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Key trends in the resource sustainability of platinum group elements

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ABSTRACT

Platinum group elements (PGEs) are increasingly used in a variety of environmentally-related technologies, such as chemical process catalysts, catalytic converters for vehicle exhaust control, hydrogen fuel cells, electronic components, and a variety of specialty medical uses, amongst others — almost all of which have strong expected growth to meet environmental and technological challenges this century. Economic geologists have been arguing on the case of abundant geologic resources of PGEs for some time while others still raise concerns about long-term supply — yet there remains no detailed analysis of formally reported mineral resources and key trends in the PGEs sector. This paper presents such a detailed review of the PGEs sector, including detailed mine production statistics and mineral resources by principal ore types, providing an authoritative case study on the resource sustainability for a group of elements which are uniquely concentrated in a select few regions of the earth. The methodology, compiled data sets and trends provide strong assurance on the contribution that PGEs can make to the key sustainability and technology challenges of the 21st century such as energy and pollution control.

1. Introduction

Platinum group elements (PGEs) possess a range of unique chemical and physical properties. PGEs are increasingly finding important uses in a variety of environmentally-related technologies, such as chemical process catalysts (especially oil refineries), catalytic converters for vehicle exhaust control, hydrogen fuel cells, electronic components, specialty medical uses, jewellery or investment. Given the need to expand almost all of these uses to meet environmental and technological challenges this century, demand growth for PGEs can reasonably be expected to be sustained long into the future.

Global production of PGEs are dominated by South Africa due to their large resources in the Bushveld Complex, followed by Russia's Noril'sk–Talnakh field, with other countries such as Canada, Zimbabwe, and the United States play a minor but important role. Despite economic geologists claiming for some time that there are abundant PGE resources for many decades (e.g. Cawthorn, 1999; Hunt and Lever, 1969; Von Gruenewaldt, 1977), concerns are still being raised about the long-term ability to supply PGEs to meet likely future demands (e.g. Gordon et al., 2006; Yang, 2009).

Consequently, there is a clear need to provide a more convincing case of the extent of economic PGE resources to facilitate a more informed view of the likely long-term supply potential, especially with respect to key trends such as ore types, ore grades, mining depths and so on, as these can all affect extraction costs and thus the classification of mineral resources as economic or otherwise. Such a case can also inform government and industry policy on social, economic and environmental fronts (i.e. the three traditional pillars of sustainability), especially in planning long-term futures for the PGEs and their uses.

This paper presents such a detailed review of the PGE sector, updating previous work (see Mudd, 2010b). A range of comprehensive data sets are compiled, focussing on annual production statistics and mineral resources by principal ore types. The methodology adopted, while straight forward for economic geologists, provides a more persuasive case for the minimum potential PGE resources which are reasonably available for mining, including key trends which will govern the classification of economic mineral resources into the future. Given the concerns over possible future PGE supply shortages, the paper provides an authoritative case study on the resource sustainability for a group of elements which are uniquely concentrated in a select few regions of the earth.

2. Brief review of the economic geology of platinum group elements

2.1. Principal ore types

The platinum group elements comprise platinum (Pt), iridium (Ir), osmium (Os), palladium (Pd), rhodium (Rh) and ruthenium (Ru), with gold (Au) often present in PGE ores at low grades. There are broadly considered four economic types of PGE ores (Cabri, 2002; Vermaak, 1995):

- *Stratiform deposits* — where PGEs occur in large Precambrian mafic to ultramafic layered intrusions; major examples include the

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Merensky, Platreef and Upper Group 2 (UG2) reefs of the Bushveld Complex, South Africa, the Great Dyke reefs in Zimbabwe and the JM reef of the Stillwater Complex in Montana, United States of America (USA). These are usually considered primary due to their size (~10–1000 Mt) and grade (~3–23 g/t PGEs, ~0.1–0.5% Ni + Cu).
- *Norite intrusions* — where meteoritic impact is considered to have been instrumental in allowing PGE emplacement; the major example is the Sudbury Irruptive Complex in Ontario, Canada (~10–1000 Mt, 1–3 g/t PGEs, ~2–3% Ni + Cu).
- *Ni–Cu bearing sills* — sub-volcanic sills related to deep seated structural lineaments; with examples being the Noril'sk–Talnakh District (or Taimyr Peninsula) in Russia and the Jinchuan deposits in China (~10–1000 Mt, 2–15 g/t PGEs, ~3–5% Ni + Cu).
- *Placer deposits* — alluvial sedimentary deposits containing coarse PGEs (mainly Pt; generally very small in scale); the best examples are the Urals in southern Russia and at Kondyor in Russia's Far East.

The individual element grades are also critical, due to the different prices for each element. In 2010, the average Pt price was US$1611/oz, Pd was US$526/oz, Rh was US$2458/oz, Ru was US$197/oz, and Ir was US$642/oz (Butler, 2011). Some ore types are dominantly Pt (e.g. Bushveld), while others are Pd-dominant (e.g. Stillwater, most Ni–Cu-PGE deposits). For Ni–Cu-PGE projects, the relative prices of Ni and Cu are also crucial. The PGE ratios and Ni–Cu grades are therefore quite important in the economics of different PGE projects.

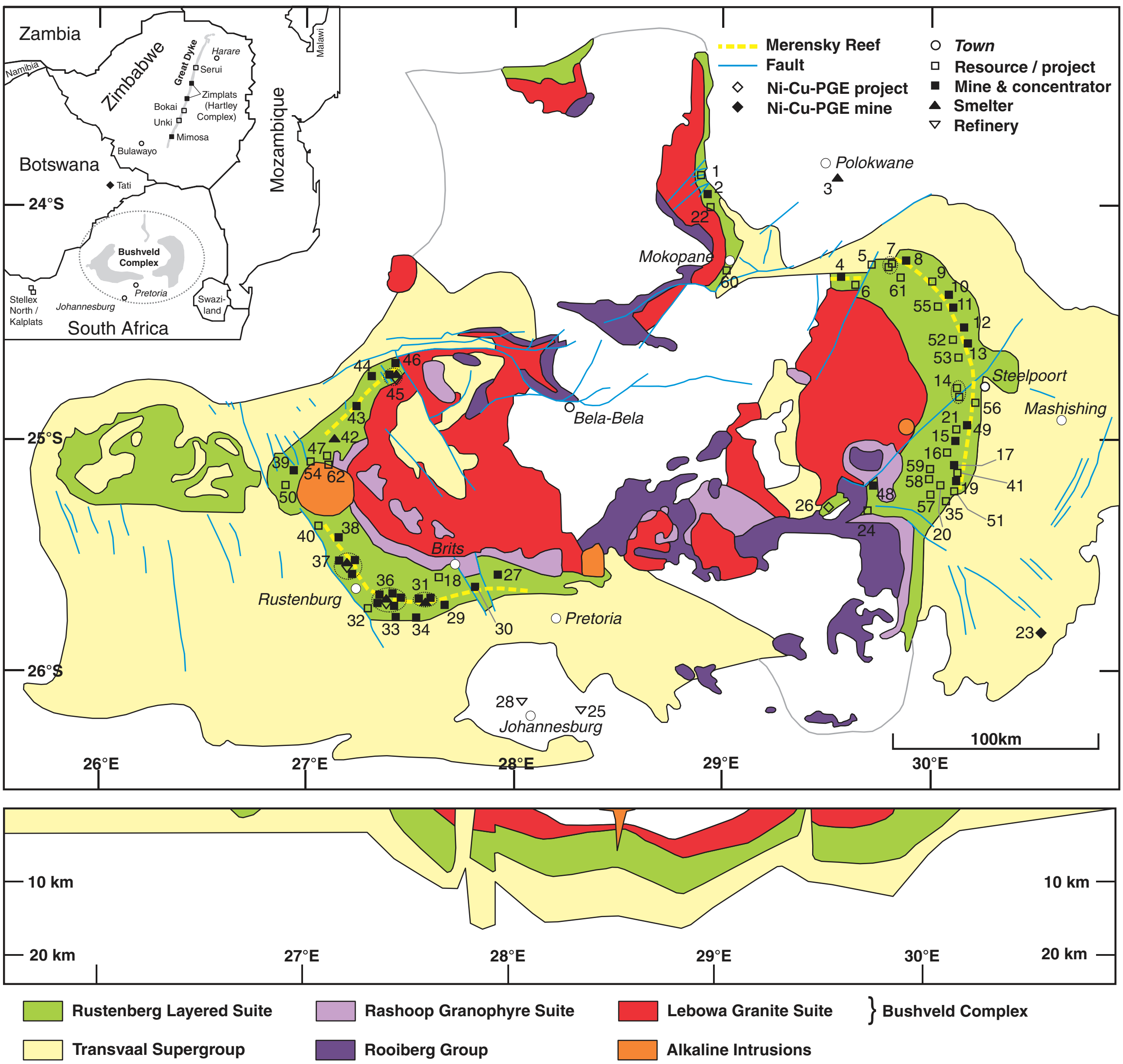

Fig. 1. Geology of the Bushveld Complex, South Africa, and operating PGE mines, smelters, refineries and projects, inset is of south-eastern Africa; all details are approximate only, based on 2010 data and most recent names. Names: 1 Boikgantsho, 2 Mogalakwena, 3 Polokwane, 4 Limpopo, 5 Mphahlele, 6 Zondernaam, 7 Liger, 8 Bokoni, 9 Ga-Phasha, 10 Twickenham, 11 Marula, 12 Smokey Hills, 13 Modikwa, 14 Kennedy's Vale-Spitzkop, 15 Mototolo, 16 Der Brochen, 17 Everest North-Vygenhoek, 18 Leeuwkop (Afplats), 19 Everest South-Hoogland, 20 Booysendal, 21 Tamboti, 22 Akanani, 23 Nkomati, 24 Loskop, 25 Impala Springs, 26 Sheba's Ridge, 27 Eland, 28 Lonmin, 29 Pandora JV, 30 Crocodile River, 31 Marikana (Lonmin) Group, 32 Townlands, 33 Kroondal, 34 Marikana PSA (AqP-AAP), 35 Berg, 36 Bathopele–Khomanani–Thembelani–Khuseleka–Siphumelele mines, Waterval Smelter, Rustenburg Refineries (former RPM Rustenberg Group), 37 Impala Group, 38 Bafokeng-Rasimone, 39 Pilanesberg, 40 Frischgewaagd (3-4-11), 41 Mareesburg, 42 Mortimer, 43 Union, 44 Tumela, 45 Northam, 46 Dishaba, 47 Magazynskraal, 48 Blue Ridge, 49 Two Rivers, 50 Platmin Other, 51 Klipriver, 52 Garatau, 53 Tubatse, 54 Rooderand-Ruighoek, 55 Tjate, 56 Grootboom, 57 Everest West-Sterkfontein, 58 Chieftains Plain, 59 Walhalla, 60 Oorlogsfontein (War Springs), 61 Lesego, 62 Sedibelo.
Main map adapted from Scoates and Friedman (2008).

Given the dominance of the Bushveld Complex in global PGE resources and production, a very brief description of the geology and history is provided below.

2.2. The Bushveld Complex, South Africa

The north-eastern region of South Africa hosts the Bushveld Complex, a large igneous complex about 450 km east–west and up to 250 km north–south. It consists of four distinct igneous suites, namely, in age order, early mafic sills, the Rooiberg Group felsites, multiple mafic and ultramafic layers of the Rustenberg Layered Series which host PGE mineralisation and the latest Lebowa Granite Suite which cross-cuts the 110 km thick Rustenberg Series. Covering of the Bushveld by younger sediments and intrusion of later magmas means that the outcrop of the Rustenberg Layered Series is limited to two basin-like lobes to the west and east and a linear lobe to the north. A geological map is given in Fig. 1, including PGE mines and projects. Further details on the geology are given by Cawthorn (2010), Cawthorn et al. (2002), Naldrett (2004), Scoates and Friedman (2008) and Vermaak (1995).

Although platinum was first reported in 1906 from the Bushveld region, it was not until 1924 that geologist Hans Merensky made the first discovery of economic platinum in the Bushveld — with this PGE layer then called the Merensky reef (Cawthorn, 2006). Another major reef layer is the Upper Group 2 (UG2) chromitite reef (first noted in 1906). The Eastern and Western Bushveld contain both the Merensky and UG2 reefs, while the Northern Bushveld contains only the Platreef. The Merensky and UG2 reefs are remarkably continuous over a strike length of more than 100 km each on both the eastern and western limbs, while the Platreef has a strike length of some 30 km, with the PGEs mineralogically associated with base metal sulfides or chromites (Cawthorn, 2010; Vermaak, 1995). Most PGE reefs also contain low grade nickel (Ni) and copper (Cu).

The Merensky reef was the first to be successfully mined commercially, while the UG2 proved more challenging to process until technology became available from the 1980s (pioneered by Lonmin). The very thin nature of the Merensky and UG2 reefs (~1 m) requires narrow mining techniques. The Platreef is much thicker (ranging from ~4 to ~200 m) and is mined by open cut at Mogalakwena due to the shallower depth and thicker reef. Depth of underground mines can range from 100 to 2000 m, with most presently active around several hundred metres deep.

3. Economic PGE mineral resources

3.1. Reported mineral resources

The elements contained in PGE ores are often reported as '4E' (Pt + Pd + Rh + Au) or '6E' (Pt + Pd + Rh + Ru + Ir + Au) grades, with osmium extremely rarely reported (3E is Pt + Pd + Au). A compilation of economic PGE mineral resources by mine or project and ore type for 2010 are given in Tables 1 to 3 for the Eastern, Western and Northern Bushveld Complex, respectively, Great Dyke resources in Table 4, other global PGE resources in Table 5 and Ni–Cu-PGE resources in Table 6. All data is derived from company annual reports (or other technical studies) based on statutory mineral resource

Table 1
PGE mineral resources — Eastern Bushveld Complex, South Africa (2010 data).

Mine/project	Principal companies	Merensky				UG2				t PGEs (4E)
		Mt ore	4E g/t	%Cu	%Ni	Mt ore	4E g/t	%Cu	%Ni	
Bokoni	Anooraq Res./Anglo American Platinum	229.6	4.82	0.09	0.21	367.6	6.28	0.06	0.17	3414.7
Booysendal	Mvelaphanda Res./Northam Platinum	255.5	4.69	0.12	0.26	580.5	3.47	0.009	0.080	3212.6
Ga Phasha	Anooraq Res./Anglo American Platinum	236.1	5.20	0.08	0.22	311.0	6.14	0.04	0.15	3137.5
Der Brochen	Anglo American Platinum	177.6	4.38	0.12	0.26	319.9	4.73	0.02	0.09	2291.0
Spitzkop-Kennedy's Vale	Eastern Platinum	343.3	2.93	0.064	0.125	262.5	4.73	0.017	0.054	2249.0
Twickenham	Anglo American Platinum	161.4	5.04	0.12	0.29	244.7	5.64	0.02	0.14	2194.3
Modikwa	Anglo American Pt/African Rainbow Minerals	208.8	2.70	0.05	0.14	272.6	5.76	0.02	0.13	2133.4
Walhalla	Aquarius Platinum	135.0	4.30			185.0	5.70			1635.0
Tamboti	Impala Platinum/Kameni	141.1	3.81			177.6	5.58			1528.2
Tubatse	Nkwe Platinum	153.2	4.45			105.8	7.18			1440.9
Lesego	Village Main Reef	77.2	6.75	0.140	0.287	119.5	6.52	0.068	0.182	1300.1
Chieftains Plain	Aquarius Platinum	85.0	4.30			115.0	5.70			1021.0
Garatau	Nkwe Platinum	69.7	4.40			78.6	5.35			727.2
Tjate	Jubilee Platinum	56.3	4.66	0.13	0.20	76.2	5.67	0.039	0.079	694.3
Limpopo (Baobab/Doornvlei/Zebedeila)	Lonmin	49.6	4.16	0.11	0.17	107.3	4.49	0.09	0.14	688.9
Marula	Impala Platinum	52.8	4.23			52.6	8.57			674.0
Mphahlele[a]	Platmin					121.4[a]	3.93[a]	0.092[a]	0.132[a]	476.6[a]
Limpopo (Dwaalkop)	Mvelaphanda Resources/Lonmin	76.1	2.98	0.11	0.17	37.6	4.35	0.09	0.14	390.1
Two Rivers	African Rainbow Minerals/Impala Platinum	22.6	3.31			56.7	3.91			296.3
Blue Ridge	Aquarius Platinum/Imbani Platinum					81.4	3.19			259.2
Mototolo	Anglo Am Pt/XK Platinum Partnership					43.4	4.16			180.7
Everest	Aquarius Platinum					34.2	3.38			115.9
Loskop Joint Venture[b]	Lonmin/Platmin					24.6	4.04[b]			99.5
Grootboom[a]	Platmin					21.6[a]	4.28[a]	0.011[a]	0.028[a]	92.4[a]
Anglo Pt Other Projects	Anglo American Platinum	2.9	8.61			10.3	5.87			85.4
Mareesburg	Eastern Platinum					15.9	3.92	0.026	0.070	62.3
Kliprivier	Nkwe Platinum					24.4	2.3			56.2
Berg[a]	Platfields					23.6[a]	2.02[a]			47.8[a]
Everest West-Sterkfontein	Aquarius Platinum					13.0	3.50			45.5
Liger (Leeuwkop-Tigerpoort)	Platfields					9.6	4.75			45.4
Everest South-Hoogland	Aquarius Platinum					6.6	2.88			19.0
Smokey Hills	Platinum Australia					3.99	4.72			18.8
Everest North-Vygenhoek	Aquarius Platinum					2.8	5.11			14.2
Sub-totals		2533.8	4.23	~0.1	~0.2	3907.4	5.10	~0.05	~0.1	30,647.4

Notes: resources include reserves (where reported).
[a] Ore type not specified, UG2 assumed.
[b] 3E grade only.

Table 2
PGE mineral resources — Western Bushveld Complex, South Africa (2010 data).

Mine/project	Principal companies	Merensky				UG2				t PGEs (4E)
		Mt ore	4E g/t	%Cu	%Ni	Mt ore	4E g/t	%Cu	%Ni	
Marikana (Lonmin)	Lonmin	342.8	4.99	0.10	0.18	559.6	5.08	0.01	0.03	4553.5
Tumela	Anglo American Platinum	170.9	7.71	0.10	0.26	365.6	5.27	0.01	0.11	3245.0
Impala	Impala Platinum	278.3	5.74			234.4	6.72			3173.0
Bafokeng-Rasimone	Royal Bafokeng/Anglo American Platinum	197.0	5.79	0.11	0.26	209.1	4.91	0.01	0.10	2168.2
Afplats-Leeuwkop Group	Impala Platinum					358.8	5.09			1826.3
Union	Anglo American Platinum	82.1	6.21	0.07	0.26	179.1	5.21	0.01	0.11	1442.3
Dishaba	Anglo American Platinum	48.2	6.95	0.10	0.23	136.2	5.01	0.01	0.12	1017.3
Zondereinde (Northam)	Northam Platinum	68.4	7.09			62.6	5.06			802.1
Eland	Xstrata					153.1	4.31			660.4
Pandora JV	Anglo American Platinum/Lonmin					154.1	4.22	0.01	0.02	651.0
Siphumelele	Anglo American Platinum	27.0	6.16	0.12	0.24	97.6	4.92	0.01	0.10	647.0
Magazynskraal 3JQ	Bakgatla/Pallinghurst/Anglo American Platinum	47.0	6.58			63.5	4.65			604.5
Frischgewaagd 3-4-11 (WBJV)	Wesizwe/Anglo American Platinum	45.1	6.35			56.4	4.54			542.5
Thembelani	Anglo American Platinum	27.9	5.14	0.10	0.24	75.5	4.95	0.01	0.10	516.9
Rustenburg Other	Anglo American Platinum	22.6	6.40	0.10	0.22	57.8	5.33	0.01	0.10	452.7
Khomanani	Anglo American Platinum	23.3	5.88	0.10	0.23	51.3	4.80	0.01	0.10	383.2
Pilanesburg (Tuschenkomst-Ruighoek)[a]	Platmin/Moepi					109.3[a]	3.10[a]	0.024[a]	0.087[a]	339.0[a]
Khuseleka	Anglo American Platinum	10.4	5.11	0.10	0.21	65.4	4.16	0.01	0.10	325.1
Projects 1–3 (PGM-Wes. WBJV)	Platinum Group Metals/Wesizwe Platinum	23.5	7.27			32.6	4.50			318.0
Crocodile River	Eastern Platinum/Gubevu					63.2	4.05			256.0
Sedibelo[a]	Itereleng Bakgatla Mineral Resources/Platmin					42.6[a]	4.38[a]			186.5[a]
Marikana (PSA)	Anglo American Platinum/Aquarius Platinum					34.9	5.02			175.4
Bathopele	Anglo American Platinum	1.5	4.18			44.9	2.96	0.01	0.10	139.0
Ledig 1–2	Wesizwe Platinum	10.7	6.00			13.2	4.56			124.7
Kroondal	Anglo American Platinum/Aquarius Platinum					20.1	5.55			111.5
Townlands	Aquarius Platinum					16.3	6.29			102.7
Rooderand[a]	Nkwe Platinum/Platinum Australia					24.8[a]	3.80[a]	0.027[a]	0.051[a]	94.2[a]
Schietfontein	Xstrata					22.9	2.29			52.4
Zilkaatsnek	Xstrata					4.3	2.50			10.8
Frischgewaagd 1	Wesizwe Platinum	0.3	6.66			0.3	4.30			3.3
Sub-totals		1427.1	6.01	~0.1	~0.22	3267.2	4.94	~0.01	~0.1	24,924.6

Notes: resources include reserves (where reported).
[a] Ore type not specified, UG2 assumed.

reporting codes (e.g. Australia's JORC Code, South Africa's SAMREC or Canada's NI-43-101), with all mineral resources inclusive of ore reserves (where reported). A summary is shown in Table 7, giving a global resource of ~90,700 t PGEs (4E, or ~2.91 billion oz). This should be considered a reliable estimate as of 2010, since all mineral resources are reported under statutory codes, although whether all projects proceed to production is dependent on economics, mining conditions, processing characteristics, site-specific environmental issues (especially land use, water, mine waste management), energy, and so on. The Bushveld Complex (including Ni–Cu-PGEs) clearly dominates with 70.9% of reported global PGE resources — only the Noril'sk–Talnakh field comes close in size to the Bushveld.

Another important aspect of PGE resources is the proportion of individual elements (due to different element prices and demands). Given that not all companies report PGE resource grades as 6E, only 4E (or 3E) was included in Tables 1 to 6. Based on the Bushveld resources where 6E grades are sometimes reported, 6E grade is typically about 1.16 times the 4E grade. An approximate breakdown by individual element is given in Table 8, based on ore-weighted grades where 4E or 6E split data is reported. Although Ru and Ir can be highly variable between ore types and region, the UG2 reef clearly has higher Ru and Ir grades than Merensky and Great Dyke ore.

The evolution of reported mineral resources over time for some of the major mines in the Bushveld and Great Dyke is shown in Fig. 2, with a comparison of 2010 PGE mineral resources to cumulative production from 2000 to 2010 in Table 9. This shows that most major producers have continued to increase total resources over

Table 3
PGE mineral resources — Northern Bushveld Complex, South Africa (2010 data).

Mine/project	Principal companies	Resources				t PGEs (4E)
		Mt ore	4E g/t	%Cu	%Ni	
Mogalakwena	Anglo American Platinum	2779.9	2.20	0.11	0.18	6124.6
Akanani	Lonmin/Incwala Resources	291.9	3.84	0.12	0.22	1121.4
Boikgantsho	Anooraq Res./Anglo American Platinum	280.8	1.31	0.08	0.13	367.9
Oorlogsfontein (War Springs)[a]	Platmin	47.0	1.11[a]	0.10	0.13	52.1
Rooipoort	Caledonia Mining Corp.	18.1	1.28	0.11	0.19	23.3
Sub-totals		3417.7	2.25	0.11	0.18	7689.3

Notes: resources include reserves (where reported).
[a] 3E grade only.

Table 4
PGE mineral resources — Great Dyke, Zimbabwe (2010 data).

Mine/project	Principal companies	Resources				t PGEs (4E)
		Mt ore	4E g/t	%Cu	%Ni	
Zimplats	Impala Platinum	1879.0	3.63	0.11	0.13	6818.5
Serui	Amari Res./Zimbabwe Mining Development Corp.[a]	~138[a]	~4[a]			550
Unki	Anglo American Platinum	119.3	4.01	0.15	0.22	478.1
Bokai	Eurasian Nat. Res. Corp./Zimb Mining Development Corp.	91.6	3.62	0.17		331.6
Mimosa — South Hill	Aquarius Platinum/Impala Platinum	86.6	3.74	0.12	0.14	323.6
Mimosa — North Hill	Aquarius Platinum/Impala Platinum	48.6	3.64	0.11	0.14	177.0
Sub-Totals		2363.1	3.67	0.11	~0.12	8678.8

Notes: resources include reserves (where reported).
[a] Only PGEs reported, ore tonnage and grade approximated.

Table 5
PGE mineral resources — miscellaneous worldwide (2010 data).

Mine/project	Principal companies	Resources				t PGEs (4E)
		Mt ore	3E g/t	%Cu	%Ni	
Skaergaard (Greenland)	Platina Resources	1520.0	0.86			1307.2
Stillwater (USA)	Stillwater/Norilsk Nickel	37.01	16.8	0.07	0.1	621.7
Nokomis-Duluth (USA)	Wallbridge/Antofagasta	823.9	0.67	0.64	0.20	550.6
NorthMet (USA)	Polymet Mining	1029.4	0.292	0.238	0.067	300.9
Arctic-Ahmavaara (Finland)	Gold Fields	187.77	1.22	0.175	0.069	229.3
Kalplats (South Africa)	African Rainbow Minerals/Platinum Australia	137.4	1.53			210.2
Lac des Iles (Canada)	North American Palladium	35.5	3.99	0.07	0.09	141.5
Marathon (Canada)	Marathon PGM	121.0	1.05	0.236		127.6
Arctic-Konttijärvi (Finland)	Gold Fields	75.24	1.30	0.097	0.046	97.6
Eagle's Nest (Canada)	Noront Resources	21.6	4.44	0.98	1.39	95.9
Nunavik (Canada)	Jilin Jien Nickel/Goldbrook Ventures	27.15	2.83	1.10	0.89	76.7
Panton (Australia)	Platinum Australia	14.3	4.89	0.075	0.27	69.9
Munni Munni (Australia)	Platina Resources	23.6	2.84	0.15	0.09	67.0
River Valley (Canada)	Anglo American Platinum/Pacific North West	33.0	1.36	0.10	0.02	44.9
Pedra Blanca (Brazil)	Anglo American Platinum/Solitario	12.9	2.27	0.03	0.23	29.4
Thunder Bay North-Current Lake (Canada)	Magma Metals	10.79	2.13	0.24	0.19	23.0
Weld Range (Australia)	Atomaer Holdings	6.3	1.7			10.7
Maracás (Brazil)	Unknown	17.26	0.30			5.3
Broken Hammer (Canada)	Wallbridge Mining	0.251	3.79	1	0.10	1.0
Parkin (Canada)	Wallbridge Mining	0.351	1.93	0.69	0.59	0.7
Sub-totals		4134.7	0.97	~0.37	~0.13	4011.0

Note: Resources include reserves (where reported).

time. A similar trend is evident for the Noril'sk–Talnakh field over the past 5 years (i.e. resources remaining at ~11,000 t PGEs).

3.2. Comparison of PGE resource estimates

The USGS (2009) reserves figure of 71,000 t PGEs (while 2010 global PGE reserves were reported as 66,000 t PGEs; USGS, var.) compares to the 2009 global production of ~465 t PGEs and the cumulative production from 1900 to 2009 of ~13,300 t PGEs. The compilation of company reported PGE mineral resources in 2010 (Tables 1–6) of ~90,700 t PGEs significantly exceeds the USGS reserves figure. Historically, the USGS used to report 80,000 t PGEs in their 'reserves base' category (e.g. USGS, 2009), although this category is no longer reported (from 2010) due to the perceived uncertainty in this classification. In addition, the USGS (2009) reserves figure for South Africa was 63,000 t PGEs, which compares

Table 6
Ni–Cu-PGE mineral resources — miscellaneous worldwide (2010 data).

Mine/project	Principal companies	Resources				t PGEs (3E)
		Mt ore	3E g/t	%Cu	%Ni	
Noril'sk–Talnakh (Russia)	Norilsk Nickel	2188.4	4.95	1.45	0.77	10,843.2
Maslovskoy (Russia)	Norilsk Nickel	215	6.53	0.51	0.33	1404.0
Sheba's Ridge (South Africa)	Aquarius Platinum/Anglo Am Pt	764.3	0.90	0.07	0.19	687.9
Nkomati (South Africa)[a]	Norilsk Nickel	407.7	0.87[a]	0.13	0.35	356.0
Kingashskoye-Verkhnekingashskoye (Russia)	Unknown (formerly Norilsk Nickel)	484.55	0.63	0.45	0.21	305.5
Vale Inco Sudbury (Canada)	Vale Inco	112.3	2.33	1.53	1.20	262.2
Kevitsa (Finland)	First Quantum Minerals	275	0.87	0.41	0.31	239.3
Birch Lake (USA)	Franconia Minerals	216.81	0.85	0.52	0.17	183.8
Jinchuan (China)	Jinchuan	~432	~0.2	~0.88	~1.39	86.4
Ferguson Lake (Canada)	Starfield Resources	44.2	1.93	1.02	0.68	85.1
Tati-Selkirk (Botswana)[a]	Norilsk Nickel	135.3	0.57[a]	0.27	0.23	77.0
Maturi (USA)	Franconia Minerals	119.9	0.38	0.67	0.25	45.6
Kola Peninsula (Russia)	Norilsk Nickel	546.3	0.08	0.30	0.63	42.6
Dumont (Canada)	Royal Nickel Corp.	2105.27	0.016		0.27	34.2
Kabanga (Tanzania)	Xstrata/Barrick Gold	58.2	0.58	0.33	2.63	33.8
Mokopane (South Africa)	Blackthorn Resources	39.7	0.55	0.085	0.146	21.9
Kaukua-Haukiaho (Finland)	Finore Mining	30.670	0.68	0.21	0.14	20.7
Sudbury-Onaping Depth (Canada)	Xstrata	15.7	0.97	1.25	2.74	15.3
Shakespeare (Canada)	Ursa Major Minerals	14.02	0.88	0.36	0.34	12.3
Eagle (USA)	Rio Tinto	4.8	1.2[b]	2.40	2.82	5.8
Dikoloti (Botswana)	Discovery Metals, Xstrata	4.1	1.2	0.5	0.7	4.9
Denison (Canada)	Vale Inco/Lonmin	0.7	6.30	0.96	0.55	4.4
Kuhmo Group (Finland)	Altona Mining	9.819	0.41[b]	0.08	0.38	4.0
Sudbury-Fraser Morgan (Canada)	Xstrata	8.65	0.26	0.55	1.85	2.3
Shebandowan West (Canada)	North American Palladium	1.46	1.20	0.62	0.93	1.8
Las Aguilas (Argentina)	Marifil Mines/Pacific Coast Nickel Corp.	4.603	0.31	0.41	0.41	1.4
Wildara-Horn (Australia)	Breakaway Resources	0.6	0.5	0.3	1.39	0.3
Werner Lake-Big Zone (Canada)	Puget Ventures	0.172	1.21[b]	0.26	0.62	0.2
Sub-totals		8240.3	1.79	0.58	0.52	14,781.8

Notes: resources include reserves (where reported).
[a] 4E grade.
[b] Approximate only.

Table 7
Summary of global PGE mineral resources (2010 data).

	Mt ore	4E g/t	%Cu	%Ni	t PGEs (4E)
Merensky Reef, Eastern Bushveld Complex, South Africa	2533.8	4.23	~0.1	~0.2	10,707.1
UG2 Reef, Eastern Bushveld Complex, South Africa	3907.4	5.10	~0.05	~0.1	19,940.3
Merensky Reef, Western Bushveld Complex, South Africa	1427.1	6.01	~0.1	~0.22	8582.6
UG2 Reef, Western Bushveld Complex, South Africa	3309.7	4.94	~0.01	~0.1	16,342.0
Platreef, Northern Bushveld Complex, South Africa	3417.7	2.25	0.11	0.18	7689.3
Great Dyke, Zimbabwe	2363.1	3.67	0.11	~0.12	8678.8
Miscellaneous, Global	4134.7	0.97[a]	0.37	0.13	4011.0
Nickel–copper-PGEs, Global	8240.3	1.79[a]	0.58	0.52	14,781.8
Totals	29,333.6	3.09	~0.26	~0.25	90,732.8

[a] Mostly 3E grade.

reasonably to the total from Tables 1–6 of ~64,330 t PGEs. The USGS estimate of Russian reserves is 6200 t PGEs while data in Table 6 shows a much higher value of 12,595 t PGEs.

The total of ~90,700 t PGEs (2010 data) also compares to the 2009 value of ~78,850 t PGEs from Mudd (2010b), which also has several exploration stage projects missing. This demonstrates that PGE mineral resources are being maintained (which is also confirmed by Fig. 2) and generally expanded.

The compiled data set includes no resources for China, since there is no practise of public reporting of mineral resources and mine production (compared to 'western' norms in any case). According to Zhu (2006), China had identified 308 t PGEs in various mineral resources by 1997, of which only 23.3 t PGEs were considered as economic. The spread was 53.8% Pt, 39.5% Pd and 1–2% each for Rh, Ir, Ru and Os. The dominant resource and producer was the large Jinchuan Ni–Cu-PGE complex in Gansu province. Overall, China would appear to be very minor in PGEs.

Tentative concerns were raised in the late 1960s about the future availability of Pt, with reasonably confident assessments pointing to extractable Merensky reef resources of at least 6220 t Pt from 1970 to 2000 (Hunt and Lever, 1969) — over this same period South African production was 2245 t Pt (noting present resources in Tables 1–6). The extent of recoverable resources was linked to ore grades and mining depth, with considerable potential for continuing to increase resources for some time (Hunt and Lever, 1969) — a prediction strongly confirmed by Fig. 3.

Although Gordon et al. (2006) suggested that Pt could be in short supply within a few decades as demand continues to grow, this proposition is not supported by the available PGE resources data. As noted by Cawthorn (1999, 2007, 2010), most resources in the Bushveld Complex are only estimated to a mining depth of 2 km (the current economic mining limit), with considerable potential for additional PGEs known at greater depths as well as in other lower grade reefs (1–3 g/t) not currently exploited — potential PGEs could reach 311,000 t (~10 billion oz) in the Bushveld alone (Cawthorn, 2007, 2010). Thus the critical sustainability issues in the future are not resource size but the associated environmental, social, economic and political aspects.

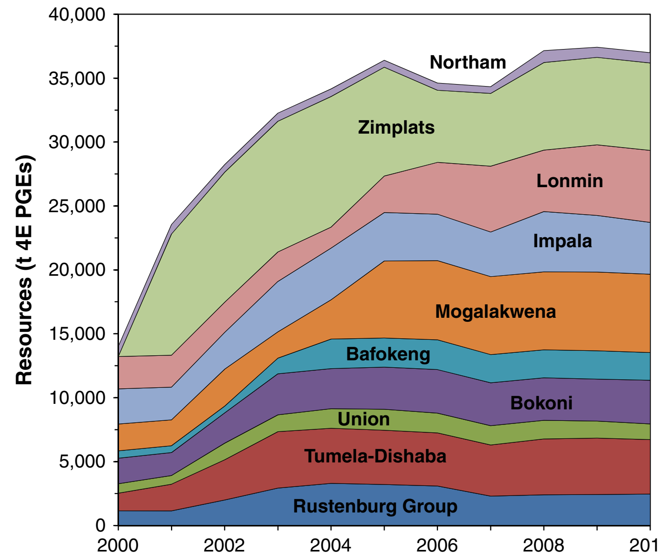

Fig. 2. PGE resources for selected major mines of the Bushveld and Great Dyke from 2000 to 2010.

4. Mining and processing of PGE ores

4.1. Overview

The mining of PGE ores is through conventional underground or open cut techniques. The next stage is grinding and gravity-based (or dense media) separation, followed by flotation to produce a PGE-rich concentrate. The run-of-mine ore grades are typically several g/t, while concentrates are some 100s of g/t (Vermaak, 1995). Concentrate is then smelted to produce a PGE-rich Ni–Cu matte, with the PGEs extracted and purified at a precious metals refinery (including Ni–Cu by-products). The processing is therefore more analogous to base metals rather than Au, which primarily relies on cyanide leaching and hydrometallurgy. Smelting of concentrates from Ni–Cu mining can also be a moderate source of PGEs (e.g. Russia, Canada; see later tables). Further details on PGE ore processing are given by Bulatovic (2010), Cole and Ferron (2002), Merkle and McKenzie (2002) and Vermaak (1995).

Table 8
Approximate PGE grades by individual element and ore type (weighted average of available 2010 data; number of data points in brackets).

(All g/t)	Pt	Pd	Rh	Ru	Ir	Os	Au
Eastern Bushveld — Merensky Reef	2.47 (13)	1.29 (13)	0.13 (13)	~0.25 (4)	~0.04 (4)	~0.2[a]	0.28 (13)
Western Bushveld — Merensky Reef	3.78 (13)	1.69 (13)	0.29 (13)	~0.56 (1)	~0.12 (1)	~0.1[a]	0.27 (13)
Eastern Bushveld — UG2 Reef	2.42 (19)	2.08 (19)	0.44 (19)	~0.84 (6)	~0.20 (6)	~0.2[a]	0.08 (19)
Western Bushveld — UG2 Reef	2.97 (5)	1.47 (5)	0.56 (5)	~1.04 (2)	~0.26 (2)[b]	~0.1[a]	0.04 (5)
Platreef	0.99 (4)	1.12 (4)	0.07 (2)	–	–	–	0.15 (3)
Great Dyke	1.81 (5)	1.35 (4)	0.16 (4)	0.14 (3)	0.07 (3)	0.016[c]	0.27 (5)
Miscellaneous	0.16 (17)	0.66 (17)	0.05 (4)	–	–	–	0.12 (12)
Ni–Cu-PGEs	0.75 (14)	2.49 (14)	–	–	–	–	0.17 (14)

[a] Based on data from Barnes and Maier (2002), Cawthorn et al. (2002), Godel et al. (2007).
[b] Consistent with Oberthür (2002).
[c] Data based on personal communication (Zimplats) (and Oberthür, 2002).

Table 9
Comparison of 2010 mineral resources to cumulative production from 2000 to 2010 for some major PGE mines.

	Total mineral resources (2010)			Cumulative production (2000 to 2010)		
	Mt ore	4E g/t	t PGEs (4E)	Mt ore	4E g/t	t PGEs (4E)
Rustenburg Group	505.0	4.88	2463.5	113.3	4.36	414.2
Tumela-Dishaba	720.8	5.91	4261.4	72.2	5.32	310.0
Union	222.0	5.52	1225.9	59.7	3.85	168.1
Bokoni	597.1	5.72	3414.7	15.0	4.45	54.1
Bafokeng-Rasimone	406.1	5.34	2168.2	25.3	4.41	89.8
Mogalakwena	2779.9	2.20	6124.6	62.4	3.41	144.1
Impala	535.9	7.57	4056.7	168.0	4.80	575.5
Lonmin	1212.0	4.65	5635.8	138.9	4.97	411.6
Northam	131.1	6.12	802.0	22.9	5.36	108.6
Zimplats	1879.0	3.64	6839.6	19.8	3.21	53.0

Note: resources include reserves (where reported).

4.2. Production trends

The historical global production of PGEs by country is shown in Fig. 3, with nominal and real prices over time inset. The boom/bust cycle of nominal prices is evident, though in real terms PGE prices have been stable on average over the long-term. Demand by use is shown in Fig. 4. The severe impact of the ongoing global financial crisis is evident, as demand declined substantially from 2007 to 2009 (mainly due to the collapse of autocatalyst demand for new vehicles), although it began to recover in 2010.

A detailed compilation of PGE production statistics for 2010 in the Bushveld Complex is given in Table 10, other PGE projects in Table 11 and Ni–Cu-PGE projects in Table 12. As shown, the overall average PGE ore grade is 3.8 g/t (4E) in the Bushveld, though higher for Stillwater in the USA. For Ni–Cu-PGE projects the ore grade is highly variable (with only yield commonly reported and not assayed ore grade), with the relatively high Pd content of the Taimyr Peninsula ore standing out. The yields for the earliest Bushveld PGE mines are given in Table 13, showing similar grades to current mines (allowing for somewhat lower extraction efficiency). The recent trends in PGE ore grades by company are shown in Fig. 5, demonstrating a gradual decline for most companies, with only a couple showing stable grades.

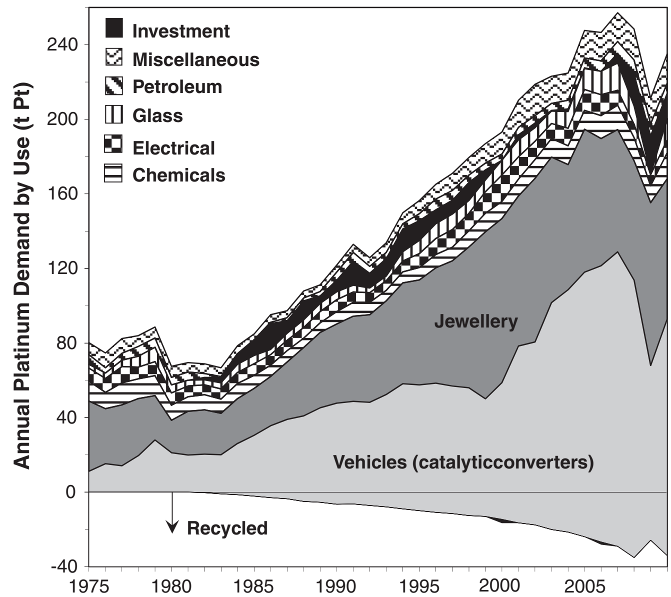

Fig. 4. Recent global platinum demand by use (JM, 2011).

In comparing production versus resources (i.e. Tables 10–12 versus 1–6), ore grades can be expected to decline in the future to a minor extent, but this will more critically depend on the balance of ore types developed and processed, such as a preference for shallower low grade Platreef over deeper Merensky/UG2 projects.

A major trend in the Bushveld over the past few decades is the emergence of UG2 ore as the dominant source. The processing of UG2 ore was more difficult than Merensky ore, due to its high chromite content, and the ability to treat UG2 ore was pioneered by Lonmin in the 1980s. By the 1990s, the process technology had

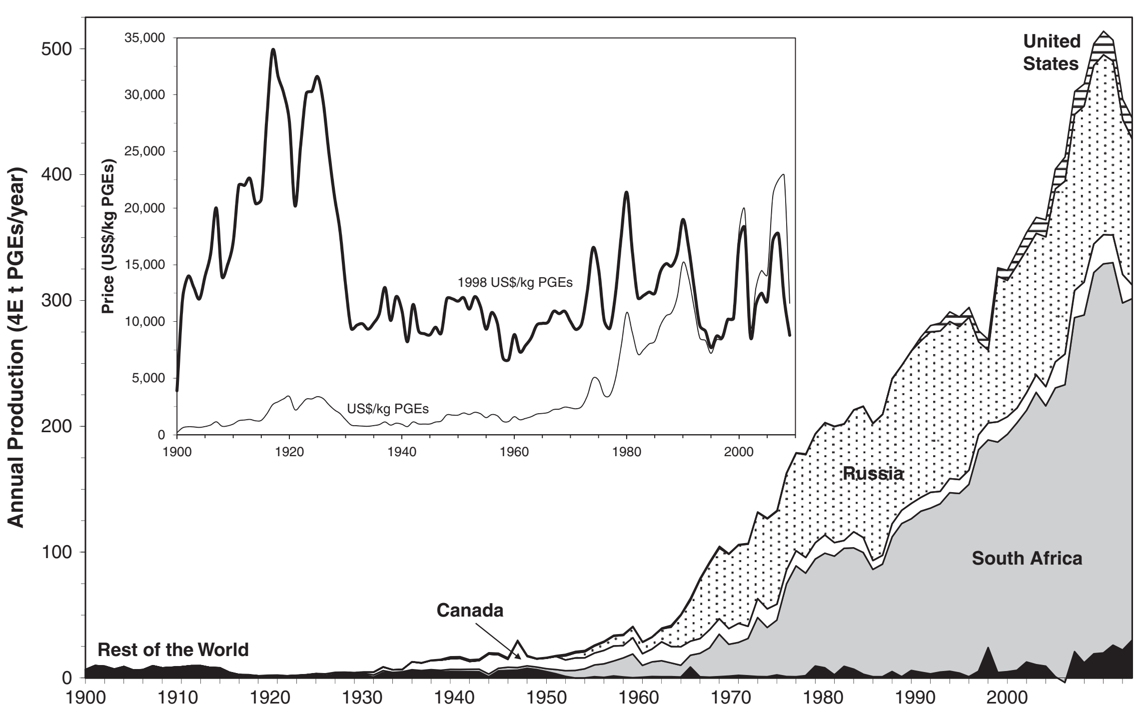

Fig. 3. Historical global production of PGEs by country, including nominal and real price data — inset.
Data combined from CMSA (2008), Kelly et al. (2010), Loferski (2010), NRC, var.; SADME (2007), and Vermaak (1995).

Table 10
Major PGE mines — Bushveld Complex, South Africa (2010 data).

Mine/project	t ore milled	4E g/t	kg Pt	kg Pd	kg Rh	kg Ru	kg Ir	kg Au	t Ni	t Cu	Ore source	Mine type	Principal owners
Bathopele[a]	3,107,000	3.02	4403.8	2544.0	768.2	1346.6		43.5	300	100	UG2$^{100\%}$	UG$^{100\%}$	Anglo Platinum$^{100\%}$
Khomanani[a]	1,317,000	4.38	3144.2	1467.9	301.7	391.9		124.4	700	400	UG2$^{28.3\%}$, Mer.$^{71.7\%}$	UG$^{100\%}$	Anglo Platinum$^{100\%}$
Thembelani[a]	1,447,000	4.23	3035.4	1620.3	438.5	755.7		62.2	500	200	UG2$^{80.2\%}$, Mer.$^{19.8\%}$	UG$^{100\%}$	Anglo Platinum$^{100\%}$
Khuseleka[a]	1,967,000	3.97	4095.9	2021.5	472.7	715.3		130.6	900	500	UG2$^{55\%}$, Mer.$^{45\%}$	UG$^{100\%}$	Anglo Platinum$^{100\%}$
Siphumelele[a]	1,032,000	5.09	2991.8	1306.2	223.9	211.5		143.1	700	500	UG2$^{0.1\%}$, Mer.$^{99.9\%}$	UG$^{100\%}$	Anglo Platinum$^{100\%}$
Tumela[b]	4,488,000	4.02	9423.3	4378.9	1427.5	2233.0		140.0	1000	500	UG2$^{80.5\%}$, Mer.$^{19.5\%}$	UG$^{100\%}$	Anglo Platinum$^{100\%}$
Dishaba[b]	1,908,000	4.79	4864.0	2233.0	600.2	833.5		115.1	800	400	UG2$^{43.7\%}$, Mer.$^{56.3\%}$	UG$^{100\%}$	Anglo Platinum$^{100\%}$
Union	5,543,000	3.37	9454.4	4183.0	1449.3	2407.1		108.9	800	300	UG2$^{64.7\%}$, Mer.$^{35.3\%}$	UG$^{100\%}$	Anglo Platinum$^{85\%}$
Bafokeng	2,407,000	4.31	5826.9	2392.7	417.5	722.3	139.5	323.9	2251	1425	UG2$^{3.2\%}$, Mer.$^{96.8\%}$	UG$^{100\%}$	AngloPt$^{33\%}$, RBH$^{67\%}$
Bokoni[c]	1,044,084	4.12	1953.1	1309.3	195.9	234.4		112.0	700	400	UG2$^{32\%}$, Mer.$^{68\%}$	UG$^{100\%}$	AngloPt$^{49\%}$, AnRes$^{51\%}$
Mogalakwane[d]	10,380,000	2.60	8468.5	8807.5	513.2	531.8		901.9	8500	5600	Platreef$^{100\%}$	OC$^{100\%}$	Anglo Platinum$^{100\%}$
Twickenham	58,000	4.20	112.0	99.5	18.7	34.2		3.1	nd	nd	UG2$^{100\%}$	UG$^{100\%}$	Anglo Platinum$^{100\%}$
Modikwa	2,270,000	5.25	4089.7	4007.6	849.0	1211.4	299.3	105.2	663	410	UG2$^{100\%}$	UG$^{100\%}$	AngloPt$^{50\%}$, ARM$^{41.5\%}$
Mototolo JV	2,262,000	3.33	3436.6	2021.5	581.6	1125.8		46.7	300	100	UG2$^{100\%}$	UG$^{100\%}$	AngloPt$^{50\%}$, Xstrata$^{50\%}$
Kroondal JV	6,180,000	2.59	7477.7	3780.9	1385.0	2330.5	552.7	62.9	400	100	UG2$^{100\%}$	UG$^{100\%}$	AngloPt$^{50\%}$, AqPt$^{50\%}$
Marikana JV	2,230,000	2.65	2566.5	1188.8	431.1	879.8	204.7	25.1	100	100	UG2$^{100\%}$	UG$^{100\%}$	AngloPt$^{50\%}$, AqPt$^{50\%}$
Everest	150,000	3.09	158.5	82.6	20.5	nd	nd	2.6	nd	nd	UG2$^{100\%}$	UG$^{100\%}$	Aquarius Platinum$^{100\%}$
Two Rivers	2,920,000	3.95	4382.2	2537.4	735.0	1220.2	295.0	59.4	nd	nd	UG2$^{100\%}$	UG$^{100\%}$	ARM$^{55\%}$, Implats$^{45\%}$
Northam	2,038,225	5.19	6099.4	2999.7	799.9	1352.0	293.0	100.0	1752	957	UG2$^{50.8\%}$, Mer.$^{49.2\%}$	UG$^{100\%}$	Northam Platinum$^{100\%}$
Implats	13,531,000	4.60	27,100.5	14,284.2	3784.9	8157.5			4900	nd	UG2$^{60.2\%}$, Mer.$^{39.8\%}$	UG$^{100\%}$	Implats$^{100\%}$
Marula	1,545,000	4.36	2180.1	2257.9	457.2	845.9		nd	216.6	nd	UG2$^{100\%}$	UG$^{100\%}$	Implats$^{73\%}$
Crocodile River	1,860,925	4.10	1957.1	851.8	332.5	742.7		14.0	nd	nd	UG2$^{100\%}$	UG$^{100\%}$	Eastplats$^{87.5\%}$
Marikana (Lonmin)	11,175,000	4.64	21,595.1	10,129.2	3019.2	4700.5	1009.9	471.1	2972	1824	UG2$^{75.6\%}$, Mer.$^{24.4\%}$	UG$^{98.8\%}$, OC$^{1.2\%}$	Lonmin$^{82\%}$
Eland	900,000[e]	4.5[f]	1940.9	842.3	318.8	nd	nd	nd	nd	nd	UG2$^{100\%}$	OC$^{100\%}$	Xstrata$^{74\%}$, Ngazana$^{26\%}$
Blue Ridge	1,082,043	2.39	1094.1	539.0	171.8	231.0	47.7	17.8	nd	nd	UG2$^{\sim15\%}$, Mer.$^{\sim85\%}$	UG$^{100\%}$	AqPt$^{50\%}$, Imbani$^{50\%}$
Pilanesberg	2,905,912	1.72	1149.2[g]	528.6[g]	138.7[g]	nd	nd	57.1[g]	nd	nd	UG2$^{100\%}$	OC$^{100\%}$	Platmin$^{72.4\%}$
Smokey Hills	397,876	3.58	430.3[g]	442.5[g]	88.8[g]	nd	nd	36.6[g]	nd	nd	UG2$^{100\%}$	UG$^{\sim50\%}$, OC$^{\sim50\%}$	Platinum Australia$^{79\%}$
Total	86.15 Mt	3.80	143,431	78,858	19,941	>28,000		>3207	>28,500	>14,000	UG2$^{\sim65.6\%}$, Mer.$^{\sim22.3\%}$	UG$^{85.4\%}$, OC$^{14.6\%}$	

Notes: JV — joint venture; UG2 — upper group 2 reef; Mer. — Merensky reef; OC — open cut; UG — underground; AngloPt — Anglo Platinum; AqPt — Aquarius Platinum; RBH — Royal Bafokeng Holdings; AnRes — Anooraq Resources; ARM — African Rainbow Resources; nd — no data.
[a] Formerly part of the RPM Rustenburg group.
[b] Formerly part of the RPM Amandelbult group.
[c] Formerly known as Lebowa.
[d] Formerly known as Potgietersrust.
[e] Approximate estimate only.
[f] Ore grade assumed from resources.
[g] Production based on total 4E split from resources.

been adapted and proven, and numerous projects began to mine the UG2 reef in conjunction within existing mines (e.g. Bokoni, Rustenburg Group), or new PGE projects were developed based solely on UG2 resources (e.g. Kroondal, Twickenham). Furthermore, the Mogalakwena project was developed on the northern Platreef by Anglo American Platinum in the mid-1990s, becoming the first commercial mine in this region. The Mogalakwena project is mined by large scale open cut due to the shallower and thicker nature of the reef, although it is lower in grade than the Eastern or Western Bushveld. The recent proportion of ore types for South Africa and Zimbabwe is shown in Fig. 6.

In general, most Bushveld projects use underground mining techniques (~85% of ore), although there are some open cut mines where the reefs outcrop or subcrop. For many recent projects, a

Table 11
Major PGE producers — Great Dyke, Zimbabwe, Lac des Iles, Canada and Stillwater, USA (2010 data).

Mine/project	t ore milled	4E g/t	kg Pt	kg Pd	kg Rh	kg Ru	kg Ir	kg Au	t Ni	t Cu	Ore source	Mine type	Principal owners
Mimosa (Zimbabwe)	2,277,000	3.86	3149	2382	251	~220	~112	426	2776	2270	Great Dyke[100%]	UG[100%]	Aquarius Platinum[50%], Implats[50%]
Zimplats (Zimbabwe)	4,094,849	3.00	5408	4391	480	~707	602	3131	2231	2231	Great Dyke[100%]	UG[100%]	Implats[87%]
Lac des Iles (Canada)	649,649	6.06	152	2956	–	–	–	125	179	298	–	UG[100%]	North American Palladium
East Boulder (USA)	708,523	17.14	2519	8428	62	–	–	280	525	374	JM Reef[100%]	UG[100%]	Norilsk Nickel[51.5%]
Stillwater (USA)	362,880	12.68	933	3203							JM Reef[100%]	UG[100%]	Norilsk Nickel[51.5%]
Total	7.44 Mt	5.08	12,009	18,404	793	~700	~300	1308	6432	4875			

Table 12
Major Ni–Cu-PGE producers (2010 data).

Mine/project	t ore milled	%Ni	%Cu	PGEs g/t	kt Ni	kt Cu	kg Pt	kg Pd	kg Au	Mine type	Owners
Nkomati (South Africa)	5,058,000	0.39	0.17	0.94	10.1	5.6	373	1866	–	OC, UG	Norilsk Nickel[50%], ARM[50%]
Tati (South Africa)	8,380,000	0.23	0.23	>0.36[a]	12.0	11.9	435	2612	–	OC[100%]	Norilsk Nickel[85%], Botswana[15%]
Vale Sudbury (Canada)	2,660,000	1.78	1.53	>1.60[a]	22.4	34.0	1089	1866	1306	UG[100%]	Vale Inco[100%]
Taimyr Peninsula (Russia)	16,118,000	1.41	2.31	7.51	196.5	348.4	20,619	84,654	–	UG[~90%], OC[~10%]	Norilsk Nickel[100%]
Kola Peninsula (Russia)	8,336,000	0.67	0.29	–[b]	39.0	17.3	–[b]	–[b]	–	UG, OC	Norilsk Nickel[100%]
Jinchuan (China)	~8300,000[c]	~1.3[c]	~2.4[c]	~0.2[c]	~90[c]	~150[c]	~800[c]	~800[c]	–	UG[100%]	Jinchuan Nickel[100%]
Kambalda[c,d] (Australia)	1,060,823	3.01[c]	0.22[c]	~0.8[c]	26.8[c]	1.9[c]	~144	~637	–	UG[100%]	BHP Billiton[100%,d]
Total	~49.9	1.02	1.34	>2.7	396.8	569.1	23,460	92,435	>1300		

OC — open cut; UG — underground; ARM — African Rainbow Resources.
[a] Yield not assay grade.
[b] PGE production included in Taimyr Peninsula.
[c] Approximate data only (adapted from Mudd, 2010a).
[d] All Western Australian Pt–Pd assumed to be from Kambalda only.

small scale open cut is used initially to facilitate the development of underground mining (e.g. to make decline construction more economic). A major trend in the Bushveld is the increasing depth of underground mines, with current underground and open cut mine depths compiled in Table 14. It is worth noting that Impala Platinum only reports resources to a maximum depth of 2350 m at present (although some gold mines in the Witwatersrand Basin to the south of the Bushveld now reach more than 4 km in depth). The trend of increasing mine depth is also strongly evident in the Sudbury Basin Ni–Cu-PGE field in Canada, where mines now reach a maximum depth of ~2.5 km (Mudd, 2010a). Depth is important since it is more expensive for safety, haulage, ventilation (especially cooling against the geothermal gradient), costs, and a range of site-specific factors.

5. Discussion

To further examine potential future PGE production scenarios, a linear trend line is developed for production from 1960 to 2009, shown in Fig. 7 (with a coefficient of correlation of 0.960). Two simple 'peak PGE' models are also shown in Fig. 7, based on the application of a logistic curve to cumulative PGE production and resources using a Hubbert-style peak model (further explained in Glaister and Mudd (2010); see Mohr (2010) also). One model uses ~90,700 t PGEs remaining and a second model with ~338,400 t PGEs remaining (i.e. Cawthorn's geological estimate of global Bushveld resources plus the rest of the world), with both using cumulative production to 2009 of ~13,300 t PGEs. The statistical fit to actual production data would appear to be excellent, with coefficients of correlation of 0.982 and 0.975 for each peak model, respectively. The linear model gives annual production of ~1280 t PGEs by 2100, representing very low growth rates, with cumulative production (2010 to 2100) of ~80,400 t PGEs. The first peak model, using ~90,700 t PGEs of resources, reaches peak production of ~1496 t PGEs in 2043, while the second model using ~338,400 t PGEs of resources reaches peak production of ~5056 t PGEs in 2066. Both models have growth rates similar to historic trends. The substantive difference between the three models shows the critical importance of the remaining resources in underpinning future production scenarios — and therefore the need to justify PGE resources more thoroughly (as done in this paper).

It is abundantly clear, based on the key trends in Bushveld and Great Dyke reported PGE resources, as well as their respective geology, that the extent of geologic PGE resources is not the primary issue — since presently known resources, in combination with increasing resources as further exploration and development proceeds, can sustain and even grow production for some decades, at the very least until the latter part of this century.

At some Bushveld Complex mines there have been allegations of significant environmental and social impacts such as water pollution, unfair village relocation, economic disparity and compensation issues (Curtis, 2008; Mnwana and Akpan, 2009; Rajak, 2008). Selected issues can be investigated and addressed (e.g. water), while social and wealth distribution issues remain vexed. In theory, South Africa's black economic empowerment (BEE) policies are intended to address this historic disadvantage for communities, but progress is often perceived to be slow or non-existent, leading to a select few to argue for possible nationalisation of mining in South Africa (with similar sentiments in Zimbabwe). Furthermore, the electricity supply crisis in South Africa is affecting production (Yang, 2009), often limiting activities at mines and mills, though most now operate at close to full capacity. The ongoing social and economic transformation in Russia could also affect Noril'sk's capacity, depending on government policies.

Table 13
Early PGE ore processing yields (Cawthorn et al., 2002; RPM, 1957).

Site	Period	t ore milled	kg Pt	g/t Pt (yield)	g/t PGEs (yield)[a]
Waterberg	March to August 1926	4150	14	~3.4	~4.2
Waterberg	~1926 to ~1929	160,000	1150	~7.1	~9.0
Platreef	~1926 to ~1930	110,000	650	~5.9	~7.4
Rustenburg	1955	~1,600,000	~6,200[b]	~3.9	~6.0

[a] PGE yield based on 80% Pt, since this period produced ores which were dominantly Pt.
[b] South African PGE production in 1955 was 11,870 kg, and assuming 80% of this came from Rustenburg, this gives ~9500 kg PGEs and using 65% Pt in PGEs by this time, gives some 6200 kg Pt.

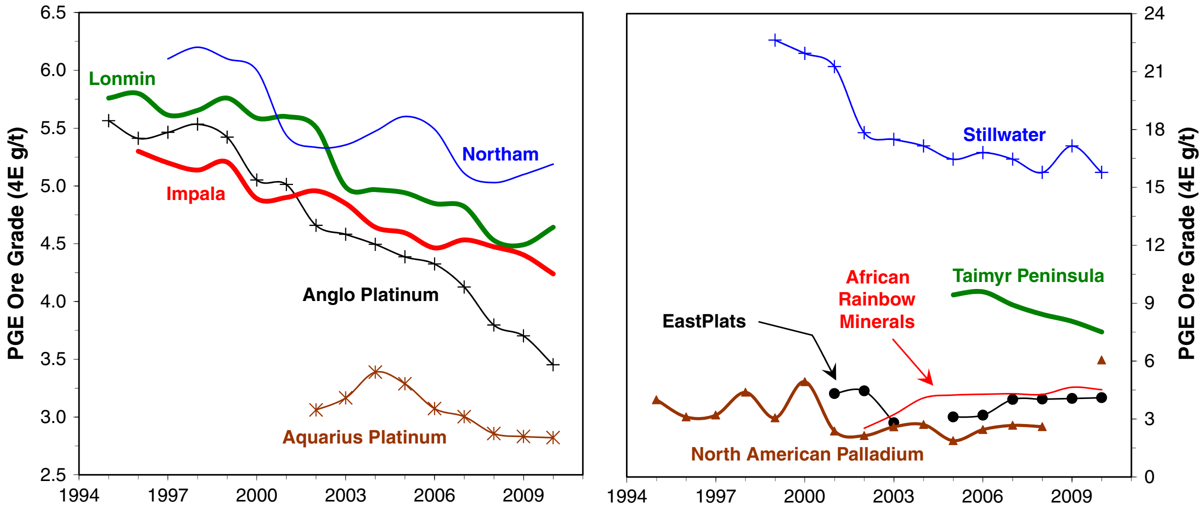

Fig. 5. Recent PGE ore grades by company during processing.

Other emerging issues are environmental in nature, such as energy consumption and greenhouse gas emissions, with most mines showing increasing energy and greenhouse gas emissions intensity over time (Mudd, 2012).

Finally, economic conditions are crucial to PGE demand. Twice in the past two decades alone PGE production slumped in response to poor global economic conditions (i.e. early 1990s and late 2000s). The relative prices for each of the PGEs, as well as substitution and ongoing technological development, will also influence PGE demand and supply.

None of these issues discussed above relate to geologic aspects of PGE resources but are all social, political, environmental, technological and/or economic in nature. The future supply of PGEs in the coming decades will be more critically determined by all of these factors rather than the present extent of reported economic PGE resources.

6. Conclusion

This paper has compiled and presented an extensive array of data on platinum group element resources and production, especially some key trends over time. The extent of economic PGE resources are clearly substantial and mostly concentrated in the Bushveld Complex in South Africa, followed by the Noril'sk–Talnakh field in Russia and Great Dyke in Zimbabwe. The 2010 global resources of ~90,700 t PGEs significantly exceeds the USGS reserves estimates, demonstrating the strong merit of detailed resource compilations as completed in this paper. The mining and processing of different PGE ores are now relatively straight forward, especially the three main Bushveld reefs, and future trends in ore grade will be governed by the balance of reef and mine types rather than ore processing technology. However, it is also clear that the primary factors which will influence PGE supply and the classification of economic mineral resources in the next few decades will be social, environmental, political and economic factors — certainly not geological factors or resource depletion. Overall, there is certainly room for optimism in the ability to increase PGE supply and resources in the medium term, mindful of social, environmental and economic factors.

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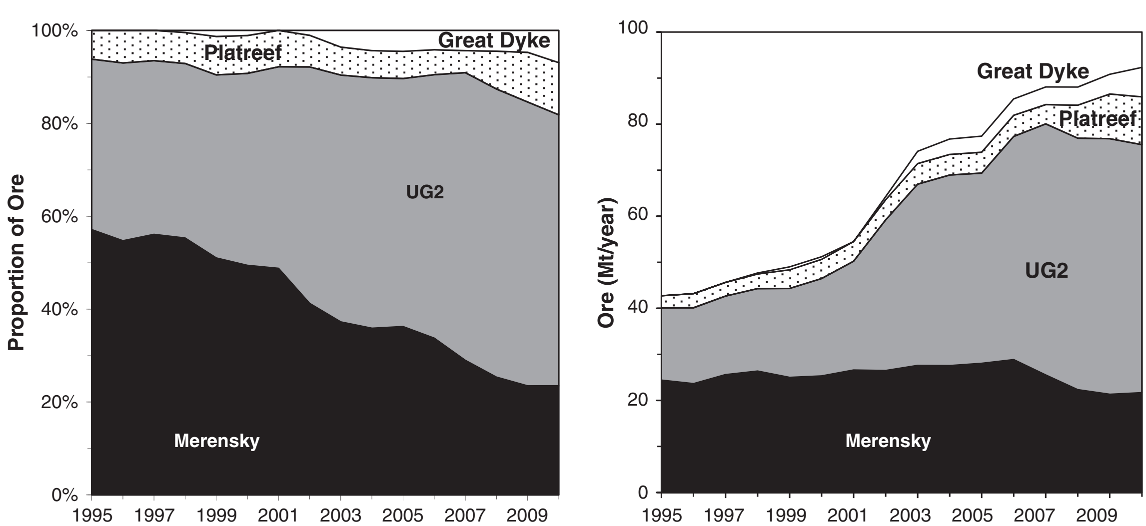

Fig. 6. Proportion of PGE ore by type for South Africa and Zimbabwe.

Table 14
Approximate operating depths for underground and open cut PGE mines, Bushveld Complex, Great Dyke and Stillwater.

Western Bushveld	Operating depths (m)	Eastern Bushveld	Operating depths (m)	Open cut project	Operating depths (m)
Bathopele	40 to 300	Twickenham	~110	Mogalakwena	60 to 240
Khomanani	635 to 1245	Modikwa	0 to 450	Marikana JV	Up to 200
Thembelani	600 to 900	Mototolo JV	0 to 450	Eland	Up to 105
Khuseleka	300 to 1000	Bokoni	0 to 500	Pilanesberg	Up to 180
Siphumelele	600 to 1350	Everest	Up to 250		
Tumela	160 to 850	Blue Ridge	Up to 275		
Dishaba	30 to 1250	Pandora JV	0 to 300		
Union	150 to 1500				
Bafokeng	50 to 500	Others			
Kroondal JV	0 to 450	Mimosa (Zimbabwe)	60 to 200		
Northam	1200 to 2200	Zimplats (Zimbabwe)	'Shallow'		
Impala	~800 to 1000	East Boulder (USA)	Up to ~500		
Marikana JV	0 to 450	Stillwater (USA)	Up to 595		

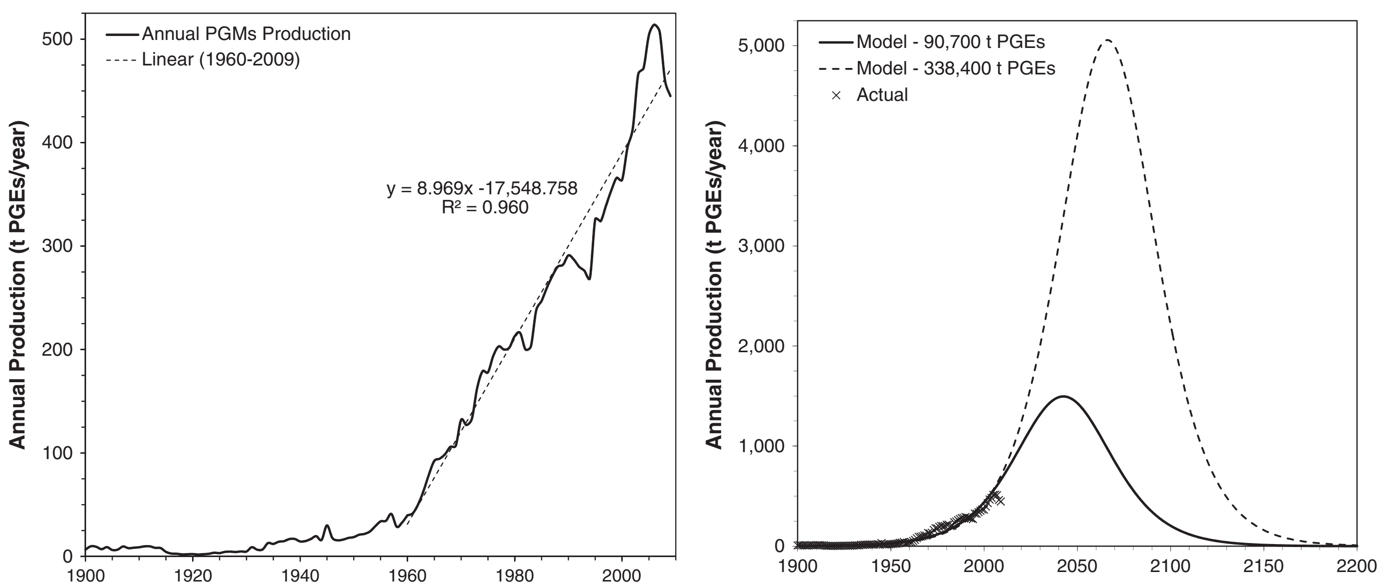

Fig. 7. Linear trend line for PGE production (1960 to 2009) (left); two 'peak PGE' models (right).

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