ba, 1550 ppm Pb, and 494 ppm Mo in the same hole. Another hole intersected 9 m @ 0.21 ppm Au and 0.59 ppm Pd. Primary and supergene silver, chalcopyrite, chalcocite, bornite, pyrrhotite, linarite, pyrite, and marcasite have been recognised for this unusual type of remobilised mineralisation.

Status: Advanced prospects, with continuing evaluation by companies and BMR.

Source: Joint BMR–Melbourne University studies carried out by D. Hoatson, with assistance from Hunter Resources Ltd, Whim Creek Consolidated NL, and Samim Australia Pty Ltd; Hoatson & England (1986); Hoatson & Keays (1987); Williams & others (in press); De Angelis & others (1988); Hunter Resources Quarterly Reports for the periods ending 31 March 1986, 31 December 1986, 30 September 1987, 31 December 1987, 31 March 1988, 30 June 1988.

(30) Munni Munni South

Location: Eastern margin of the Munni Munni Complex, near the Zebra Hill dyke.

Title holders: Hunter Resources Ltd (51%), Mount Gipps Ltd (49%).

Classification: 6(a).

Geology and PGMs: Prospect covers a 6 km long northeast-trending linear altered pyroxenite-gabbronorite near the exposed southern boundary of the Munni Munni Complex. The altered rocks have been interpreted to represent the eastern marginal phase of the Munni Munni Complex, which also traverses the large Zebra Hill dyke. A zone of anomalous Cu and PGM mineralisation has been delineated along a gabbro-pyroxenite contact. Minor drilling along a 2 km section of the altered pyroxenite-gabbronorite has recorded weaker (though still interesting) PGM values than in the main mineralised horizon at Munni Munni. Results from different holes include: 2.0 m @ 0.22 ppm Pt, 0.51 ppm Pd, 0.12 ppm Au; and 3.0 m @ 0.06 ppm Pt, 0.38 ppm Pd, 0.03 ppm Au.

Status: Grass roots prospect.

Source: Hunter Resources Quarterly Report for the period ending 31 December 1986.

(31) Rudall River

Location: 290 km southeast of Marble Bar, in the Paterson Province, east of the Pilbara Block.

Title holder: Unknown.

Classification: ?6(b).

Geology and PGMs: Small (1.2 by 0.5 km) serpentinite plugs and sills intrude Early Proterozoic quartzite, quartz-mica schist, and quartz-mica-feldspar gneiss in the Rudall River area. In January 1971, North West Oil & Minerals Co. NL announced Pt values of 1.99 to 6.65 ppm from the surface to depths of 117.6 and 239.5 m in four drill holes. The assays were carried out by atomic absorption spectrophotometry (AAS). On the basis of these results the company estimated reserves of 1030 t of ore averaging 3.82 ppm in the Jason orebody. Additional Pt values were reported in another two holes, drilled into the Tom Tit body, 2 km south of the Jason deposit. The Geological Survey of Western Australia inspected the Rudall River prospects in June 1971, to verify the Pt occurrence. Rock chip samples from near the drill holes returned a maximum Pt value of 0.13 ppm, and panned creek samples, which were further concentrated by bromoform and magnetic separation, were, except for one sample, all less than 0.13 ppm Pt. A non-magnetic fraction of one sample yielded 0.64 ppm Pt, and 13.20 ppm Au. The high Pt levels reported by the company can probably be attributed to inter-element interference effects during the AAS determinations.

Status: Minor economic significance.

Source: Blockley (1971).

(32) Toorare Pool

Location: Near the western margin of the Munni Munni Complex.

Title holder: Hunter Resources Ltd.

Classification: 6(b).

Geology and PGMs: Similar mafic-ultramafic rock types suggest this complex may be related to the nearby Munni Munni Complex. Anomalous PGM levels have been reported from some prospective horizons.

Status: Grass roots prospect.

Source: Hunter Resources Quarterly Report for the period ending 31 December 1986.

Halls Creek Mobile Zone

(33) Eastmans Bore–Louisa Downs

Location: 130 km southwest of Halls Creek.

Title holder: Helix Resources NL.

Classification: 7.

Geology and PGMs: The Eastmans Bore–Louisa Downs mafic-ultramafic intrusive body is a steeply dipping folded sill consisting of dunite, peridotite, pyroxenite, anorthosite, norite, and gabbro. The sill intrudes metasediments and acid volcanics of the Early Proterozoic Biscay Formation, and is intruded by Bow River Granite. The intrusion, which has a strike length of approximately 10 km, is at the intersection of the King Leopold and Halls Creek mobile zones. Chromitites in the ultramafics show marked lateral variation, with layers bifurcating and converging over short distances. Cross-cutting faults which displace the chromitites by up to 1.2 km, have divided the sill into separate blocks. The chromitites generally average 20 cm thick, but are up to 50 cm thick. Four areas exceeding 1 ppm PGMs have been delineated by soil and rock geochemistry, with PGM levels averaging 3 ppm over a 300 m strike length in one area. Maximum concentrations recorded are 7.5 ppm (6.6 ppm Pd + 0.9 ppm Pt). Potential for PGMs may also exist within the gabbroic units stratigraphically above the extensively explored chromitites, as in the Stillwater Complex.

Status: Advanced prospect.

Source: Helix Resources NL 1986 Prospectus; Hoatson (1984).

(34) Lamboo–Loadstone Hill

Location: 45 km southwest of Halls Creek.

Title holder: West Coast Holdings Ltd, with a possible ownership component by Hunter Resources Ltd.

Classification: 7.

Geology and PGMs: The prospect covers chromitite horizons in a sill, with an oval outcrop, composed of Alice Downs Ultrabasics rock types. Serpentinised peridotite with subordinate pyroxenite and gabbro are the major rock types, with narrow chromitite horizons (up to 15 cm thick) defining the rhythmic layering. Soil assays up to 1.2 ppm PGM have been reported and persistent anomalism (> 0.1 ppm PGM) delineates a target zone at the top of a peridotite unit that extends for 14 km. Drilling has indicated that PGM mineralisation is associated with chromite-bearing peridotites at various levels in the intrusion, and in particular in the upper 200 m of the ultramafic series below the gabbro contact. Strike length of mineralisation is 11.5 km. Pt-Pd minerals occur with chalcopyrite, pyrrhotite, pyrite, pentlandite, chromite, and silicates. Local high Au values (9.46 ppm in LDH 4) are associated with talc schists. The best drilling results are (Note: as with Munni Munni, recent analytical check assays by Hunter Resources have shown that the Pt levels reported in 1987 were 62% to 74% too low; the following Pt data have not been corrected for this underestimation): LDH 1: 1.0 m @ 0.49 ppm Pt, 0.90 ppm Pd, 0.07 ppm Au; LDH 4: 3.0 m @ 0.02 ppm Pt, 0.03 ppm Pd, 9.46 ppm Au, and 23 m @ 0.11 ppm Pt, 0.30 ppm Pd, 0.03 ppm Au; LDH 10: 4.0 m @ 0.32 ppm Pt, 0.48 ppm Pd, 0.04 ppm Au; LDH 16: 3 m @ 0.28 ppm Pt, 0.50 ppm Pd; and LDH 21: 10 m @ 0.22 ppm Pt, 0.42 ppm Pd, 0.26 ppm Au; LDH 32: 5 m @ 0.46 ppm Pt, 0.81 ppm Pd, 0.02 ppm Au. The potential of the intrusion is enhanced by the widths of mineralisation (e.g. up to 15 m in LDH 16), and the high Pt : Pd ratio of 1 : 1, with some intersections exceeding 2 : 1.

Status: Continuing evaluation.

Source: Hunter Resources Quarterly Reports for the periods ending 31 December 1986, 30 September 1987, 31 December 1987, 30 June 1988.

(35) Panton

Location: 65 km north-northeast of Halls Creek.

Title holders: Minsaco Resources Pty Ltd (76%), North Broken Hill Holdings Ltd (17%), Ampol Mining Pty Ltd (7%).

Classification: 7.

Geology and PGMs: The Panton Sill is a southerly plunging synclinal structure, composed of Early Proterozoic Alice Downs Ultrabasics and McIntosh Gabbro rock types. The basal units consist of altered peridotite, and tremolite-chlorite schist, which grade into alternating layers of gabbro, leucogabbro, and anorthosite near the top of the intrusion (Fig. 15). Total stratigraphic thickness is in the order of 1.5 km. The peridotite contains chromitites up to 15 cm thick, which can be traced for 1.5 km along strike. High PGM levels up to 3.1 ppm have been reported in chromite, with sperrylite forming small (15–90 μm) inclusions in chromite and chlorite-rich matrix.

Dry Creek Mining NL has located significant Au anomalies with Pt indications in the alluvial and eluvial watersheds surrounding the Panton Sill.

Status: Advanced prospect.

Source: Hamlyn (1977); *Gold Gazette*, 28 August 1988.

(36) Springvale

Location: 60 km north of Halls Creek.

Title holder: Australmin Pacific NL, with a possible ownership component by Peko-Wallsend Operations.

Classification: 7.

Geology and PGMs: The Springvale Complex is a large shallow-dipping sill that is composed dominantly of McIntosh Gabbro type rock types. Its outcrop area is broadly oval. Unlike in the Panton and Lamboo complexes,

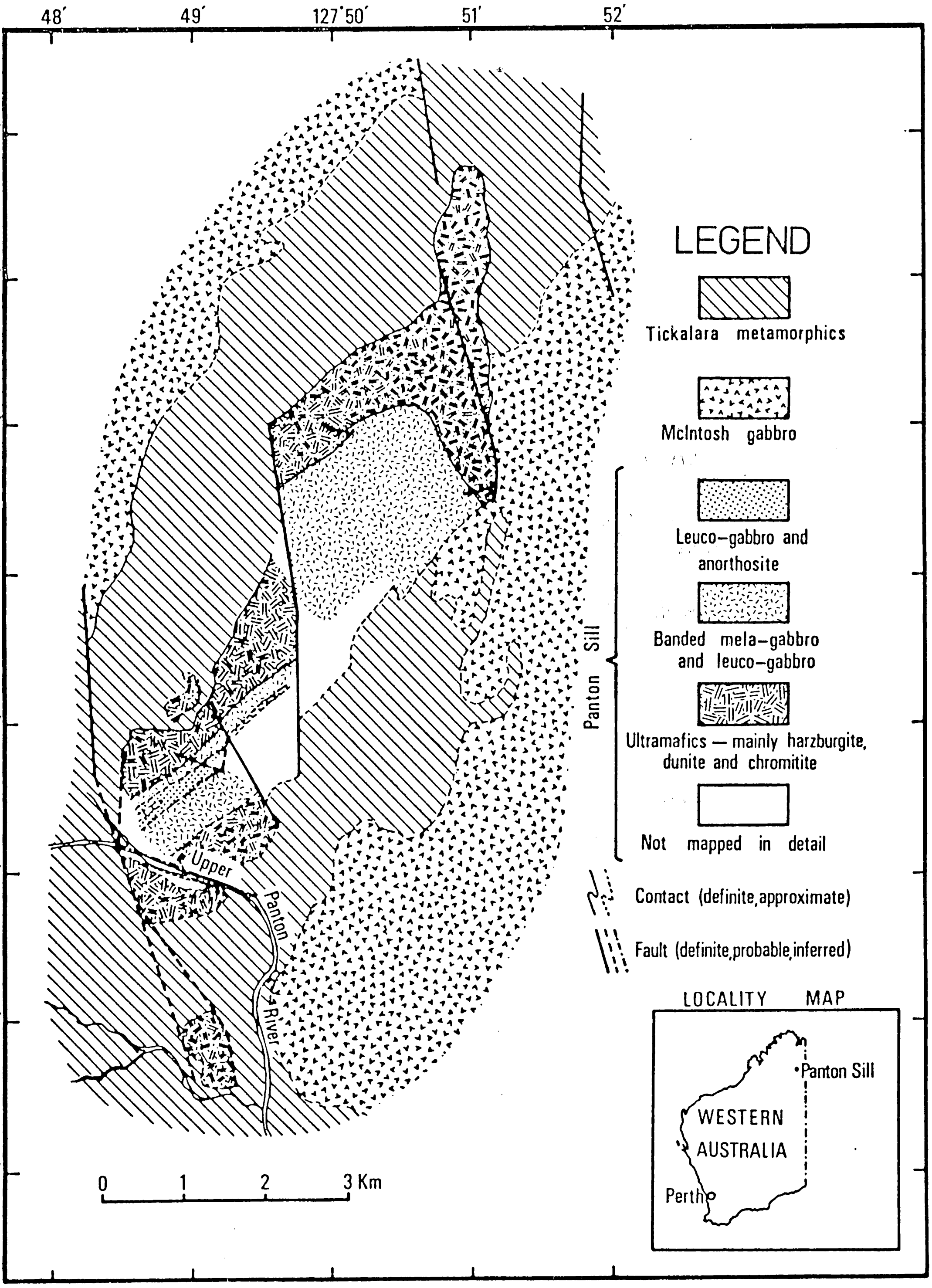

Fig. 15. Geology of the Panton Sill, Halls Creek Mobile Zone, east Kimberleys, WA. Reproduced from Hamlyn (1980), by permission of *American Journal of Science*.

Alice Downs Ultrabasics rock types are rare in the Springvale intrusion. Weakly anomalous PGM levels are associated with two chromite-rich horizons in the layered mafic stratigraphy.

Status: Grass roots prospect.

Source: Louthean (1987).

Canning Basin

(37) McWhae Ridge

Location: On the northern margin of the Canning Basin, 280 km southeast of Derby.

Title holder: Unknown.

Classification: 10.

Geology and PGMs: Anomalous Ir, with associated elevated levels of Pt, V, Co, Ni, Cu, As, Sb, Pb, Th, and rare earth elements, occurs in a Late Devonian deep-water limestone sequence. The stratigraphic position of the anomaly appears to coincide with a major global biotic extinction. Similar Ir anomalies have been observed throughout the world in thin clay horizons at the Cretaceous–Tertiary boundary, and have been put forward as evidence that the Ir and biota extinctions were caused by a large asteroid or comet impact on the earth. The Ir anomaly attains 20 times background levels in the Canning Basin limestones, and reaches a maximum of 0.3 ppb. These PGM concentrations have no economic significance.

Status: No economic significance.

Source: Playford & others (1984); McLaren (1985).

Other Western Australian occurrences: Yilgarn and Pilbara Blocks

Riverina Gold NL have reported anomalous Pd (up to 6.9 ppm), and Pt (up to 0.85 ppm) levels in surface samples at **Mount Alexander,** 100 km west of Leonora in the Yilgarn Block. The prospect covers gossanous horizons associated with gabbroic intrusions.

Osmiridium has been reported in the Tim Gold Lode at **Copperfield,** 100 km northwest of Menzies in the Yilgarn Block. The titled area (owned by Copperfield Gold NL) encompasses a northwest trending sequence of amphibolites, with minor sediments, anorthosites, ultramafics and gneissic granite. The rock sequence and mineralised lodes have been disrupted by northeast trending faults, with gold mineralisation known to occur over a 6.5 km strike extent.

At the **Triberton Prospect** (owned by T. Plotts and R. Neaves, with a possible ownership component by Maritana Gold NL), 70 km southwest of Marble Bar in the east Pilbara Block, a deformed sequence of mafics, ultramafics, pyroxenite, schist, chert, sediments and felsic rock types has been recognised. Sampling along 6 km of the strike extent of the sequence returned some wide, but low-grade Au and Ag levels. Of particular interest was a a sulphide-rich zone in an ultramafic schist, which gave encouraging Pt and Pd values, but poor Au grades.

Status: All prospects at grass roots level of exploration.

Source: Louthean & Seidel (1988).

SOUTH AUSTRALIA

Broken Hill Block

(38) Boolcoomata

Location: 30 km northeast of Olary, and 20 km northwest of Mingary.

Title holder: Unknown.

Classification: ?9(a).

Geology and PGMs: In 1913, the South Australian School of Mines reported a sample containing 1.55 ppm Pt from near Boolcoomata in the Olary region. The exact location and type of sample is unknown. Proximity to the PGM occurrences in the Broken Hill district suggests this sample is possibly related to serpentinite sills and may be of remobilised (?hydrothermal) origin.

Status: Unknown.

Source: South Australian Mining Review, 1913, **18,** 12.

(39) Mingary

Location: 20 km west of the New South Wales–South Australia border, on the Broken Hill railway line.

Title holder: Unknown.

Classification: ?9(a).

Geology and PGMs: Platinum has been reported from Mingary, but no details of geology or PGM levels are recorded. It is possible the occurrence may be related to serpentinite sills, similar to the Mulga Springs–Round Hill PGM occurrences in the Broken Hill district (see Nos. 50, 51, p. 51).

Status: Unknown.

Source: Barrie (1965).

Kanmantoo Fold Belt

(40) Nairne

Location: Nairne pyrite deposit, Shepard's Hill Quarry, Brukunga, 47 km east of Adelaide.

Title holder: Unknown.

Classification: 9(c) or 9(d).

Geology and PGMs: The Cambrian Nairne pyritic beds occur at the base of the Kanmantoo Group, an 8 + km thick sequence of fine grained quartzite, and metamorphosed greywacke, and siltstone. The sulphides comprise pyrite, pyrrhotite, chalcopyrite, galena, sphalerite, with minor arsenopyrite and tetrahedrite. There is a strong correlation between S and graphite. The graphite varies from 1 to 2.4% in the ore beds, and, with the S, is believed to be of biogenic origin. The extensive strike length of the pyritic beds (traced for 100 km) and mineral relationships suggests a sedimentary origin for the sulphides, although considerable remobilisation occurred during amphibolite-facies metamorphism. A palladium diantimonide ($PdSb_2$) mineral grain measuring 6 by 13 μm has been reported to be in contact with chalcopyrite in a tension-gash vein sample from Ore Body 1. The PGM mineralisation appears to be hydrothermal; no mafic-ultramafic host rock is evident.

Status: No economic significance.

Source: Graham (1978)

Other South Australian occurrences: Gawler Block

Researchers from the Universities of Melbourne and Adelaide have delineated anomalous Ir and Pt levels in sediments from **Lake Acraman,** 220 km west of Port Augusta. Green shales containing thin bands of sand are enriched in Ir, Pt, Au, and Cu. The sediments are 1000 times richer in Ir than surrounding rocks, and copper sulphides in the anomalous sediments are also enriched in Pt. This region is believed to be the site of a Precambrian meteorite impact that was responsible for a blanket of incandescent debris that was ejected some 300 km to the east over a shallow sea covering the area now known as the Flinders Ranges.

Status: No economic significance.

Source: MU Research, September Vol. 4, No. 3. Insert in *The University of Melbourne Gazette,* Spring 1988, Vol. 14, No. 3.

NORTHERN TERRITORY

Pine Creek Geosyncline

(41) Coronation Hill

Location: 220 km southeast of Darwin, in the South Alligator Valley.

Title holders: Broken Hill Pty Co. Ltd (45%), Noranda Pacific Ltd (45%), Norgold Ltd (10%).

Classification: 9(c).

Geology and PGMs: The Coronation Hill Au-PGM deposit is an unusual PGM occurrence in that the mineralisation shows no mafic-ultramafic rock association or obvious derivation from these types of rocks. The Coronation Mine–Hill area consists of a gently folded basinal sequence of interbedded tuff, rhyolite, argillite, and shale of the Coronation Sandstone, that unconformably overlies tightly folded carbonaceous shale, schist, and ferruginous siltstone of the Koolpin Formation. Within and to the west of the Coronation Hill U-Au mine pit, the volcanic-sedimentary rocks are overlain by polymictic conglomerate and poorly sorted sandstone (both part of the Coronation Sandstone). The polymictic rock has been variously interpreted as a vent breccia, agglomerate, or debris-flow conglomerate. The mine area is transected by a series of north and west-trending faults that strike at 45° to the northwesterly trending Pallette and Clear Springs faults. These latter faults define part of the graben structure of the South Alligator River Valley.

The gold and PGM mineralisation is in altered volcanics and clastics of the Coronation Sandstone east and southeast of the old Coronation Hill U-Au open-cut mine. The mineralisation is distinct from the other South

Alligator deposits in that the Au is associated with Pd and Pt, but U and Cu are of very low tenor. The mineralised zone contains altered felsic volcanics, tuff, sandstone, and felsic porphyry of the Coronation Sandstone, carbonaceous shale of the Koolpin Formation, and altered mafic rocks possibly belonging to the Zamu Dolerite. The dominant styles of alteration associated with the fine-grained disseminated Au-PGM mineralisation (invisible to the naked eye) are sericitisation and silicification, with minor hematite, chlorite, and pyrite present. Drill intersections at Coronation Hill represent some of the best Au intersections recently reported in Australia, e.g. DDH 6: 78.4 m @ 12.3 ppm Au. Noranda's June 1988 quarterly report stated a proved-probable reserve, using a 1 ppm cut-off, of 3.41 million tonnes grading 5.58 ppm Au, 0.24 ppm Pt, and 0.82 ppm Pd; and a possible reserve of 2.2 Mt at 6.8 ppm Au, 0.31 ppm Pt, and 0.95 ppm Pd. This indicates an overall resource of 34.1 t Au. The mineralisation is partly oxidised to depths of 80 m, and is open-ended to the south, east, and at depth. Mineralisation persists to at least 300 m vertical depth. There is a positive correlation between Au and the dominant PGMs, Pt and Pd, with the latter metals contributing about 10–20% of the precious metal gross value of the deposit. Of the PGM component, only about 30% is the more valuable PGM, namely Pt. The average grade of 163 samples with > 1 ppm Au, was 0.61 ppm Pt, 1.15 ppm Pd, and 7.72 ppm Au. The Pt/Pd ratios for high Au samples range from 0.30 to 0.88, with nearly 50% of the samples falling in the range 0.50 to 0.65. Preliminary metallurgical studies from a mineralised surface sample have identified native platinum, native palladium, stibiopalladinite, and ?porpezite (a variety of gold which contains up to 10% Pd) in gravity concentrates. Significant drill intersections include:

Hole/interval(m)	*Pt(ppm)*	*Pd(ppm)*	*Au(ppm)*	*Pt/Pd*
CHDDH 6				
12.0–26.0	2.07	4.22	13.78	0.49
CHDDH 8				
48.0–54.0	0.78	1.52	14.52	0.51
98.0–100.0	3.54	6.33	3.63	0.56
CHDDH 10				
96.0–100.0	2.41	4.77	12.57	0.51
CHDDH 11				
30.0–34.0	1.35	3.56	14.25	0.38
CHDDH 17				
90.0–94.0	1.46	4.65	13.20	0.32
CHDDH 18				
142.0–160.0	0.81	2.66	14.01	0.30
CHDDH 23				
18.0–34.0	1.02	3.46	13.69	0.30
CHDDH 29				
70.0–80.0	0.79	2.48	7.54	0.32
CHDDH 53				
352.0–364.0	0.17	0.47	3.91	0.36
CHDDH 94				
188.0–204.0	0.32	1.52	11.95	0.21
CHDDH 103				
298.0–314.0	0.84	2.49	14.78	0.34

Status: Advanced prospect, potential mine, subject to Federal Government policy and results of environmental impact studies.

Source: Noranda Pacific Ltd Quarterly Reports for the periods ending 31 December 1985, 31 March 1986, 30 June 1986, and 30 September 1986; Needham & Stuart-Smith (1987); *Gold Gazette*, 29 February and 15 August 1988.

(42) Coronation Hill area

Location: Palette, El Sherana, El Sherana West, and Rockhole are approximately 7.5 km northwest, 13 km northwest, 13.3 km northwest, and 19 km northwest, respectively, of Coronation Hill.

Title holders: Broken Hill Pty Co. Ltd (45%), Noranda Pacific Ltd (45%), Norgold Ltd (10%).

Classification: ?9(c).

Geology and PGMs: Platinum is associated with Au ± U at a number of localities in the South Alligator Valley region. The precise nature of the metal association is not yet established, but in many cases the Au is separate from the U mineralisation. At Palette, one sample yielded 0.3 ppm Pt, 0.64 ppm Pd, and 0.015 ppm Au, with other grab samples returning Au contents of 20.85 ppm, and 61.0 ppm. Of 250 reconnaissance rock chip samples from El Sherana and El Sherana West, 10 samples exceeded 1.0 ppm Au. Composite chip sampling (2 m intervals) from the walls of the El Sherana West open pit returned average grades of 0.38 ppm Pt, 0.66 ppm Pd, and 6.37 ppm Au. At El Sherana and Palette, the acid volcanics of the El Sherana Group, as seen at Coronation Hill, appear to be absent. Samples from adit dumps and tailings at Rockhole have returned Au levels up to 16 ppm. The proximity, and similar geological settings and metallic associations, suggest these prospects may be similar to Coronation Hill and potentially may host substantial amounts of precious metals. The South Alligator Valley region clearly represents a new PGM province of considerable importance.

Status: Grass roots prospects. Evaluation continuing.

Source: 1987 BHP Gold Mines Limited Offer Document.

(43) Jabiluka

Location: 225 km east of Darwin.

Title holders: Pancontinental Mining Ltd (65%), Texaco Oil Development Co. (35%).

Classification: 9(d).

Geology and PGMs: The Jabiluka unconformity-related uranium deposit (207 000 t of U_3O_8) contains significant Au (average grade of about 10 ppm) and Pd. The host rocks are mainly Early Proterozoic metasediments of the Cahill Formation, and consist of chlorite and/or graphite schist and their brecciated equivalents. An angular unconformity separates these rocks from overlying Middle Proterozoic sandstone and minor volcanic interbeds. Mineralisation consists of open-space-filling pitchblende and uraninite, with lesser disseminated material. Gold is closely associated with U and forms inclusions or veins in uraninite, and occurs with Pb- and Ni-tellurides. Palladium values are associated with the U-Au mineralisation, but the minerals have not been recognised. Chlorite, pyrite, and quartz are commonly associated with the U. It is believed that structural preparation with low-pressure conditions was significant during mineralisation. Various origins have been proposed for the unconformity-related U deposits of the Alligator Rivers region, but recent thermodynamic modelling has shown that oxidised, low-pH and chloride-rich brine solutions, possibly derived in the terrestrial, hematitic sediments of the Middle Proterozoic cover rocks, could be favourable for the transport of Au, U, Pd as chloride complexes. Reduction of the ore-forming solutions by the interaction of the solutions with graphite and/or ferrous iron-bearing biotite may have been a mechanism for ore precipitation. For this model, Nd and Sr isotopic data indicate the U and probably also the Au and Pd at Jabiluka were derived from within the cover rocks.

Status: Mineable resource of U-Au.

Source: Hegge (1977); Wilde & Bloom (1988).

Georgina Basin

(44) Desert Syncline

Location: Near the southern margin of the Georgina Basin, 50 km west of the Queensland-Northern Territory border.

Title holder: Unknown.

Classification: 10.

Geology and PGMs: Drilling in the core of the Desert Syncline has delineated a carbonaceous shale–calcareous siltstone–thin bedded carbonate sequence in the Hay River Formation. Laminated sulphide-bearing carbonaceous shale in the Middle Cambrian lower Hay River Formation (Ordian black shale interval) are reported to contain up to 1.5 ppm Pt, up to 0.8 ppm Pd, and up to 0.3 ppm Au. These precious metals are associated with anomalous concentrations of Ni, Zn, V, Mo, Th, and U.

Note: Recent preliminary check neutron-activation analyses (at the Geology Department, Melbourne University) of three sections of Desert Syncline drill core reported to have strongly anomalous PGM levels (DDH Hay River 11A, depths of 32.75 m, 33.58 m, 49.68 m) have shown that the PGM levels were of background concentrations only. It is likely that the original PGM levels reported are due to analytical error, but further check assaying is required to confirm this.

In many of the PGM occurrences listed in this report, PGM mineralisation appears to be associated with the presence of graphitic units in the mineralised host stratigraphy. This repeated association, evident in Archaean to Palaeozoic rocks, suggests that graphitic sediments may be an important source rock for PGMs, which are later remobilised and concentrated by magmatic-hydrothermal processes.

Status: Unknown.

Source: Shergold (1985).

Other Northern Territory occurrences: Murphy Inlier

Golden Plateau NL have detected anomalous Pt, Pd, and Au values in a stream sediment sampling program in the Calvert Hills 1:250 000 Sheet area, near the Queensland-Northern Territory border. The Murphy Inlier is an Early Proterozoic tectonised province exposed between the Middle Proterozoic McArthur and South Nicholson basins. The source and significance of the anomalies have yet to be evaluated, but Golden Plateau has also located anomalous Au levels in another area that coincides with the tectonised unconformity between the Cliffdale Volcanics and overlying Westmoreland Conglomerate (McArthur Basin).

Status: Prospect being evaluated.

Source: Golden Plateau NL Quarterly Report for the period ending 30 September 1987.

QUEENSLAND

New England Fold Belt

(45) Coolangatta

Location: Beach section between Currumbin Creek and Tweed Heads, immediately north of the New South Wales border.

Title holder: Unknown.

Classification: 2.

Geology and PGMs: Alluvial Pt has been found in beach sands from the mouth of the Tweed River to the mouth of Currumbin Creek, a distance of 10 km. Small flattened Pt grains are associated with osmiridium, gold, cassiterite, monazite, zircon, topaz, magnetite, ilmenite, and tourmaline grains. The source of the Pt is unknown.

Status: Minor economic significance.

Source: Ball (1905); Dunstan (1913).

(46) Gympie and Widgee Mountain

Location: 20 km southeast of Kilkivan, 150 km north-northwest of Brisbane.

Title holder: Valdora Minerals Ltd at Widgee Mountain.

Classification: 9(a, c).

Geology and PGMs: Platinum has been reported in the Lucknow, Alma, Lady Mary and Au-bearing reefs, and Warren Hasting's Shaft at Gympie. The Pt occurs with native gold, galena, and pyrite in quartz veins that intrude slate, tuff, and conglomerate. In the vicinity of the reefs and in Brickfield Gully the Pt also occurs in gold-bearing alluvium; one nugget is reported to have weighed 12.4 g.

Valdora is exploring the Widgee Mountain area, where undifferentiated Palaeozoic serpentinite and metamorphic rocks and Triassic granite comprise the area of interest. Base-metal sulphide occurrences related to faults occur in granite, serpentinite, and metasediments-metavolcanics. Early exploration has shown that several prospects carry significant Au and PGM values.

Status: Minor economic significance.

Source: Dunstan (1913, 1920); Louthean & Seidel (1988).

(47) Wateranga

Location: 80 km northeast of Mundubbera, midway between Brisbane and Rockhampton.

Title holder: Noble Resources NL.

Classification: 5.

Geology and PGMs: Alaskan and placer-type PGM mineralisation is being investigated in the Wateranga, Goondicum, Hawkwood, and Boyne intrusions of the Wateranga district. These small Palaeozoic–Mesozoic complexes occur along major lineaments and consist of norite, olivine gabbro, pyroxenite, and anorthosite. The Wateranga intrusion shows evidence of differentiation and layering with the development of titaniferous magnetite horizons. The Queensland Department of Mines reported PGM values in a surface sample of 9 and 14 ppm in a magnetite-apatite-bearing pyroxenite from the Wateranga Gabbro. Check analyses of old Queensland Mines drill core failed to delineate any PGM mineralisation, but a 51 m wide zone of titaniferous and locally apatite-rich magnetite pyroxenite may correlate with the surface material.

Status: Grass roots prospect.

Source: Louthean & Seidel (1988); *Mining Monthly,* December–January, 1986–87, 25.

(48) Westwood

Location: 30 km southwest of Rockhampton.

Title holders: Southern Pacific Petroleum NL (40%), Central Pacific Minerals NL (40%), Mackenzie-Forbes & Clark (20%).

Classification: 9(a).

Geology and PGMs: Palladium and Au mineralisation occurs in small irregular quartz veins in a fractured dioritic rock at the Westwood Au mines. Associated minerals include malachite, azurite, chalcocite, bornite, covellite, chalcopyrite, hematite, ilmenite, magnetite, arsenopyrite, and millerite. The Pd occurs largely as porpezite (Pd-bearing Au), which forms irregular to subrounded grains up to 0.3 mm and is associated with chalcopyrite and bornite as disseminations and in veins. Highest Pd values reported from the shaft area are 10.94 ppm Pd, 6.12 ppm Au, 15.03 ppm Ag, and 2.2% Cu, and a sample from a small trench 180 m east of the shaft assayed 5.13 ppm Pd, 2.07 ppm Au, 7.83 ppm Ag, and 1.0% Cu.

A number of small (< 30 km^2 in area) gabbroic intrusions in the Westwood district are being evaluated for their PGM potential. These include the Fred Creek, Midgee, Westwood, Windah, Halton, Boogargan, Eulogie Park, and Mount Gerard intrusions. These bodies appear to form part of a 400 km long linear zone of ?Permian mafic intrusions that extends from Westwood southeast to near Gympie. Other intrusions in this zone include Goondicum, Wateranga, Wigton, and Goomboorian near Gympie.

Status: Grass roots prospect.

Source: Shepherd (1956); Ostwald (1979); S. Reeves, M.Sc. studies at Geology Dept, Melbourne University.

Hodgkinson Fold Belt and Laura Basin

(49) Russell and Laura Rivers

Location: Russell River Goldfield is 80 km south-southwest of Cairns; and Laura River 210 km northwest of Cairns.

Title holders: Russell River Goldfield — unknown; Laura River — Gold Copper Exploration Ltd, with a possible ownership component by Paut Resources NL.

Classification: 2.

Geology and PGMs: Alluvial Au and Pt have been reported on terraces between Cooppooroo and Wairambar Creeks, in the Russell River Goldfield. No details are given for the geology except that decomposed basalt up to 12 m thick rests directly on the Au-Pt-bearing washdirt. The Pt forms minute flakes and is subordinate in abundance to the fine-grained Au.

Gold Copper Exploration Ltd has delineated significant amounts of alluvial Au and Pt in the Laura River, 200 km northwest of Cairns. The mineralisation extends over a distance of 15 km in the Laura River, between Laura and the mouth of Kennedy Creek, and also in Mosman River and Kennedy Creek, which are tributaries of the Laura River. Residue concentrates from bulk alluvium samples recorded up to 840.5 ppm Pt and 6.1 ppm Pd, indicating an exceptionally high Pt/Pd ratio. Gold levels averaged 0.30 g/m^3 for the 140 m^3 of bulk samples. In 1987, Gold Copper Exploration Ltd announced that Laura River contained a potential mineable resource of 2.5 million cubic metres of in-situ coarse alluvial auriferous and platiniferous gravels. Potentially mineralised Tertiary sediments occur in the prospective areas, but the original source rocks of the PGMs and Au have yet to be identified.

Status: The Russsell Goldfield occurrence may be of significance given the potential economic status of the Laura River deposits.

Source: Jack (1888); The Stock Exchange Company Review Service–Gold Copper Exploration Ltd, Operations for 1985–86.

Other Queensland occurrences: Mount Isa and Georgetown Blocks

Valdora Minerals Ltd have reported low but geochemically significant Pd values from the **Copper Canyon** prospect, and Pt from the **Mount McCabe** area, 25 km south of Cloncurry. Sporadic Au values between 1–3 ppm have been found from heavy-mineral and rock chip sampling programs. Valdora Minerals Ltd are investigating the **Marimo Slate** of the Mount Isa Block, a Proterozoic formation with carbonaceous shale units for a large-tonnage polymetallic base- and precious-metal deposit, similar to that observed in the Kupferschiefer shales of central Europe.

Strategic Minerals Corporation Ltd (50%) and Golden Plateau NL (50%) have delineated anomalous Pt (up to 0.12 ppm), Pd (up to 0.38 ppm), and Au (up to 0.08 ppm) concentrations in a hydrothermally altered, titanium-rich gabbroic intrusion, at **Prospect Bore,** 80 km south of Croydon in the

Georgetown Block of northern Queensland. The intrusion occurs on the northwest trending Borer River fracture zone. In the region, variably altered gabbros, felsic volcanics, intrusive felsic porphyries, quartzite, and graphite-bearing breccias have been defined by drilling. Other gabbroic intrusions to the south of the Prospect Bore intrusion have also been reported to have anomalous Pt and Pd levels.

Status: Both prospects being evaluated.

Source: Louthean & Seidel (1988).

NEW SOUTH WALES

Broken Hill Block

(50) Mulga Springs

Location: 15 km northeast of Broken Hill.

Title holders: Held by Cyprus Minerals Australia Co.; Delta Gold acquired the right to 100%, and sold half equity rights to Mount Gipps Ltd and 25% to Mumbil Mines Ltd. Cyprus has a 5% net profit interest, with a possible ownership component by Arimco.

Classification: 9(a).

Geology and PGMs: The Mulga Springs prospect occurs in an arcuate serpentinite body that extends for 1.5 km. Platinum-group mineralisation has been delineated in two settings. Platinum, Pd, and Au levels are associated with chalcopyrite-pentlandite-pyrrhotite mineralisation near the basal contact of the serpentinite intrusion, and in remobilised sulphides in the footwall gneissic rocks. Mumbil Mines believes the mineralisation has similarities to the komatiitic volcanic PGM association (e.g. Kambalda) and the intrusive dunite PGM type (e.g. Agnew). Surface sampling at Mulga Springs has obtained Pt concentrations of up to 4 ppm, with sampling at eight other ultramafic bodies yielding up to 2.2 ppm Pt. The best PGM intersections have been obtained at the southern end of the Mulga Springs Complex at depths of 40 to 50 m. Results include: DDH MS 4: 13.06–17.06 m @ 5.1 ppm Pt, 6.9 ppm Pd, and 0.89% Cu, which included 1m @ 18.0 ppm Pt, 24.6 ppm Pd, and 2.5% Cu; DDH MS 24: 26.0–27.0 m @ 2.08 ppm Pt, and 4.44 ppm Pd. Recent drilling indicates the PGM mineralisation is rarely more than 1 m thick, and is patchily distributed. The Mulga Springs prospect illustrates the importance of structural elements in controlling the distribution of hydrothermally remobilised-type PGM mineralisation; delineation of ore grade and tonnage is difficult because of the narrow intervals and patchy distribution of the mineralisation.

Status: Advanced prospect.

Source: Mumbil Mines Annual Report 1985; Mumbil Mines Quarterly Report for the period ending 31 March 1986; Mount Gipps Ltd 1985 Prospectus.

(51) Mulga Springs area

Location: The Round Hill and Mount Darling Creek prospects are 4 km northwest and 10 km southwest respectively of Mulga Springs. The Magnetic Hill occurrences are 22 km southwest of Broken Hill.

Title holders: Delta Gold NL, Mount Gipps Ltd and Cyprus Minerals, with a possible ownership component by Arimco at Round Hill. Mount Gipps (50%), Delta Gold NL (25%), and Mumbil Mines NL (25%) at Mount Darling Creek.

Classification: 9(a).

Geology and PGMs: Surface gossans at Round Hill contain up to 6.2 ppm Pt and 21 ppm Pd. The best drill intersections returned 0.22 ppm Pt and 0.25 ppm Pd between 40.12 and 40.92 m. Drilling failed to locate the down-dip extensions of the mineralisation, and it is believed that the gossans may have resulted from supergene enrichment, or represent narrow discontinuous sulphide pods. The Mount Darling Creek prospect covers two structurally emplaced bodies of serpentinised peridotite that crop out over a 1.5 km strike length. Gossans occur along a contact between the serpentinite and gneissic rocks. Samples from the gossan float and exposures in small prospect pits near the contact between the serpentinite and gneiss yielded Pt and Pd values up to 17.3 ppm and 21.9 ppm, respectively. Drill intersections include 4.2 m @ 0.81 ppm Pt, 1.90 ppm Pd, and 7.6 m @ 0.9 ppm Pt, 1.5 ppm Pd. Anomalous PGM levels are also associated with Cu-Ni mineralisation in ultramafic intrusives at three occurrences near Magnetic Hill, southwest of Broken Hill. The Round Hill, Mulga Springs, Mount Darling and Magnetic Hill PGM prospects occur along a broad northeast-southwest trend coinciding with the Broken Hill base-metal sulphide lode direction, and possibly reflecting a structural control for the emplacement of the serpentinite intrusions.

Status: Grass roots prospect.

Source: Mumbil Mines NL Quarterly Report for the period ending 31 December 1985; Mumbil Mines Annual Report 1985; Barnes (1986).

Girilambone Anticlinorial Zone, Lachlan Fold Belt

(52) Fifield

Location: 80 km northwest of Parkes, in central New South Wales.

Title holders: Separate titled areas held by Helix Resources NL and Noble Resources NL. Farm-in agreements with Chevron Resources at the Owendale intrusion.

Classification: 5, 2(c), and 9(a).

Geology and PGMs: Composite Early Devonian intrusive complexes of the concentric-Alaskan type occur in the Fifield area. These include the Owendale intrusive complex (also called Kelvin Grove intrusion), which is a circular body consisting largely of biotite diorite, diorite, hornblendite, pyroxenite, and serpentinite. The largest body, the Tout intrusive complex (also called Flemington intrusion), measures 5 by 12 km, and contains hornblende melasyenite, hornblende meladiorite, hornblende pyroxenite, quartz-hornblende monzonite, and augite monzonite. The Murga intrusive complex (also called Wanda Bye intrusion) is composed of similar rock types to the other intrusions, with hornblende pyroxenite, augite hornblendite, meladiorite, and quartz diorite predominant.

Drilling along the southern and southeastern margins of the Owendale intrusion delineated high PGM levels in a medium to coarse-grained clinopyroxenite. Significant intersections include, DDH FKD 1: 1.57 m @ 13.19 ppm Pt, 0.90 ppm Pd, and 0.5 ppm Rh, and DDH FKD 6: 0.41 m @ 10.35 ppm Pt, 0.5 ppm Pd. The mineralised clinopyroxenite is low in S (< 0.04%), Se, Te, Sb, Bi, As, and Sn and characterised by high Pt/Pd ratios. The platinum-group minerals generally occur as euhedral, 15 to 30 μm crystals of Fe-platinum coexisting with erlichmanite and Al-F-sphene, fluorite, and trapped in cracks in magnetite, usually near ilmenite. Several platinum-group minerals have been tentatively identified and include platinum-isoferroplatinum, cooperite, geversite, platarsite, sperrylite, stibiopalladinite, and erlichmanite. The zoned form of the intrusions, alkaline character of the rock types, paucity of orthopyroxene, and low Ni and Cr contents suggest the Fifield intrusions do not conform to the layered intrusive-PGM model, but may have affinities with the Alaskan-Ural type deposits. Hydrothermal solutions possibly derived from or driven by late dunite intrusive plugs may have remobilised the PGMs into monomineralic clinopyroxenite zones.

A different style of hardrock PGM mineralisation has been recognised by Helix Resources NL at the Tout intrusion, 10 km southwest of the Owendale intrusion. Anomalous Pd and Pt levels are associated with elevated Cu, Ag, and Au concentrations in pyroxenitic rocks that are traversed by a pervasive fracture zone. The metal association and structural control may indicate that hydrothermal fluids were important in remobilising the disseminated sulphides of magmatic origin into areas with a favourable structural framework. It is probable that similar base-metal sulphide-PGM associations of magmatic-hydrothermal origin will be defined in other intrusions of the Fifield–Nyngan province.

The Fifield district has been the largest producer of Pt in eastern Australia: total Pt and Au production of 640 kg and 197 kg respectively. The Pt has been won from placer deposits that cover an area of 5 by 10 km in the vicinity of the Tout and Murga intrusive complexes. The Pt is usually associated with Au in Tertiary gravels, in buried leads which have redeposited Pt eroded from Tertiary gravels, and in recent alluvium derived from gravels and leads. The two major leads are the Platina and Fifield Leads, although recent drilling has shown that the alluvial Pt also occurs well away from the old mining areas. The Pt and Au occur as coarse grains generally in depressions in the bedrock and in washdirt 10 cm above bedrock. Nuggets range up to 42 g. The Platina Lead has produced 474 kg of Pt at grades of 5 to 13 ppm , and 124 kg of Au at 1.5 ppm to 4.6 ppm. The source of the Pt is believed to be the nearby intrusive complexes. Golden Shamrock Mines Ltd have recently reported an inferred resource of 1.3 million cubic metres of alluvial and eluvial material containing 0.186 ppm Pt and 0.188 ppm Au for the Fifield deep leads.

Status: Advanced prospect.

Source: Suppel & Barron (1986 a, b); Suppel & others (1987); Louthean (1987); Barrie (1965); Helix Resources NL Technical Report 2011 (1987).

(53) Fifield–Bourke region

Location: A 320 km long north–south trending belt extending from Fifield through Nyngan to Bourke.

Title holders: Various joint venture agreements, namely, Helix Resources NL–Chevron Resources; Austplat Minerals NL–Mount Gipps Ltd–Golden Shamrock Mines Ltd; Noble Resources NL–Poseidon; and Platinum Search NL–Lachlan Resources NL.

Classification: ?5.

Geology and PGMs: The Honeybugle Complex, 40 km southwest of Nyngan, is one of several mafic-ultramafic intrusives in a north-northwest-trending belt between Fifield and Bourke, that show similarities to the concentric Alaskan-type intrusions. The Honeybugle Complex comprises a southern composite zone (7 by 18 km) of hornblende pyroxenite, lherzolite, peridotite, and anorthositic norite, while a monotonous suite of hornblendite, monzonite, and meladiorite forms the northern subzone (7 by 8 km). The country rocks are schists and metasediments of the Ordovician Girilambone Group. Sampling of sulphide-bearing peridotite from old dumps has returned up to 0.17 ppm Pt and 0.04 ppm Pd.

Recent trenching and costeaning by a number of companies exploring in the Fifield–Nyngan district suggest that supergene enrichment of Pt in the weathered zone may be an important mineralising mechanism that offers scope for a potential bulk, low-grade, surficial deposit. The irregular distribution and narrow widths of ores typical of Alaskan-type settings necessitates some transporting and concentrating mechanism if a large viable deposit is to be formed. In the Fifield-Nyngan district there has been secondary mobility of the PGMs in the weathered bedrock and overlying in situ soil profile. The soils, which are rarely more than 2 m thick, and the weathered bedrock up to 40 m thick, have anomalous Pt levels, in some cases over extensive widths. companies have reported the following Pt intersections from the weathered zone in intrusions that trend from the south to the north: (1) 58 m @ 0.44 ppm at the Derriwong Complex, 25 km south of Fifield (Platinum Search NL), (2) localised occurrences of up to 0.38 ppm Pt at the Avondale intrusion, 12 km south of Fifield (Helix Resources NL), (3) an 82 m wide zone grading 0.54 ppm at the Owendale Complex, Fifield (Helix Resources NL), (4) at Bulbodney Creek, 8 km southwest of Tottenham, one of the best PGM drill intersections in Australia returned 16 m @ 3.4 ppm, and included 8 m @ 5.2 ppm (Helix Resources NL), (5) 2 m @ 17.5 ppm at the Honeybugle Complex, 40 km southwest of Nyngan (Helix Resources NL), and (6) widespread anomalous levels reported at the Gilgai intrusive, 20 km west of Nyngan (Platinum Search NL). The near-surface and laterally continuous mineralisation may be amenable to open-cut mining, and metallurgical extraction would be a cost efficient gravity separation process since the Pt is largely in the native or alloy form and coarse-grained.

Status: Continuing prospects, of potential economic status.

Source: Hoatson (1981); Helix Resources NL 1986 Prospectus; Helix Resources NL 1987 Annual Report.

Bogan Gate Synclinorial Zone, Lachlan Fold Belt

(54) Coolac–Goobarragandra belt

Location: East of Gundagai.

Title holder: Helix Resources NL.

Classification: 3 and 2(a).

Geology and PGMs: Serpentinite, serpentinised harzburgite, chromitite, and mafic dykes comprise the north-south trending Coolac–Goobarragandra serpentinite belt. Rocks in the belt show evidence of deep-seated deformation and syntectonic recrystallisation. The serpentinite contains small deposits of podiform chromitite with minor Cu. Copper mineralisation is also related to lenses or hydrothermal pipe-like bodies of massive sulphide with intense alteration. Gold and As mineralisation is associated with the abutting Silurian Honeysuckle volcanics and metasediments, and the Young Granodiorite. Platinum has been tentatively identified as inclusions in magnetite grains, and in sulphide ore from the Bogong copper mine; a heavy-mineral stream sediment sample assayed 0.31 ppm Pt.

Status: Evaluation continuing.

Source: Helix Resources NL 1986 Prospectus.

Molong Anticlinorial Zone, Lachlan Fold Belt

(55) Wellington

Location: On the Macquarie River, 50 km southeast of Dubbo.

Title holder: Unknown.

Classification: 2.

Geology and PGMs: Small quantities of Pt, Os, and Pd have been obtained as a by-product of Au dredging on the Macquarie River. Total recorded production during 1950–58 is less than 6.0 kg of Pt concentrate. The source of the Pt is unknown.

Status: Minor economic significance.

Source: Barrie (1965).

New England and Lachlan fold belts

(56) New South Wales coast

Location: Various.

Title holders: Various.

Classification: 2.

Geology and PGMs: Pt has been reported in heavy-mineral beach sands along the New South Wales coast. Approximately 2.8 kg was produced at Ballina and Evans Head on the north coast. Other localities include: (1) Black Head, (2) Brunswick River, (3) Byron Bay, (4) Coffs Harbour, (5) Gerringong, (6) Lake Macquarie, (7) Macleay River, (8) Murrumarang, (9) Seal Rock Bay, (10) Shellharbour, (11) Swansea, (12) Ulladulla, (13) Pambula, and (14) Woodburn. The source and economic significance of the Pt in these areas is unknown.

Status: Minor economic significance.

Source: Flack (1967).

(57) Other New South Wales occurrences

Location: Various.

Title holders: Various. Alluvial Prospectors Ltd at Mount Little Dromedary.

Classification: Various.

Geology and PGMs: Platinum has also been reported from: (1) Aberfoyle River, (2) Condobolin, (3) Cudgegong River, (4) Dubbo, (5) Grafton, (6) Narromine, (7) Ophir, and (8) Turon. The economic significance of these occurrences is unknown.

Alluvial Prospectors Ltd have delineated anomalous Pt, Pd and Au levels at Mount Little Dromedary, near Bawley Point and Goalen Head. Hydrothermally altered shonkinitic rock types, containing pyrite, chalcopyrite and magnetite have been reported from the region.

Status: Unknown.

Source: Flack (1967); Louthean & Seidel (1988).

VICTORIA

Lachlan Fold Belt

(58) Errinundra

Location: At the Boulder Mine, Errinundra, near Club Terrace, eastern Victoria.

Title holders: Golden Shamrock Mines Ltd and Austplat Minerals NL.

Classification: ?9(c).

Geology and PGMs: Gold and Pt-Os mineralisation is associated with quartz veining in slates. This metal association is rare and has not been reported elsewhere in Australia. The Boulder Mine was a small high-grade Au producer in the early 1900s with Au grades ranging from 85 to 142 ppm. Austplat have estimated a potential resource of 150 kg of Au at the mine, with the PGM component yet to be calculated. A sample of quartz submitted to the Victorian Mines Department in the early 1920s assayed 80.4 ppm Pt, 25.6 ppm Os, trace Au, and 17.1 ppm Ag.

Status: Minor economic significance.

Source: Kenny (1937); Louthean (1987); Louthean & Seidel (1988).

(59) Mount Leura

Location: Mount Leura, near Camperdown, western Victoria.

Title holder: Unknown.

Classification: 11.

Geology and PGMs: Spinel lherzolite xenoliths in basanites from the Newer Volcanics at Mount Leura, western Victoria contain pentlandite-pyrrhotite-chalcopyrite inclusions along grain boundaries and within fractures in the silicates. Discrete grains of a Pt-sulphide and Pd-stannide minerals exsolved from the pentlandite have been identified using SEM techniques.

Status: Little economic significance, but indicates that sulphide fluids containing PGMs occur in the upper mantle.

Source: Keays & others (1981b).

(60) Thomson River

Location: 6 km southwest of Walhalla, eastern Victoria.

Title holder: Golden Shamrock Mines Ltd.

Classification: 9(a).

Geology and PGMs: The Thomson River copper mine (also called Coopers Creek) at the southern end of the Walhalla–Woods Point auriferous belt, was one of the first examples of hardrock PGM mining in Australia, albeit as a by-product of Cu-Ni mining. The mineralisation is an example of hydrothermal remobilisation of Au, and to a lesser degree Pt and Pd, from an original magmatic setting. The host rock for the Cu-Ni-Au-Ag-PGM mineralisation is a Devonian hornblendite dyke, faulted, sheared, and hydrothermally altered by carbonate-bearing solutions. Gold was remobilised from the magmatic Cu-Ni sulphides, and redeposited in quartz-carbonate-chalcopyrite-pyrite stringers. It was noted that the PGMs were less mobile than the Au, with 1 to 10 μm sized sperrylite grains occurring along fissures in pyrite grains, and merenskyite situated in chalcopyrite. Intermittent mining since its discovery around 1864 produced about 13 200 t of ore, of which only about 10 kg of Pt was exploited. One of the best drill hole intersections recently reported by Austplat Minerals NL assayed 36 m @ 0.78 ppm Pt, 1.08 ppm Pd, 0.39 ppm Au, 1.25% Cu, 0.2% Ni, and 8.6 ppm Ag. In 1981, CRA Exploration Pty Ltd estimated reserves as 40 000 t averaging 3.2 ppm Pt, 3.6 ppm Pd, 2.7% Cu, 9.5 ppm Ag, and 2.5 ppm Au.

Status: Evaluation of old mine continuing.

Source: Keays & Kirkland (1972); Cochrane (1982); Louthean (1987); Louthean (1988) in *The Bulletin,* 5 April 1988, 136–137.

(61) Thomson River area

Location: East Walhalla copper and platinum mine, 0.8 km east-northeast of Walhalla; Hunts gold mine, Gaffneys Creek; and New Loch Fyne gold mine, 1.5 km southeast of Matlock.

Title holders: Various.

Classification: 9(a).

Geology and PGMs: Anomalous PGM levels have been reported from several Cu mines in the Walhalla–Matlock area. The East Walhalla mine is located in a bulge in a member of the Woods Point Dyke Swarm. Quartz veinlets are developed along faults in a hornblendite and disseminated chalcopyrite occurs in the dyke. A sample from the shaft assayed 3 ppm Pt, 0.6% Cu, 5 ppm Ag, and 1 ppm Au. Surface sampling suggested that Pd may be the dominant PGM. Mineralisation in the Hunt's gold mine occurs in a network of quartz veinlets developed in the Hunt's Diorite Dyke and adjacent fractured silicified sedimentary rocks. Chalcopyrite-bearing samples from the dump near the northern shaft yielded up to 1.0 ppm Pt, 2.9% Cu, 8.3 ppm Ag, and 2.9 ppm Au. Chalcopyrite is associated with hornblende-rich portions of a mafic dyke and quartz veining at the New Loch Fyne gold mine. The most Cu-rich phase of the dyke has concentrations up to 5.6 ppm Pt, 4.9% Cu, 24.9 ppm Ag, and 7.4 ppm Au.

Status: Various.

Source: Cochrane (1982).

(62) Turtons Creek

Location: 10 km north of Foster, southern Victoria.

Title holder: Alluvial Prospectors Ltd.

Classification: ?2(e).

Geology and PGMs: Alluvial Pt and/or Os is associated with Au in the Turtons Creek, Stockyard Creek, and Livingstone Creek region of Foster. The proportion of PGMs to Au is small, the former occurring as crystalline grains or in platy pieces up to 5 mm square. The source of the PGMs may be Cambrian greenstones, or Early Devonian sedimentary rocks in the Waratah Bay–Foster district.

Status: Minor economic significance.

Source: Ferguson (1936); Murray (1876).

(63) Waratah Bay

Location: Near Walkerville in south Gippsland.

Title holder: Alluvial Prospectors Ltd.

Classification: ?2(e).

Geology and PGMs: Cambrian greenstone, basic lava, tuff, chert, shale and dolerite crop out along the coast from Point Grinder to Walkerville, at Waratah Bay. These rocks form the base of the structural high called the Waratah Bay Axis, and are overlain by steeply dipping Early Devonian sandstone, mudstone, shale, and conglomerate of the Liptrap Formation. Structural evidence indicates that the Cambrian greenstones underlie the area extending from the outcropping Waratah Bay greenstones and the Howqua greenstones of central Victoria. Platinum and Os grains have been found in beach sands at Waratah Bay. The source rocks of the PGMs have not been identified; however, the sedimentary rocks of the Liptrap Formation which may have been derived from the Waratah Bay Axis ultramafics may be a potential source. Alternatively the PGMs may be related to auriferous quartz veins in the Foster–Waratah Bay district.

Status: Grass roots prospect.

Source: Alluvial Prospectors Ltd Prospectus 1986.

(64) Other Victorian occurrences

Location: Various.

Title holders: Unknown, except Helix Resources NL at Mount Deddick.

Classification: Various.

Geology and PGMs: Minor platinum-group minerals have been reported from residues from: (1) a crushing plant at Jallukar, west of Ararat; (2) from Glendhu reef at Crowlands; and (3) from alluvium in the Upper Yarra River, east of Melbourne.

Helix Resources NL is exploring the **Mount Deddick** region of the Lachlan Fold Belt in northeastern Victoria, for PGM-Au mineralisation. Previous investigators reported Pt values up to 16.3 ppm associated with base-metal sulphide mineralisation in acid porphyry dykes. Other rock types in the tenement area include Ordovician and Silurian intrusives and various acid volcanics and sediments. Preliminary stream gravel and rock chip sampling detected trace levels of Au, but no PGMs.

Status: Minor economic significance.

Source: Personal communication with personnel at the Victorian Geological Survey; Helix Resources NL Quarterly Report for the period ending 31 March 1988.

TASMANIA

Adamsfield and Dundas Troughs

(65) Adamsfield

Location: Near Lake Gordon, 75 km west of Hobart.

Title holder: Metals Exploration Ltd.

Classification: 2(a) and 3.

Geology and PGMs: The Adamsfield Ultramafic Complex is one of several Cambrian ophiolite-alpine-type intrusions in the Adamsfield and Dundas Troughs. The north-south-trending Adamsfield Complex, which forms an arcuate belt 15 km long and less than 1 km wide, is composed of three major rock types: dunite, olivine orthopyroxenite, and orthopyroxenite. These rocks form an anticlinal structure, with well-developed layering of all rock types in the northern part of the complex, while massive dunite and orthopyroxenite occur in the southern part. The transition from massive to layered rocks is marked by a zone of intense, high temperature deformation, where layers are folded and boudinaged. Adamsfield has been a major producer of Os (production about 480 kg) since its discovery in 1925. Adamsfield, Savage River, Mount Stewart, and Wilson River have collectively produced about 970 kg. Alluvial Os and chromite have been mined from the Main Creek, Adam River, and Football Hill areas in the Adamsfield district. The Os is derived from Late Cambrian sedimentary rocks unconformably overlying the complex as well as directly from the ultramafic rocks. It generally forms irregular grains, 0.5 to 1.5 mm across, but nuggets up to 50 g have been found. Rare Os has been reported in serpentinite but no occurrence has been noted in unaltered ultramafic. Compositionally it is strictly rutheniridosmine and iridosmine. The PGM potential of the Adamsfield region, especially for a small to moderate size alluvial resource, must be regarded as promising. As at Fifield, NSW, greater exploration emphasis should be directed towards the hardrock source of PGMs.

Status: Grass roots prospect.

Source: Varne & Brown (1978); Cabri & Harris (1975); Louthean (1987).

(66) Heazlewood

Location: Near Waratah, in northwest Tasmania.

Title holder: Metals Exploration Ltd.

Classification: 2(b) and 4.

Geology and PGMs: The Heazlewood Complex in western Tasmania is probably the largest intrusion of ophiolitic character in Australia. Covering an area of 30 square kilometres, and at least 5 km in thickness (personal communication, D. Peck, University of Melbourne, 1987), the complex consists of a basal tectonised layered dunite sequence, followed by a layered sequence of harzburgite, dunite, pyroxenite, and gabbro. Quartz-tholeiitic dolerite, pillowed basalt, and high-magnesium andesitic lava occur with the intrusive rocks. PGMs associated with Australian ophiolites are rare, but precious metals occur in tectonised dunite and intensely serpentinised ultramafics of the Heazlewood Complex. Native Pt, laurite, and a possible Os bearing sulphide (?erlichmanite) have been documented with base-metal sulphides and Ni-Fe alloys in chromitite, and native Pt or a Pt-bearing sulphide in a dunite pipe (personal communication, D. Peck). The chromitites occur as lenticular bodies associated with pegmatitic norite in a hybrid zone interpreted to have resulted from magma mixing. Hardrock sources are of low grade, mining being largely restricted to eluvial deposits and stream placers buried by Tertiary lavas. Platinum-group minerals shedding from the Heazlewood Complex have been reported in the nearby Nineteen Mile Creek, Savage River, Whyte River, Long Plain, Brown Plain, Corinna, Mount Stewart, Wilson River, and Huskisson River regions; they are dominantly rutheniridosmine, which contains high Ru levels relative to the Adamsfield iridosmine grains. Associated heavy minerals include gold, gold alloyed with platinum, chromite, picotite, magnetite, pyrrhotite, and pyrite.

Status: Grass roots prospect.

Source: Rubenach (1973); Ford (1981); Mertie (1969).

(67) Serpentine Ridge–Wilson River

Location: In the Wilson River valley, 18 km northwest of Rosebery.

Title holders: Callina NL 80%, other companies 20%.

Classification: 2(b).

Geology and PGMs: Osmiridium and Au occur over a 6 km strike length of the layered dunite, harzburgite portion of the Serpentine Ridge Complex. Wilson River and Rileys Creek were worked for Os and Au in the early 1900s, and are one of the few areas in the world to have generated coarse-grained Os in commercial quantities. One hard-rock Os prospect was discovered during this time. Exploration in 1986 delineated colloidal Au particles and Os in bulk sample grades of up to 0.42 g/ m^3, with the Ir-Os values related to discrete inclusions in chromite grains. Total PGMs (low magnetic separation range) were 7.5 ppm in the Lippy Jane area and 32 ppm from Rileys Creek. A feasibility study begun in 1986 is based on the processing of 250 000 m^3 of alluvium per annum to produce 112 500 t of chromite-PGM concentrate.

Status: Potential economic resource.

Source: Louthean (1987).

Tasman Fold Belt System

(68) Other Tasmanian occurrences

Location: Various.

Title holders: Various.

Classification: 2(a) and/or 2(b).

Geology and PGMs: Os-Ir occurrences have been reported from several places in western Tasmania. These include: (1) Fourteen Mile Creek, on the South Gordon track from Maydena, 25 km east of Adamsfield, where the PGMs are believed to be derived from the Styx River ultramafic complex; (2) Florentine, Weld, Serpentine, and Boyes rivers, in the Gordon district; (3) at the Brookside Mine on the west coast at Corinna; (4) Badger Plains 15 km north of Corinna; (5) Pieman River, Barnes Creek, Riley Creek, Harman River, Keygan Creek, Betts Creek, and Limestone Creek, all in the north Renison Bell district; (6) Dundas district east of Zeehan; (7) Spero River and Birchs Inlet on the west coast; (8) Rocky Bay Harbour, Surprise Bay and Osmiridium Beach near South Cape; and (9) the Salisbury Goldfield near Beaconsfield.

Status: Unknown.

Source: Reid (1921); Ford (1981); Personal communication, K. C. Morrison; 1 : 500 000 Mineral Deposits and Metallogenic Map of Tasmania, Tasmanian Department of Mines, 1988.

RECOMMENDATIONS

Australia has no significant history of PGM mining, processing, or marketing, and thus there is a lack of experience and data with which to assess current and projected future interests in these commodities. The domination of PGM supply by South Africa and the Soviet Union is a negative factor for any possible growth into this market by Australia.

It is the opinion of the authors that a comprehensive database covering a diverse number of topics pertaining to PGM exploration, ore genesis, and reserves in the Australian region, and mining, metallurgy/processing, marketing, and economics worldwide, should be compiled. Because of the interrelationships between these factors and the delineation of ore-grade mineralisation in Australia, it is probable that such a database would contribute to the discovery of PGM deposits in Australia. It should be available to industry, government, and academia, while efforts should be made in the near term to formulate revised economic models and forecasts for Australia's possible entry into the PGM market as a supplier. Variables for which information is lacking, such as Japanese and US interest in potential production, refinery capabilities, etc., should be identified and quantified using an expanding database. These efforts are clearly justified in view of the effect an Australian PGM production industry would have on the national economy, and upon Australia's economic relations with other industrialised nations seeking an expanded supply base.

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APPENDIX 1. COMPOSITIONS OF PGM MINERALS MENTIONED

Mineral	*Ideal formula*	*Mineral*	*Ideal formula*
Anduoite	$RuAs_2$	Millerite	NiS
Arsenopalladinite	$Pd_8As_{2.5}Sb_{0.5}$	Moncheite	$PtTe_2$
Atheneite	$(Pd,Hg)_3As$?	Osmiridium	(Ir,Os)
Braggite	(Pt,Pd)S	Palladoarsenide	Pd_2As
Clausthalite	PbSe	Platarsite	PtAsS
Cooperite	PtS	Platiniridium	(Ir,Pt)
Cubanite	$CuFe_2S_3$	Polydymite	Ni_3S_4
Erlichmanite	OsS_2	Potarite	PdHg
Geversite	$PtSb_2$	Ruarsite	RuAsS
Godlevskite	$(Ni,Fe)_7S_6$	Ruthenarsenite	RuAs
Heazlewoodite	Ni_3S_2	Rutheniridosmine	(Os,Ir,Ru)
Hollingworthite	RhAsS	Sperrylite	$PtAs_2$
Irarsite	IrAsS	Stibiopalladinite	$Pd_{5+x}Sb_{2-x}$?
Iridosmine	(Os,Ir)	Stillwaterite	Pd_8As_3
Isoferroplatinum	Pt_3Fe	Sudburyite	PdSb
Kotulskite	PdTe	Tetraferroplatinum	PtFe
Laurite	RuS_2	Temagamite	Pd_3HgTe_3
Mackinawite	$(Fe,Ni)_{1.1}S$	Tulameenite	Pt_2FeCu
Melonite	$NiTe_2$	Violarite	Ni_2FeS_4
Merenskyite	$PdTe_2$	Vysotskite	PdS
Michenerite	PdBiTe		

APPENDIX 2. ANNUAL OUTPUT OF PLATINUM-GROUP METALS IN AUSTRALIA SINCE PRODUCTION BEGAN IN 1894 (kg)

Sources: Geary & others (1956); Kalix & others (1966); Department of Mines, Western Australia, Annual Reports; *Australian Mineral Industry Annual Review*.

PLATINUM

Year	*NSW*	*WA*	*Vic.*	*Year*	*NSW*	*WA*	*Vic.*	*Year*	*NSW*	*WA*	*Vic.*
1894	32.9	—	—	1926	12.3	—	—	1958	0.7	—	—
1895	12.8	—	—	1927	7.0	—	—	1959	—	—	—
1896	75.6	—	—	1928	11.0	—	—	1960	0.1	—	—
1897	60.9	—	—	1929	4.0	—	—	1961	0.1	—	—
1898	38.7	—	—	1930	4.8	—	—	1962	0.1	—	—
1899	19.8	—	—	1931	8.8	—	—	1963	0.1	—	—
1900	16.4	—	—	1932	10.4	—	—	1964	—	—	—
1901	12.1	—	—	1933	3.5	—	—	1965	—	—	—
1902	11.6	—	—	1934	5.6	—	—	1966	0.4	—	—
1903	16.4	—	—	1935	3.0	—	—	1967	—	—	—
1904	16.6	—	—	1936	1.5	—	—	1968	—	—	—
1905	12.3	—	—	1937	1.4	—	—	1969	—	14.6	—
1906	6.4	—	—	1938	0.2	—	—	1970	—	45.0	—
1907	8.6	—	—	1939	0.2	—	—	1971	—	—	2.5(a)
1908	4.2	—	—	1940	0.4	—	—	1972	—	—	—
1909	13.6	—	—	1941	0.7	—	—	1973	—	7.0	—
1910	10.3	—	—	1942	0.1	—	—	1974	—	60.0	—
1911	14.6	—	5.7	1943	0.1	—	—	1975	—	45.0	—
1912	18.9	—	—	1944	0.1	—	—	1976	—	98.0	—
1913	13.7	—	3.9	1945	0.1	—	—	1977	—	114.9	—
1914	7.6	—	—	1946	—	—	—	1978	—	92.1	—
1915	1.7	—	—	1947	—	—	—	1979	—	85.9	—
1916	2.5	—	—	1948	—	—	—	1980	—	63.6	—
1917	8.0	—	—	1949	—	—	—	1981	—	65.1	—
1918	18.8	—	—	1950	0.5	—	—	1982	—	74.3	—
1919	6.6	—	—	1951	0.3	—	—	1983	—	54.7	—
1920	24.7	—	—	1952	—	—	—	1984	—	66.0	—
1921	7.7	—	—	1953	—	—	—	1985	—	95.0	—
1922	2.5	—	—	1954	0.7	—	—	1986	—	115.0	—
1923	18.2	—	—	1955	0.3	—	—	1987	—	130.0(b)	—
1924	20.0	—	—	1956	0.6	—	—				
1925	17.8	—	—	1957	0.5	—	—	**Total**		**1885.0**(c)	

(a) Reported as 2.5 kg PGMs from Cu concentrates; assumed to be Pt.
(b) Estimated by Coker (1988).
(c) Total also includes minor production from NSW coast.

APPENDIX 2 (continued)

OSMIRIDIUM (Tasmania)

Year	*Output*	*Year*	*Output*	*Year*	*Output*
1910	3.7	1931	39.7	1952	1.6
1911	8.4	1932	24.3	1953	1.8
1912	24.1	1933	17.0	1954	0.5
1913	39.1	1934	15.1	1955	0.7
1914	31.6	1935	7.3	1956	0.8
1915	7.7	1936	8.7	1957	2.0
1916	6.9	1937	18.2	1958	1.3
1917	10.3	1938	5.9	1959	0.1
1918	49.8	1939	8.8	1960	—
1919	51.7	1940	14.4	1961	—
1920	62.3	1941	6.4	1962	—
1921	54.3	1942	4.4	1963	—
1922	36.4	1943	2.8	1964	—
1923	20.9	1944	3.3	1965	—
1924	11.3	1945	3.4	1966	—
1925	104.3	1946	2.9	1967	—
1926	99.3	1947	3.1	1968	0.4
1927	19.6	1948	2.9	1969–77	—
1928	50.4	1949	1.2		
1929	41.0	1950(a)	1.4	**Total**	**964.0**
1930	29.5	1951	1.0		

(a) Platinum concentrates from Macquarie River, NSW, also contained 0.3 kg Os for 1950–58, which is not included in this table.

PALLADIUM (Western Australia)

Year	*Output*	*Year*	*Output*	*Year*	*Output*
1969	10.0	1976	247.0	1983	461.1
1970	—	1977	298.2	1984	523.0
1971	—	1978	229.7	1985	476.0
1972	—	1979	213.9	1986	428.0
1973	23.0	1980	328.2	1987	490.0(b)
1974(a)	164.0	1981	401.1		
1975	108.2	1982	416.1	**Total**	**4817.5**

(a) 5.0 kg Ru also produced in 1974.
(b) Estimated by Coker (1988).

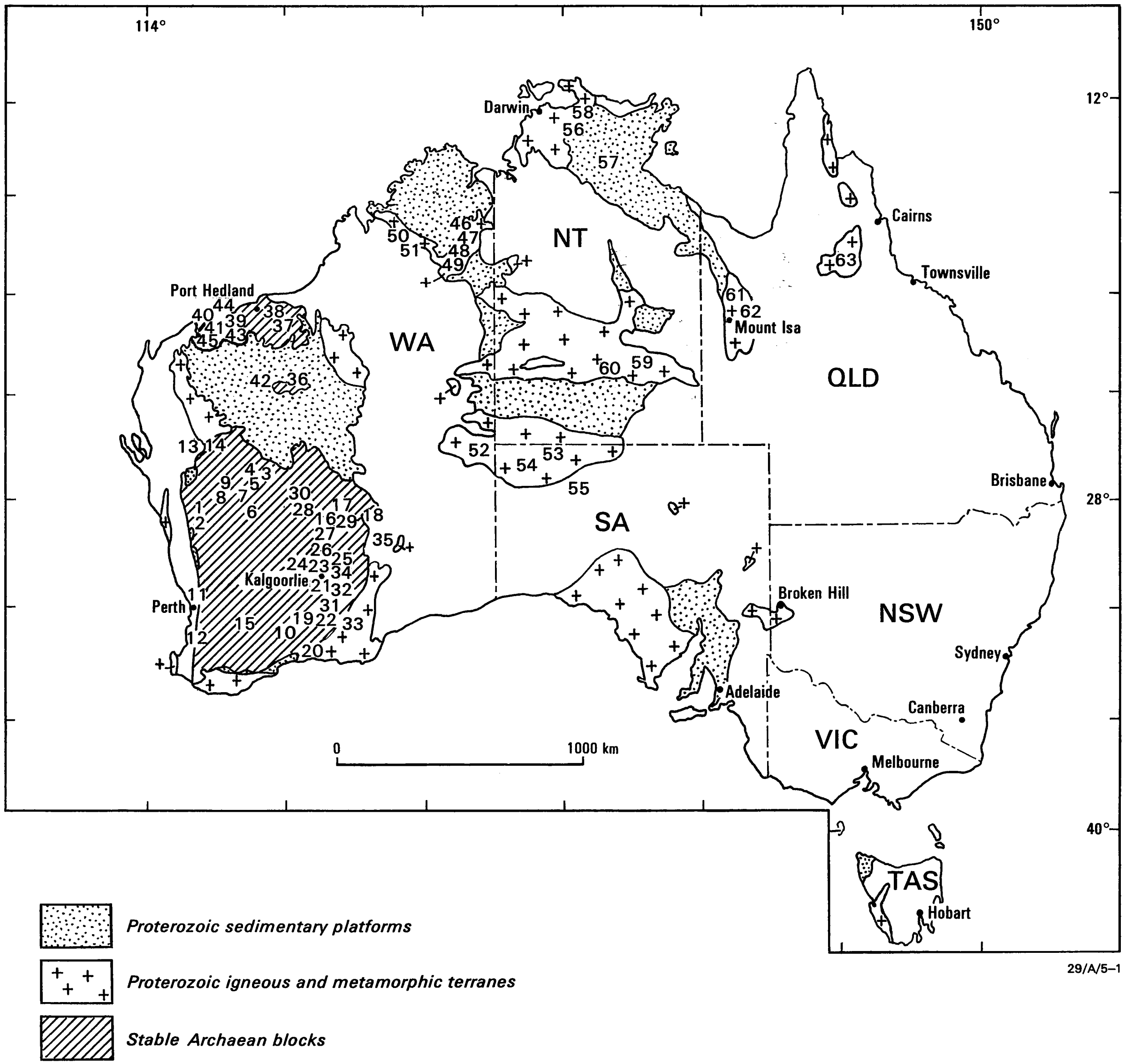

Fig. 16. Distribution of layered Archaean and Proterozoic mafic-ultramafic intrusions in Australia (numbers refer to intrusions listed in Appendix 3).

APPENDIX 3. LAYERED ARCHAEAN AND PROTEROZOIC MAFIC-ULTRAMAFIC INTRUSIONS IN AUSTRALIA

Locality no. in Figure 16	*Name and 1:250 000 Sheet area*	*Areal extent (km)*	*Thickness (m)*	*Form/orientation*	*Main rock types (see footnote)*	*Layering/fabrics*	*Mineralisation*	*Comments*	*References*
WESTERN AUSTRALIA									
Yilgarn Block (Archaean)									
1.	**Wadgingarra Gabbro** Yalgoo, SH/50-2	8 x 3	1300	Folded sill forming S-plunging syncline	GG (top); G, QG, QDD, AN, N, P (base)	Well banded	Cu-quartz veins in adjacent shales	Shearing confined to centre of complex	Muhling & Low (1977)
2.	**Buddadoo Gabbro** Yalgoo, SH/50-2	8.5 x 2.5	2400	Sill trending NNW	Do, GG (top); G, AN, Px (oxide zone); AN, G, Px (bottom)	Rhythmic layering; cumulate features	Vanadiferous-titaniferous magnetite in oxide zone. Oxide zone can be traced for 4.6 km and varies from 1–190 m wide	Also small gabbro and gabbro-pyroxenite-peridotite complexes showing weak layering occur NE and NW of Yalgoo	Baxter (1978)
3.	**Barrambie Intrusion** Sandstone, SG/50-16	21 x 0.5 Discontinuous along strike for 80 km	500 to 1700	Vertical sill, trending largely NW	AN, G, Mt G	Layered, cumulates	Vanadiferous-titaniferous magnetite occurs in both G and AN. Ore reserves of 37.5 Mt @ 0.46% V_2O_5	V potential investigated by Greenstone Investment Pty Ltd and Ferrovanadium Corp. NL. Believed to be genetically similar to complexes at Youanmi, Wyemandoo, Yarrabubba, Gabanintha	Baxter (1978); Tingey (1985)
4.	**Gabanintha** Glengarry, SG/50-12	7 x 0.5	Thin < 500?	Gabbro strikes NNW dipping 50–60°W	Coarse-grained ANG, G	Cumulates	V-magnetite concentrated in ANG. Ore reserves of 8.56 Mt @ 1.24% V_2O_5,15.5% TiO_2	Drilled by Mangore (Aust.) Pty Ltd. G poorly exposed between magnetite bands. Complex extensively faulted, fragmented magnetite-rich zones	Baxter (1978) Elias & others (1982)
5.	**Yarrabubba** Sandstone, SG/50-16	Small	Thin	Gabbro foliationi dips 50–80° E	ANG	Foliated	Single band of V-magnetite 2.0 km long x 1–3 m wide. Inferred reserves of 1.98 Mt @ 1.3% V_2O_5	Drilled by Mangore (Aust.) Pty Ltd. Complex intruded by granite, dolerite dykes, and quartz veins	Baxter (1978)
6.	**Windimurra Intrusion** Youanmi, SH/50-4	Large 85 x 35	Approx. 9 km	Steep-sided, fault bounded tabular body	Large gabbroic intrusion with AN bands	Banded	At least six lenticular magnetite bands, less than 130 m long and 3 m wide. Minor chromitite cycles with PGM levels in ultramafic rocks	V potential reviewed by Mangore (Aust.) Pty Ltd. Nearby Narndee Complex is being investigated by Hunter Resources, BHP Minerals, and other companies	Baxter (1978); Ahmat (1983)
7.	**Nulyercamyer Hill** Cue, SG/50-15	150 km^2		Large intrusive body	Meta G with AN bands	Differentiated	Au in metagabbro		De La Hunty (1973)
8.	**Dalgaranga Hill** Cue, SG/50-15	12+ x 3		Multiple sills	Meta G	Coarse grained, pegmatoidal in places. Ultramafic at base to acidic pegmatoid at top			De La Hunty (1973)

APPENDIX 3. LAYERED ARCHAEAN AND PROTEROZOIC MAFIC-ULTRAMAFIC INTRUSIONS IN AUSTRALIA (continued)

Locality no. in Figure 16	*Name and 1:250 000 Sheet area*	*Areal extent (km)*	*Thickness (m)*	*Form/orientation*	*Main rock types (see footnote)*	*Layering/fabrics*	*Mineralisation*	*Comments*	*References*
9.	**Mount Charles** Cue, SG/50-15	14 x 2			Meta G	Differentiated	Disseminated pyrite up to 2 cm and minor chalcopyrite	Associated pegmatite bodies in gabbro which are possibly related to nearby granites. Also several serpentinite sills (after dunite and/or peridotite intrusives or volcanics) throughout Sheet area, i.e. Moyagee Siding, Scott Bore (minor Ni-sulphides), Lake Austin, Lennonville, Wattagee Well, and large (area) body at Cullculli Hill	De La Hunty (1973)
10.	**Bremer Range** Lake Johnston, SI/51-1	8 x 4		Moderately dipping sill complex trending NW	LG, Px	Layered	Discontinuous magnetite grading 0.23–0.5% V_2O_5 occurs at the base of a pyroxenite phase	Drilled by Unimin Laporte JV. See also Lake Medcalf Complex nearby	Baxter (1978)
11.	**Coates Gabbro** Perth, SH/50-14	1 x 0.5		Gabbro strikes 120°, dipping 70° SW	Three layers: LG, MtG, G	Layered cumulates	Magnetite lenses at core of gabbro. Pyrite, pyrrhotite, pentlandite associated with minor chalcopyrite. Ore reserves of 45 Mt @ 0.51% V_2O_5 (primary ore), + 0.88% V_2O_5 (surface ore)	Drilled by Mangore (Aust.) Pty Ltd. Anomalous Pt and Pd occur with Px and quartzites of Yarawindah Brook mafic-ultramafic complex, 100 km N. of Perth	Baxter (1978)
12.	**Tallanalla** Collie, SI/50-6	Small	Thin	Dyke that strikes 130°, dipping 50–60° SW	G, Do		Lenticular magnetite bands up to 500 x 2 m contain 1.12% V_2O_5, 19.8% TiO_2	Poor surface exposure	Baxter (1978); Wilde & Walker (1982)
13.	**Imagi Well** Byro, SG/50-10	Partly concealed, small intrusion		Regional strike of sequence is 020°, dipping at 80–85° W	Varies from QA to PxA; amphibolite facies		Discontinuous chromite lenses in amphibolite and metanorite	Prospect investigated by EZ Industries, which indicated chromite reserves were too small to warrant detailed drilling	Baxter (1978)
14.	**Taccabba Well** Byro, SG/50-10	Concealed intrusion		NE strike with steep westerly dip	Sequence of felsic and mafic rocks of granulite facies	Banded	Chromite in one thin ultramafic unit can be traced for 1.5 km strike length. Trace pyrite and chalcopyrite associated with Cr horizon	Investigated by Pacminex Pty Ltd, which stated reserves too small to warrant further exploration for chromite. No surface expression, intrusion marked by 20 m of Murchison River alluvium	Baxter (1978); Williams & others (1983)
15.	**West Bendering** Corrigin, SI/50-3	Small			LH, H, S	Layered	Chromite bands in amphibolite-lherzolite member, Cr up to 10%	Drilled by EZ Industries. High-grade metamorphosed complex	Baxter (1978); Chin (1986)
16.	**Red Knob** ((2 km W of Red Knob). Laverton, SH/51-2	3 x 2		Sill, equidimensional in plan	Px to LG	Layered		Also folded ultramafic-mafic complex at Benalla Hill displays some layering	Gower (1976)
17.	**Mt Weld** (two bodies, 3 km NE and 6 km E of Mt Weld). Laverton, SH/51-2	4 x 2.5		Sills	Px to LG	Layered			Gower (1976)

Locality no. in Figure 16	Name and 1:250 000 Sheet area	Areal extent (km)	Thickness (m)	Form/orientation	Main rock types (see footnote)	Layering/fabrics	Mineralisation	Comments	References
18.	**Mt Venn** Rason SH/51-3	12 x 4		S-plunging synformal sill structure	LG, W, N, G (no olivine-bearing rocks)	Rhythmic layering. Gravity stratification of minerals	Cu-Pb in quartz veins in mafic rocks. Ni mineralisation associated with massive sulphides	Transition from ultramafic rocks at northern end of complex to leucogabbros at southern end. Younger discordant granites, faulting common. Being investigated by Hunter Resources Ltd	Louthean (1987)
19.	**Lake Medcalf** (5 km S of Lake Medcalf). Lake Johnston, SI/51-1	Concealed intrusion		Sill at southern end of N-plunging Gordon anticline. East-facing	Ranges from LG to olivine-rich ultramafics	Layered; magnetite concentrations	Magnetite horizon returned Ti-24%, V-0.54%, Cr-145 ppm, Ni-127 ppm, Cu-243 ppm	One of the lowest units of Maggie Hays Formation. Apart from magnetite-rich horizons, complex masked by lateritic cover	Gower & Bunting (1976)
20.	**Desmond** (to the E of Desmond). Ravensthorpe, SI/51-5	17 x 2	Approx. 1600	Conformable sills, flows, plunging synformally towards SE	P, S	Spinifex, porphyritic pillow basalts, skeletal amygdaloidal	Cu, Ag, Au, Magnesite		Thom & others (1977)
21.	**Ora Banda**	23 x 2	2000	Sill	G, N, OPx, P	Phase and cryptic layering well developed in most intrusions but rhythmic layering only present in the larger intrusions, i.e. Ora Banda, Mt Monger, Mission. Cumulate textures well developed and adcumulus growth the dominant form of postcumulus enlargement. Igneous lamination is weakly developed throughout the sills	Most if not all sills envisaged as high-level injections contemporaneous with volcanics		Williams & Hallberg (1972); Williams (1970); Sofoulis (1966)
	Mt Hunt	2 x 0.5	400	”	G, NG, Opx, P				
	Yilmia West	3 x 0.8	750	”	G, NG, N, OPx, P				
	Yilmia East	2 x 0.5	>500	”	OPx, N, NG				
	Carowlyme 1	2.4 x ?	280	”	OPx, N, G				
	Carowlyme 2	2.1 x ?	280	”	NG, G,				
	Carowlyme 3	3.2 x ?	>150	”	OPx, NG, G,				
	Carowlyme 4	0.8 x ?	240	”	OPx, NG, G,				
	Carowlyme 5	0.5 x ?	90	”	G, NG				
	Carowlyme 6	1.1 x ?	210	”	N, NG,				
	Carowlyme 7	0.5 x ?	>300	”	G, NG, N, OPx, P				
	Mt Monger	4.2 x 0.8	920	”	G, NG, N, OPx, P				
	Mt Monger Nth	1.6 x ?	400	”	NG, N, OPx, P				
	Mt Monger Sth	1.6 x ?	750	”	OPx, N, NG				
	Turkey Dam 1	1.1 x ?	300	”	N, NG				
	Turkey Dam 2	1.1 x ?	90	”	N, NG				
	Peters Dam 1	4.5 x ?	900	”	G, NG, N, OPx, P				
	Peters Dam 2	0.6 x ?	300	”	N, NG				
	Seabrook	3.7 x 0.8	430	”	G, NG, N, OPx, P				
	Seabrook East	2.1 x ?	210	”	OPx, N				
	Mission Kalgoorlie, SH/51-9; Kurnalpi, SH/51-10; Widgiemooltha, SH/51-14	10.0 x 2.0	?1900	”	G, NG, N, OPx, P				
22.	**Mt Thirsty** Norseman, SI/51-2	20.0 x ?2.5	Thin	Anticlinal sill	Serpentinised Du + H (base) grading through N, G, to GG (top)		Anomalous Pt and Pd in soils, and Cu-Ni sulphides in mafic-ultramafic rocks	‘Differentiation’ may be structural repetitions rather than multiple intrusions	Louthean (1987)
23.	**Bulong Complex** Kurnalpi, SH/51-10	37 x 4	4600	?Multiple, canoe shaped, consists of a number of sills	Serpentinised P, Du, Px through to G, Do with N intrusions	Layering pronounced. Cumulates, ‘cross-bedding’	Chromite occurs at base of N-intrusions, with Cr zone 15–20 cm wide by 1 km along strike. Cr associated with serpentine	Complex locally bifurcates along strike	Baxter (1978)
24.	**Hampton Complex** Kurnalpi, SH/51-10	42 x 1	600–900	Steeply dipping? sills	Serpentinised P, Du. Not as differentiated as the Bulong Complex			Follows N-S lineament; probably genetically related to Bulong Complex 4 km to east	Williams (1970)

APPENDIX 3. LAYERED ARCHAEAN AND PROTEROZOIC MAFIC-ULTRAMAFIC INTRUSIONS IN AUSTRALIA (continued)

Locality no. in Figure 16	*Name and 1:250 000 Sheet area*	*Areal extent (km)*	*Thickness (m)*	*Form/orientation*	*Main rock types (see footnote)*	*Layering/fabrics*	*Mineralisation*	*Comments*	*References*
25.	**Several small complexes in Morelands Formation and Malgabbie Formation** Kurnalpi, SH/51-10	Largest are Carr Boyd, Bulong, and Hampton complexes		Sills	Variable Px	Layered in most examples			Williams (1970)
26.	**Carr Boyd Complex** Kurnalpi, SH/51-10	75 km^2	2900 (at mine)	Lobate intrusion	T, OAN, Du, B, H, N	Layered, cyclic	PGMs detected in a pyroxenite, and in stream sediment samples from the mine area. Carr Boyd nickel mine: 1.3 Mt @ 1.65% Ni, 0.57% Cu	Bronzite and norite pegmatoids cut the complex	Schultz (1975); Purvis (1972); Louthean (1987)
27.	**Mount Kilkenny** Edjudina, SH/51-6	8 x 5	600	Asymmetric synclinal sill, plunging gently SSW	G, T, Do, serpentinised G	Simply layered, cumulate textured		Duck Hill (2 x 2 km), Mt Boyce (3 x 0.5 km) are smaller layered complexes in Sheet area. Complex at Pyke Hill (4 x 2 km) contains G, Du, S, and is not layered.	Jaques (1976); pers. comm., L. Jaques, BMR
28.	**Numerous mafic, ultramafic sills** Leonora, SH/51-1	Largest are Agnew Bluff (6 x 3 km) and, 10 km to the SE (along strike), Mt Adamson	Thin	Folded sills	P, Px, Du; Px; G, Px	Some cumulate features, layering not pronounced	Local Au and PGMs	Massive sulphides containing PGMs occur near base of a peridotite unit of Boxies Bore intrusion at Heron Well prospect, 20 km S of Leonora; also occur in gossans at Fly Bore, 80 km NNW of Leonora	Louthean (1987)
29.	**Windarra** Laverton, SH/51-2	Individually small (< 1 km), along strike of greenstone belt	< 20–700 +	Series of sills or near-surface intrusives along NNW trending synclinal-anticlinal greenstone belt	Completely altered, metamorphosed, sepentinised sequence probably after Du, P, Px	Metamorphic textures dominate	Windarra Ni-sulphide deposit; reserves 5.4 Mt @ 2.18% Ni, 0.2% Cu	Some Pt, Pd associated with Ni mineralisation: 0.15–0.17ppm Pt and 0.77–2.3ppm Pd	Roberts (1975)
30.	**Perseverance** Sir Samuel, SG/51-13	Small (< 1.5 km) part of Leonora–Wiluna Greenstone Belt	Perseverance ultramafic horizon 20–700 m	Lens	Perseverance ultramafic is a body of Du-S surrounding a core of Du	Metamorphic textures	Perseverance Ni sulphide deposit reserves 33 Mt @ 2.2% Ni	Meta basic-ultrabasic type, typical of greenstone belts of Eastern Goldfields Province	Martin & Allchurch (1975)
Yilgarn Block (?Early Proterozoic)									
31.	**Killaloe Hill** Norseman, SI/51-2	< 2 km^2	600	Sill	OPx, G	Differentiated, with basal OPx		Several smaller (in area) sills along northern edge of Sheet area	Doepel (1973)
32.	**Gnama South** Norseman, SI/51-2	1.5 x 0.7	500	Steeply dipping lenticular bodies	P, H, through to ANPx, ANN	Trace (< 1%) disseminated pyrrhotite–pentlandite–chalcopyrite	Drilling by Newmont Pty Ltd. Numerous other N-P complexes in Gnama–Yardilla district		Tyrwhitt & Orridge (1975)

Locality no. in Figure 16	Name and 1:250 000 Sheet area	Areal extent (km)	Thickness (m)	Form/orientation	Main rock types (see footnote)	Layering/fabrics	Mineralisation	Comments	References
33.	**Jimberlana Intrusion** Norseman, SI/51-2	200 x 0.5 to 2.5	1.5 to 2.5 km	Thin E-W trending 'canoe' shaped intrusive complex	Du, H, B, N, NG, G,	Layered, cumulates	Potential for Ni, Cu, Cr, precious metals, but sections of intrusion have been extensively explored, particularly by WMC Ltd	Close similarities between uppermost pyroxenite layer of Great Dyke of Zimbabwe and equivalent horizon in Jimberlana Intrusion has suggested potential for precious metals. In Great Dyke, precious metals are concentrated over 1–2 m close to boundary between feldspathic cpx-rich and opx-rich cumulates. In Jimberlana Intrusion this horizon usually present about 10 m from top of 160–185 m thick pyroxenite layer that is anomalous in Ni, Cu, Cr, Pd, Pt and Au. Drilling in Dundas Hills area tested equivalent horizon, but Pt, Pd low, rarely exceeding 0.1 ppm. Drilling at Bronzite Ridge for Cr seams at base of dunite-pyroxenite cycles revealed only minor Cr concentrations	Travis (1975); Keays & Campbell (1981)
34.	**Widgiemooltha Dyke Swarm** Kurnalpi, SH/51-10; Southern Cross, SH/50-16; Widgiemooltha, SH/51-14	Numerous thin linear features discontinuous over large strike distances	Thin	Dykes and sills; common strike 070°	Variable Px to GG with QG dominant	Layering generally rare, but has been observed, e.g. Ballona Dyke, S of Stoney Dam	Cu sulphides at Gindalbie Station	Dyke on Gindalbie Station one of the largest, at 4 x 0.5 km. Dykes of this group are ubiquitous throughout Kurnalpi, Southern Cross, Widgiemooltha Sheet areas	Williams (1970); Sofoulis (1966)
Albany–Fraser Province (Early Proterozoic)									
35.	**Salt Creek** Plumridge, SH/51-8	NE extension of large Fraser Complex		Dips steeply SE; facings W, thus overturned	Meta P	Layered on a 1–2cm scale	Discontinuous chromite lenses in basal levels. Traces of Pt with Cr in a layered mafic-felsic complex near Plumridge Lakes	Intrudes high-grade gneissic sequence. Also referred to as Datum Prospect. Chromite tested by Mineral Search & Development Ltd	Baxter (1978); Louthean (1987)
Pilbara Block (Archaean)									
36.	**Coobina Complex** Robertson, SF/51-13	Ridge 10 km long, with equi-dimensional 4 km^2 at western end, and 300 m wide dyke at eastern end		Irregular, tectonically dismembered intrusion. Foliation strikes N and NE, dipping E and SE at 40°, 70°, respectively	Meta S, serpentinised P, AN	Most textures of metamorphic or deformational-shearing origin. Some cumulate (Cr) features evident. Pseudomorphs after cumulus ol, cpx, and ?opx	200+ lenses (5–150 m long, 1–6 m wide) of chromite in the serpentinite. Coobina production 14 650 t @ 42–46% Cr_2O_3	Largest known chromite deposit in Australia (Coobina), but considered only marginally economic. Grade, discontinuity of chromite bands, logistics inhibit marketing. Coobina ultramafic is basal portion of large stratiform body that has been strongly tectonised	Baxter (1978)
37.	**Nobs Well** Yarrie, SF/51-1	Possibly genetically related to Pear Creek intrusion	Thin	Sill	Serpentinised P		Chromite pods near basal contact, with disseminated Cr throughout peridotite up to 3.1% Cr	Intrudes Archaean Duffer Formation. At the Lionel prospect, 25 km N of Nullagine, Cr and PGMs occur with ultramafics	Baxter (1978); Hickman (1983)

APPENDIX 3. LAYERED ARCHAEAN AND PROTEROZOIC MAFIC-ULTRAMAFIC INTRUSIONS IN AUSTRALIA (continued)

Locality no. in Figure 16	*Name and 1:250 000 Sheet area*	*Areal extent (km)*	*Thickness (m)*	*Form/orientation*	*Main rock types (see footnote)*	*Layering/fabrics*	*Mineralisation*	*Comments*	*References*
38.	**Pear Creek** Port Hedland, SF/50-4	Part of 70 km long intrusion extending from Pear Creek to Bamboo Creek	Thin	Sill	Serpentinised P	Tectonised intrusion	Chromite locally concentrated and disseminated in peridotite	Deposit has been drilled. Serpentinite intrudes a fault line separating Archaean Gorge Creek and Warrawoona Groups	Baxter (1978); Hickman (1983)
39.	**Balla Balla Complex** Roebourne, ST/50-3	15 km strike length. Poorly exposed	1 to 2 km	Sequence strikes 080–100°, dipping 25–30° N	Saussuritised meta G sequence, ranging from LG to AN		Ore reserves estimated at 1.94 Mt @ 0.75% V_2O_5; V contained in numerous thin (0.5 m) magnetite bands	Reviewed by Mangore (Aust). Pty Ltd. Deposits individually small. Mount Dove Complex, 65 km southwest of Port Hedland, has anomalous PGM levels	Baxter (1978); Louthean & Seidel (1988)
40.	**West Andover** Roebourne, SF/50-3	20 x 5	2000	Foliation strikes 080° dipping 50–65° N	Saussuritised meta G, S, Du, Px, hybrid rocks	Cumulates	17 lenses (200 x 2 m) of titaniferous (V) magnetite are of marginal economic interest. Weak PGM levels	Deposit reviewed by Mangore (Aust.) Pty Ltd and Garrick Agnew Pty Ltd, and currently being explored by Greater Pacific Investments Ltd JV for PGMs. Part of Andover Complex (No. 44)	Baxter (1978)
41.	**George Sherlock** Roebourne, SF/50-3	6 x 1		Elongated ENE trending sill(?)	N, G, S	Layered, cumulates	Trace chalcopyrite, pyrrhotite, pyrite in norite	No exposure; complex masked by 50 m alluvium. Sherlock Bay Ni-Cu deposit of similar setting (but exposed) is 6 km east	Miller & Smith (1975)
42.	**Prairie Downs** Newman, SF/50-16	5 x 3		Fairly equidimensional	Meta G	Moderately layered		Fault-bounded on southern margin. Serpentinite lenses in vicinity of complex	Daniels & MacLeod (1965)
43.	**Mt Langenbeck–Mt Satirist** Pyramid, SF/50-7	17 x 15	350	Elliptical domal folded sill structure	OPx, G, Do, overlying P	Layered	Mons Cupri and Whim Creek Cu-Zn deposits 30 km to NW	Potential V, Cr, Ni in magnetite-rich rocks. Ultramafic rocks intruded during sedimentation. Complex largely masked by alluvium. Extensive Proterozoic dolerites. Potential for Noril'sk-type PGM mineralisation?	Miller (1975)
44.	**Andover** Roebourne, SF/50-3	20 x 5	2000	Tectonically dissected sill(s)	S, G, AN, P, Du, amphibolite	Cyclicity of 100–200 m Du, P, Px, G, AN	Disseminated chromite occurs with ultramafic rocks. Andover V deposits are at western end of complex. Andover Pb deposit is at southern contact of intrusion with granites	Also Radio Hill, Gidley Gabbro-Granophyre, Mt Sholl and Dingo complexes of Karratha district. Most intrusions have weakly anomalous PGM levels of up to 1 ppm associated with Ni-Cu sulphides	Hickman (1983)

Locality no. in Figure 16	Name and 1:250 000 Sheet area	Areal extent (km)	Thickness (m)	Form/orientation	Main rock types (see footnote)	Layering/fabrics	Mineralisation	Comments	References
45.	**Munni Munni Complex** Yarraloola, SF/50-6	25 x 9	3630+ gabbroic zone overlying 1850 thick ultramafic zone	Tilted basinal intrusion, that dips 30 to 50° S, SE	P, W, CPx, OPx, G, N,	Layered rhythmic and cryptic lamination; cumulus and slump textures	Whundo Cu-Zn deposit, 10 km along a NE strike from the complex. Pt and Pd enriched horizon at contact of ultramafic and gabbroic zones. Hunter Resources Ltd have announced a 20 to 30 Mt resource grading 2.9 ppm Pt + Pd + Au, 0.3% Cu, 0.2% Ni to a depth of 500 m. Mineralised horizon can be traced for 12 km strike length. Minor chromitites with Opx	Similarities to Bushveld, Great Dyke, and Stillwater complexes. Has a strong magnetic signature which extends for 16 km under Fortescue Group cover. Similar, smaller intrusion at Toorare Pool. Hunter Resources is continuing evaluation of Munni Munni. To mid-1988, 56 diamond drill holes had been completed, 53 of which had intersected the mineralised horizon	Hoatson & Keays (1987); Hoatson & England (1986); Williams & others (in press)
Halls Creek Mobile Zone (Early Proterozoic)									
46.	**Panton Sill** Dixon Range, SE/52-6	11 x 3.2	1500	Southerly plunging syncline with 50° dip on western flank, 70° dip on eastern flank	Alice Downs Ultrabasics and McIntosh Gabbro. Broadly layered and consists of altered P and temolite-chlorite schist at base, which grades into alternating bands of uralitised G and LG at top	Bands range from 30 to 90 m thick	Peridotites contain disseminated chromite (with Pt values up to 3 ppm), primary segregated bands 15 cm wide over 1.5 km, and secondary veins. Chromite euhedral, generally pentagonal, rarely embayed. Also Ni, Cu sulphides are associated with the Cr-Pt. Sperrylite forms inclusions in chromite and occurs in chlorite-rich matrix	Alice Downs Ultrabasics are probably differentiates of the McIntosh Gabbro. Other intrusions near Panton Sill include: Toby, Springvale, Spring, Violet, Sally Malay, and Salt Lick Creek sills. Most are under review for PGMs	Gemuts (1971); Hamlyn (1977)
47.	**McIntosh Sill** Dixon Range, SE/52-6	14.5 x 5	6 km	Sill folded into a basin with dips 10–75° inwards	Hypersthene T, ON (at top), passing through G + OG, to OG (at base)	Layering poorly preserved; some rhythmic layering indicated by single or multiple layers of olivine		Best preserved example of a differentiated basic intrusion in the Lamboo Complex. Several large McIntosh Gabbro complexes exist NE of Halls Creek in the Dixon Range Sheet area, but few have associated Alice Downs Ultrabasics which appear critical for Pt, Cr mineralisation. Also present in Gordon Downs Sheet area, SE/52–10, and Lissadell Sheet area, SE/52-2	Gemuts (1971); Mathison & Hamlyn (1987); Hamlyn (1977)
48.	**Armanda Sill** Dixon Range, SE/52-6	10 x 3.2		Elliptical composite sill with anticlinal structure	Uralitised G, Do	Rhythmic banding defined by MG and LG		AN, P, G occur along the western margin (steep) and at the southern end of the McIntosh Sill	Gemuts (1971)

APPENDIX 3. LAYERED ARCHAEAN AND PROTEROZOIC MAFIC-ULTRAMAFIC INTRUSIONS IN AUSTRALIA (continued)

Locality no. in Figure 16	*Name and 1:250 000 Sheet area*	*Areal extent (km)*	*Thickness (m)*	*Form/orientation*	*Main rock types (see footnote)*	*Layering/fabrics*	*Mineralisation*	*Comments*	*References*
49.	**Lamboo Homestead** Mount Ramsay, SE/52-9	10 x 6.5		Elliptical body with southern margin dipping 60° S	Alice Downs Ultrabasics with McIntosh Gabbro surrounding. Ultrabasic now composed of decussate serpentine after ol and px	Rhythmic banding marked by chromite-rich (15 cm x 50 m), chromite-poor bands	Cr with low levels of PGMs reported by Hunter Resources Ltd over wide thicknesses of peridotite rock types (i.e. 23 m @ 0.11 ppm Pt and 0.30 ppm Pd)	Deposit (as probably with Panton Sill) too small, and low in grade, and contains too high a proportion of iron to be an economic source of chromium on its own, i.e. needs associated precious metals. Also 3 large (in area) bodies of McIntosh Gabbro 11 x 6, 18 x 4, 11 x 5 km, respectively 34, 40, 54 km NW of Louisa Downs Hstd. PGMs and Cr occur at the Eastmans Bore–Louisa Downs intrusion	Gemuts (1971); Hunter Resources Quarterly Reports, 1987
King Leopold Mobile Zone (Early Proterozoic)									
50.	**Wombarella Quartz Gabbro** Lennard River, SE/51-8	7 x 3	650	Layered lopolith with 45–55° inward dips	OPx, and biotite-qtz G, and qtz-N with basic tonalite	Large and small scale banding		Part of Lamboo Complex; probably comagmatic with McIntosh Gabbro and Alice Downs Ultrabasics. Quartz gabbro and tonalite show evidence of two-magma relationships. Chemistry appears unfavourable for PGMs	Derrick & Playford (1973)
Kimberley Basin									
51.	**Hart Dolerite, Woodward Dolerite** Lissadell, SE/52-2; Lansdowne, SE/52-5; Mount Ramsay, SE/52-9	Hart extensive, underlying 160 000 km^2 of the Kimberley Basin; Woodward mostly in parts of Mobile Zone	Woodward < 600 m. Hart generally < 100 m, but may form composite sills up to 3000 m (K.A. Plumb, (BMR) pers. comm.)	Dykes and sills	Tholeiitic: G, GG, Do, OD, QD, DD	Largely homogeneous; weak differentiation features	Dry Creek Mining NL consider Woodward Dolerite the primary source of Au at Dry Creek alluvial mine	Hart dolerite is one of the major dolerite bodies of the world	Dow & Gemuts (1969); Gemuts (1971); *Gold Gazette* 29 August, 1988
WESTERN AUSTRALIA, NORTHERN TERRITORY, SOUTH AUSTRALIA									
Musgrave Block (Middle–Late Proterozoic)									
52.	**Intrusions of the Giles Complex:**								
	Bell Rock	33 x 8	6000	70–80° SW dip	OAN, T	Widespread			Nesbitt &
	Blackstone	35 x 4	4000	70–80° S	OAN, T, HT, ON	layering includes	V in magnetite		Talbot
	Cavenagh	18 x 18	1800	0–15° SE	OAN, T	cryptic, rhythmic,			(1966);
	Claude Hills	18 x 0.5		?steep	Px	and igneous	Nickeliferous ochre		Nesbitt &
	N. Mt Davies	6 x 2	2000	80° N	OMG	lamination.		Folded	others
	S. Mt Davies	15 x 4	4200	70–80° N	Px, OG, AN	Rhythmic layering		Overturned, top exposed	(1970)
	Ewarara	4 x 2	300	20–30° S	OOPx, OPx	common on both		Base exposed, top removed	
	Gosse Pile	6 x 2		60° S	OOPx, OPx, H	small and large			

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	Hinkley	23 x 4	3000	var. steep	OG, ON, OHG	scales (up to 30 m thick by	Nickeliferous ochre		
	Jameson	19 x 4	5500	30° SW	OG, LH, T, HG, AN	several km). Small-scale	Several Ti-V-bearing magnetite bands		
	Michael Hills	22 x 6	6400	var. low.	LG, HG, AN, Px	layering has		Folded	
	Morgan	6 x 4		?	AN, OG	graded bedding,		No layering observed	
	Murray	6 x 4		var. steep	G	cut-and-fill,			
	Walter Hill	8 x 4	?6000	80° NE	OG, Px, H,	ripple corrugations,			
	Wingellina	16 x 2	1700	60°	Px	slump structures, etc. A mylonite	Nickeliferous ochre grading 6 Mt@ 1.32% Ni	Also called N. Hinkley	
	Mount West	6 x 2	1500	45° W	CPx, OG	layering is locally prominent.		Resembles Critical Zone of S. Mt Davies	
	Cooper, SG/52-10; Scott, SG/52-6			Most form large lopolithic sheets, i.e. Hinkley. Together cover area of at least 12 000 km^2, aligned near east–west		Intrusions in western part of complex emplaced at higher level than those of central zone, which were intruded into lower crust		Central and western intrusions of Giles Complex being investigated by BMR-GSWA-Melb. Univ.	
53.	**Musgrave Complex: possible eastern extension of Giles Complex–Mount Woodroffe Norite** Woodroffe, SG/52-12	215 km^2	3650+	Layered sill dipping 35° SE	N, Minor DD, AN, Px, ON	Macroscopic layering, due to difference in grainsize and px content, well developed. No sedimentary structures	Trace chalcopyrite in norite at Trudinger Pass. SADME collected stream sediment samples over the norite intrusions and tested for Cu, Pb, Zn, Co, Ni, Cr, V, Mn, Pt, Os, Ir, with no anomalous results, although detection limits may have been too high	Some intrusions covered by alluvium. Probably equivalent to Giles Complex	
54.	**Caroline (near Palpatjaranya)** Woodroffe, SG52-12	18 x 8		Concordant non-exposed intrusion of Giles Complex type?	AN, LT, N	Layered		Drilled by SADME. Also three small norite intrusions (plug, sill, dyke) in the Lungley Gully area, and three phases of thin dolerite dykes throughout Sheet area	
55.	**Gabbroic dykes** Everard, SG/53-13	4 x thin	100	Sub-vertical	Massive G, ON	Massive		Postdate Giles Complex	Krieg (1973)
NORTHERN TERRITORY									
Pine Creek Geosyncline (Early–Middle Proterozoic)									
56.	**Zamu Dolerite** Mt Evelyn, SD/53-5; Pine Creek, SD/52-8	20 x 5 (largest)	300	Sills commonly striking NW	Do, G, DD, QDD, amphibolite, syenite	Minor differentiation	Minor Pb	Generally metamorphosed to amphibolite facies. Conceivably prospective for Noril'sk-type PGM mineralisation	Ferguson & Needham (1978)
57.	**Several unnamed linear bodies** Hodgson Downs, SD/53-14; Roper River; SD/53-11; Urapunga, SD/53-10; Mount Marumba, SD/53-6	40 x 15 (largest)	60–300	Folded sills and lenses	Do	Uniform composition but variable texture		Intrude upper part of Roper Group (Middle Proterozoic). Widespread in Urapunga Sheet area where sills total 300 m thickness. Conceivably prospective for Noril'sk-type PGM mineralisation	Roberts & Plumb (1965); Dunn (1963)

APPENDIX 3. LAYERED ARCHAEAN AND PROTEROZOIC MAFIC-ULTRAMAFIC INTRUSIONS IN AUSTRALIA (continued)

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58.	**Oenpelli Dolerite** Alligator River, SD/53-1 Mt Evelyn, SD/53-5	35 x 15 (largest)	250	Lopoliths, some thin dykes. At least five sheets	OD, G, QD, granophyric Do, syenite	Symmetrically differentiated layers of OD, minor felsic types and cross-cutting gabbroic pegmatites. Minor rhythmic layering (in thicker OD) of cumulus ol + plag.		Extends over 20 000 km^2, including subsurface. Tholeiitic. Similar to Jurassic sills of Tasmania? Conceivably prospective for Noril'sk-type PGM mineralisation	Stuart-Smith & Ferguson (1978)
	Arunta Block (Early–Late Proterozoic)								
59.	**Attutra Metagabbro** Several small bodies near Jervois Range. Huckitta, SF/53-11	5 x 2 (largest)		Sills and stocks	G, Mt, N	Extensively altered to amphibole and chlorite. Rare holocrystalline textures preserved	Cu in quartz veins. Traces of V (1.1%) and Cu (1.4%) in small magnetite bodies in metagabbro	Union Corporation Aust. Pty Ltd found magnetite bodies were too small to warrant further exploration. Probably similar to gabbroic intrusions of Davenport Range, which generally lack internal differentiation and are fairly massive	Freeman (1986)
60.	**Mordor Complex** Alice Springs, SF/53-14	6 (diam.)		Sub-circular with later plug-like intrusions	Du, LH, Px, shonkinite, monzonite, syenite, pegmatite	Coarse cumulate textures		Complex contains potassic ultramafics to feldspar-rich rocks	Langworthy & Black (1978)
	QUEENSLAND								
	Mt Isa Block (Early to Late Proterozoic)								
61.	**Unnamed** Duchess SF/54-6	Various		Swarms of dykes, sills	Meta-Do, G, amphibolite	?Weakly differentiated	Trace sulphides	Gabbroic complex showing ?weak differentiation features; present around Mount Ulo–Selwyn, SE of Mount Isa	D. Blake (BMR), pers. comm.
62.	**Lunch Creek Gabbro** Cloncurry, SF/54-2	7 km^2	500	Sills	G, DD	Some layering; fractionated and metamorphosed		Gabbro contains rare olivine, abundant orthopyroxene, clinopyroxene, biotite, and plagioclase, and represents a subalkaline, hydrous tholeiitic, or calcalkaline type magma. Fractionated from picrite to coarse pegmatoidal leucogabbro	Blake (1987)
	Georgetown Block (Early Proterozoic to Palaeozoic)								
63.	**Sandalwood Serpentinite, Gray Creek Complex, Boiler Gully Complex** Einasleigh, SE/55-9 Atherton, SE/55-5	Various (small)		Lenticular sills	S, G, CPx, P, WH	Relict igneous textures rare, with banded metamorphic fabrics common. Serpentinisation intense	Ni, Au	Occur along narrow belt, 115 km long near the eastern faulted margin of the Georgetown Block. The mode of emplacement of the intrusions (tectonic, or in-situ crystallisation) is largely unknown	Arnold & Rubenach (1976)

AN — anorthosite; ANG — anorthositic gabbro; ANN — anorthositic norite; ANPx — anorthositic pyroxenite; AOG — anorthositic olivine gabbro; B — bronzitite; CPx — clinopyroxenite; Do — dolerite; Du — dunite; DD — diorite; G — gabbro; GG — granophyre; H — harzburgite; HG — hypersthene gabbro; HT — hypersthene troctolite; LG — leucogabbro; LH — lherzolite; LT — leucotroctolite; Mt — magnetite; MG — melagabbro; N — norite; NG — norite-gabbro; OAN — olivine anorthosite; OD — olivine dolerite; OG — olivine gabbro; OHG — olivine-hypersthene gabbro; OMG — olivine melagabbro; ON — olivine norite; OOPx — olivine orthopyroxenite; OPx — orthopyroxenite; P — peridotite; Px — pyroxenite; PxA — pyroxene amphibolite; QA — quartz amphibolite; QDD — quartz diorite; QD — quartz dolerite; QG — quartz gabbro; S — serpentinite; SD — serpentinised dunite; T — troctolite; W — websterite; WH — wehrlite.

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