

Pt/Pd and Pd/Ir ratios in mantle-derived magmas: A possible role for mantle metasomatism

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ABSTRACT

We compare concentrations of Pt, Pd, and Ir in mantle-derived magmas, ranging from tholeiitic basalts to komatiitic basalts, komatiites, and various alkaline magmas, and in oceanic and continental settings. The alkaline magmas tend to have higher Pt/Pd ratios, but lower Pd/Ir ratios than most of the other magmas. We suggest this is attributable to different melting conditions in the mantle. Under relatively "dry" melting conditions applicable to tholeiites and komatiites, Pt-alloys and Os-Ir-Ru-Rh-enriched monosulfide solid solution (Mss) behave in a refractory manner, resulting in sub-chondritic Pt/Pd and super-chondritic Pd/Ir. Under fluid-rich melting regimes in metasomatised lithospheric mantle sources that may be applicable to the generation of many alkaline magmas, the alloys/mss are more fusible, resulting in PGE ratios closer to chondrite. Bushveld magmas and some continental flood basalts also have relatively high Pt/Pd ratios and may thus contain a component of the metasomatised sub-continental lithospheric mantle. Komatiites have relatively low Pt/Pd suggesting that they are derived from a dry mantle source.

Introduction

Most mantle-derived magmas (basalts, basaltic komatiites, komatiites) show a range of Pt/Pd ratios between 0.5 and ~1.2, and Pd/Ir ratios of 3 to several 100 (Figures 1 and 2; Table 1). Barnes and Maier (1999) summarized the data then available for mantle rocks and showed that they have Pt/Pd ratios around 2 and Pd/Ir ratios of 1.3, which is close to CI chondritic ratios. As more mantle rocks have been analyzed it has been realized that there is more variability in these ratios than was originally realized (*e.g.*, Morgan *et al.*, 2001; Lorand *et al.*, 2003), but the point remains that mantle rocks have Pt/Pd ratios considerably higher and Pd/Ir ratios considerably lower than those observed in the magmas presumably derived from them by partial melting. These observations suggest that some Pt and Ir are retained in the mantle during partial melting. The purpose of the present paper is to review the available PGE data on mantle-derived magmas and to evaluate possible models for the fractionation of Pt and Ir from Pd during the partial melting process.

Concentrations of platinum-group elements in mantle-derived magmas

Platinum-group element data from mantle-derived magmas are tabulated in Table 1. The frequency distributions of Pt/Pd and Pd/Ir ratios in different magma suites are shown in Figure 1, and the ratios are plotted versus MgO in Figure 2. The PGE contents of the magmas are variable, ranging between 0.6 to 26ppb Pt, 0.5 to 25ppb Pd, and 0.01 to 2.36ppb Ir. It should be noted that these values are averages and include some

phenocryst rich samples, *i.e.* most probably do not represent pure liquids. In addition, the PGE data were generated in different laboratories and by different methods. As a result the relative errors may be significant, particularly when comparing element ratios. However, we argue that the systematic nature of the observed variations is significant.

The data are biased towards komatiites, flood basalts, MORBs, and ocean island tholeiites. Far fewer PGE data have been published on alkaline magmas including alkali basalts, carbonatites, kimberlites and melilitites. Most tholeiites and komatiites have Pt/Pd ratios around or below unity (Figures 1 and 2) suggesting that fractionation of Pt from Pd during variable degrees of partial melting in the asthenosphere and mesosphere and during ascent and emplacement in the crust is of limited importance (but see Momme *et al.*, 2002, and Maier *et al.*, 2003, who present some evidence for fractionation of Pt from Pd during crystallization of basalts). Markedly higher Pt/Pd ratios are restricted to the Victorian tholeiites, one of the Indian Ocean island tholeiites and some of the Hawaiian picrites (Table 1).

In contrast, alkaline magmas (basalts, kimberlites, carbonatites, melilitites) tend to have higher Pt/Pd ratios (Figures 1 and 2), approaching the values proposed for primitive mantle (Barnes and Maier, 1999). Alkali basalts from Mangaia in the Cook Islands are a notable exception (Tatsumi *et al.*, 2000), in that they have Pt/Pd below unity. It is unclear why this should be so, but Hauri and Hart (1993) have shown that these are HIMU basalts that may have formed under different conditions than other ocean island alkali basalts. One possibility is

Table 1. Compositional data from mantle-derived magmas.

	n	MgO	Ir	Pt	Pd	Pt/Pd	Pd/Ir
Komatiites							
Komati ¹	18	26.30	1.15	3.8	3.9	1.09	3.3
Mt. Keith ²							
west. ultram.	12	34.01	1.42	4.3	4.8	1.02	3.6
centr. ultram.	14	29.00	2.36	9.8	11.3	0.86	4.9
Pyke Hill ³	5	27.56	0.91	16.9	10.2	1.62	12.6
Alexo ⁴	3	24.71	2.27	14.6	18.1	0.83	8.6
Belingwe ⁴	1	18.10	1.11	13.1	12.4	1.06	11.2
Munro ⁴	2	28.50	1.45	9.6	9.1	1.06	6.3
Baby ⁵	5	21.14	0.77	13.5	12.4	1.10	28.9
Kostomuksha ⁶	6	27.50	1.38	9.1	11.0	0.83	7.9
Reliance ⁷	15	17.78	0.72	10.1	9.4	1.11	19.8
Finnmark ⁸	24	23.86	1.50	11.0	11.0	1.00	7.3
Continental tholeiites							
Karoo: LF ⁹	14	6.40	0.04	4.8	7.4	0.94	269.0
Hekpoort ⁹	5	8.38	0.16	7.5	7.2	1.00	52.0
Ventersdorp ⁹	7	10.97	0.28	8.7	10.6	0.81	71.5
Soutpansberg ⁹	6	5.37	0.26	9.9	7.2	1.41	28.0
Noril'sk (MK) ¹⁰	10	6.83	0.09	6.3	6.2	1.07	74.1
Noril'sk (MR) ¹⁰	10	6.94	0.07	4.7	4.0	1.24	63.9
Noril'sk (TK) ¹⁰	4	9.17	0.11	11.5	11.6	0.99	133.7
Deccan ¹¹	18	6.20	0.08	4.3	12.0	0.36	142.9
Victorian tholeiites ¹²	7	6.87	0.01	2.1	0.5	6.47	80.7
North Mountain ¹³	14	7.00	0.20	5.9	5.2	1.70	81.3
Muskox ¹⁴	11	8.39	0.22	7.4	7.9	1.70	42.2
Cape Smith: olivine spinifex ¹⁵	20	15.47	0.61	11.6	9.8	1.22	18.9
Duluth ¹⁶	2	8.41	0.20	8.6	10.0	0.88	49.7
Etendeka: Tafelberg ⁹	3	12.42	0.85	7.3	11.3	0.70	48.0
SE Greenland ¹⁷	56	9.10	0.41	6.7	7.5	0.92	21.0
E Greenland rifted margin ¹⁸	35	9.82	0.34	6.7	12.0	0.71	100.0
Oceanic tholeiites							
Kolbeinsey ⁴	6	8.20	0.03	0.7	1.5	0.63	44.9
Iceland rift ⁴	4	9.29	0.13	5.2	7.4	0.91	47.9
Transvaal: Machadodorp ⁹	5	8.55	0.18	10.0	14.3	0.70	96.0
Etendeka: Hooringbaai ⁹	3	11.67	0.56	6.7	11.8	0.59	171.0
Ocean Island tholeiite							
Indian Ocean: 706P ¹⁹	3	5.97	0.11	2.0	2.8	0.70	25.4
Indian Ocean: 707P1 ¹⁹	4	9.34	0.02	3.7	14.3	0.26	715.0
Indian Ocean: 707E ¹⁹	4	6.95	0.07	4.9	18.4	0.26	262.9
Indian Ocean: 713P ¹⁹	9	7.68	0.22	10.6	12.3	0.86	55.9
Indian Ocean: 713E ¹⁹	2	6.07	0.15	6.1	6.2	0.98	41.3
Indian Ocean: 715UP ¹⁹	3	11.09	0.27	27.0	10.2	2.65	37.8
Indian Ocean: 715LP ¹⁹	5	10.40	0.14	5.1	6.6	0.77	47.4
Indian Ocean: 715LE ¹⁹	1	6.20	0.02	2.5	7.0	0.36	350.5
Hawaii: Kilauea ²⁰	18	8.60	0.42	3.7	2.7	1.64	6.5
Ocean Island picrite							
Hawaii: Kilauea ²⁰	3	14.40	0.46	4.1	2.0	2.13	3.1
Hawaii: Loihi ²¹	2	24.00	1.32	5.7	7.5	0.75	5.5
Hawaii: Mauna Kea ²¹	1	17.20	na	2.2	2.2	1.01	na
Hawaii: Hualalai ²¹	1	13.70	na	4.7	3.8	1.24	na
Hawaii: Mauna Loa ²¹	1	21.50	0.42	3.3	2.8	1.19	6.6
Hawaii: Koolau ²¹	2	18.20	0.17	3.3	1.4	2.29	8.5
Boninites							
Boninite ²²	6	na	0.07	5.4	5.5	1.00	77.9
Izu-Bonin boninites ²³	4	9.83	0.08	3.2	3.9	1.05	82.0

Table 1. Compositional data from mantle-derived magmas. Continued

	n	MgO	Ir	Pt	Pd	Pt/Pd	Pd/Ir
Alkali basalt							
Indian Ocean: 706E ¹⁹	19	5.45	0.11	1.2	0.8	1.46	7.4
Indian Ocean: 715UE ¹⁹	2	6.04	0.03	10.2	2.4	4.20	81.0
Cameroun line ⁴		8.48	0.05	0.4	0.2	2.07	18.3
Brazil ²⁴	4	13.59	0.38	7.9	5.8	1.38	15.6
Victoria ¹²	9	10.90	0.06	3.7	0.9	6.18	20.5
Hawaii: Haleakala ²⁰	6	7.22	0.08	0.5	0.5	1.16	14.4
Hawaii: West Maui ²⁰	3	8.45	0.16	1.2	1.1	1.23	30.1
Cook Islands: Mangaia ²⁵	5	9.69	0.11	0.7	1.0	0.65	10.1
Cook Islands: Rarotonga ²⁵	5	9.7	0.14	2.1	2.0	1.07	15.0
Kimberlites							
Kaapvaal ²⁴	21	24.34	1.26	7.0	4.6	1.70	4.2
Kaapvaal ²⁶	2	27.19	0.92	1.5	1.4	1.06	1.6
Brazil ²⁴	4	29.02	1.49	10.0	6.8	1.54	4.6
Mellilitites							
Kaapvaal ²⁴	3	18.07	0.68	11.0	7.3	1.50	10.8
Carbonatite							
Brazil ²⁴	2	na	0.33	7.2	5.6	1.29	17.0
Bushveld							
High-Mg basalt (B1) ²⁷	9	12.06	0.35	16.7	12.1	1.56	95.0
Al-tholeiite (B3) ²⁷	5	6.65	0.09	10.6	6.0	1.36	87.0

1: Maier *et al.* (2003a); 2: Dowling and Hill (1992); 3: Crocket and McRae (1986)

4: Rehkamper *et al.* (1999); 5: Mainville (1994);

6: Puchtel and Humayun (2000); 7: Zhou (1994); 8: Barnes *et al.* (1988)

9: Maier *et al.* (2001); 10: Bruegmann *et al.* (1993); 11: Crocket (2002b)

12: Vogel and Keays (1997); 13: Greenough and Freyer (1995); 14: Barnes and Francis (1995);

15: Barnes and Picard (1993); 16: Theriault *et al.* (1997); 17: Phillipp *et al.* (2001);

18: Momme *et al.*, (2002); 19: Freyer and Greenough (1992); 20: Crocket (2002a)

21: Bennett *et al.* (2000); 22: Peck and Keays (1990); 23: Woodland *et al.* (2002);

24: McDonald *et al.* (1995); 25: Tatsumi *et al.* (2000); 26: Maier *et al.* (2003b)

27: Davies and Tredoux (1985).

dl = below detection limit; na = not available

that they formed at relatively larger degrees of partial melting of a more fertile source incorporating ancient subducted oceanic crust, and at greater depth (Kogiso *et al.*, 1997). Walker *et al.* (1995) suggested that HIMU basalts are derived from the core-mantle boundary. Whatever the case, it is notable that basalts at Rarotonga, an island located adjacent to Mangaia, are derived from a non-HIMU source (Kogiso *et al.*, 1997) and have Pt/Pd ratios above unity, similar to other alkali basalts.

Arc and back arc basalts have highly variable Pt/Pd ratios (*e.g.* Woodland *et al.*, 2002) and are not included in the present comparison because it is possible that some of these magmas may contain a mobile PGE component from the subducted ocean floor (probably Pd), disturbing the Pt/Pd relationships observed in the mantle-derived magmas.

Bushveld magmas also have relatively high Pt/Pd ratios (Figure 1 and 2) when compared to large-volume continental magmatism elsewhere (*e.g.* large layered intrusions, flood basalts). Based largely on lithophile trace element and isotope data, some previous workers

(*e.g.* Hamlyn and Keays, 1986; Hatton and Sharpe, 1988; Harmer and von Gruenewaldt, 1993) have suggested that Bushveld magmas formed by melting of metasomatised lithospheric mantle sources. The Kaapvaal lithospheric mantle is known to have been pervasively metasomatized by fluids, and highly alkaline melts of kimberlitic affinity (*e.g.* Grégoire *et al.*, 2003, and references therein). These workers have distinguished two types of metasomatism, namely (i) modal metasomatism that is characterized by the formation of new minerals such as amphibole, phlogopite and clinopyroxene, and (ii) cryptic metasomatism that is characterized by enrichment in incompatible trace elements and Fe (Gaul *et al.*, 2000) but where new minerals have not formed. Importantly, neither fluid- nor melt-related mantle metasomatism is likely to have a strong influence on PGE concentrations in the mantle, due to the highly chalcophile character of the PGE. As a result the PGE probably behave immobile during the equilibration of small-degree melts and fluids with mantle sulfides and/or PGM.

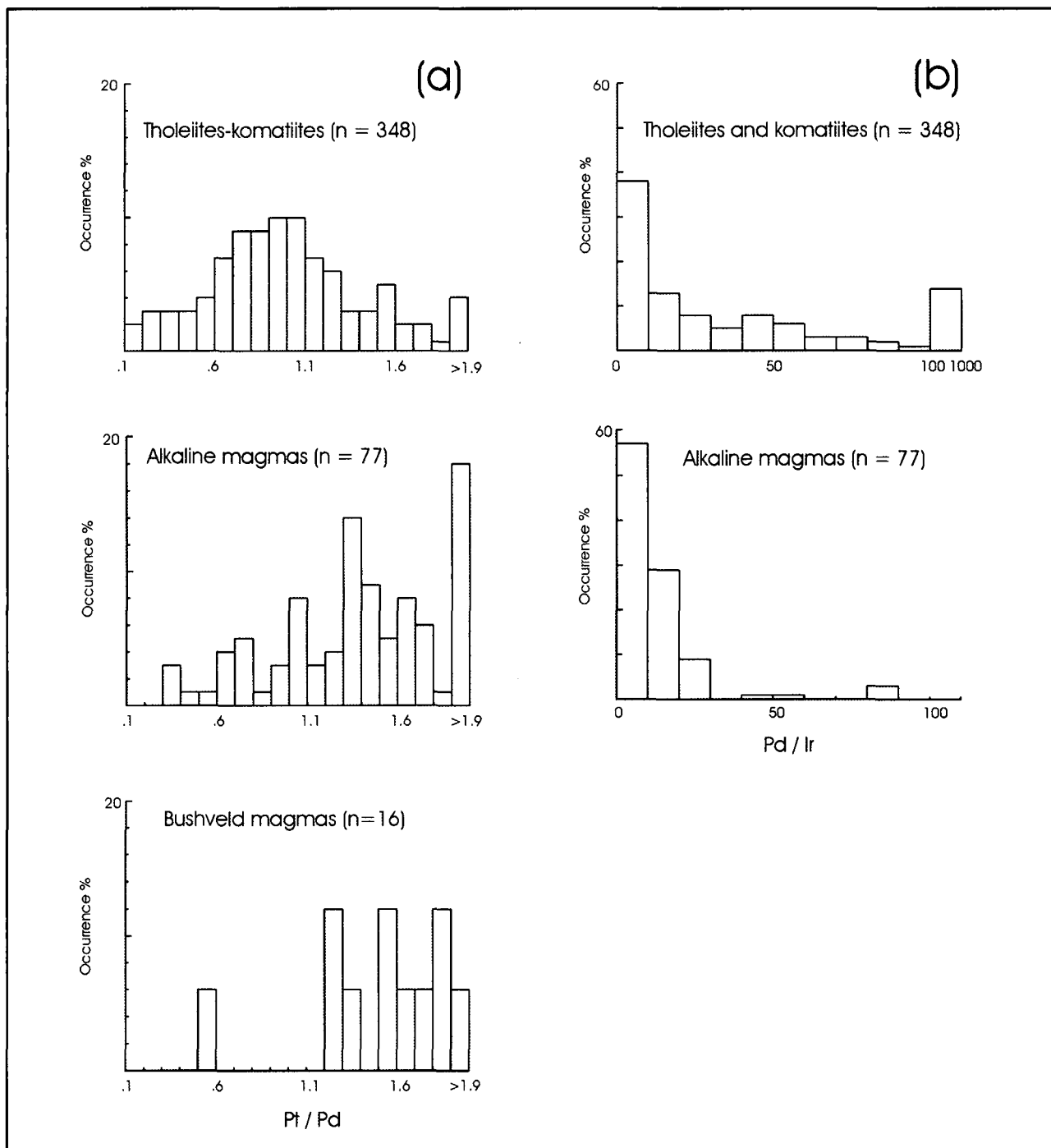


Figure 1. Frequency distribution of (a) Pt/Pd and (b) Pd/Ir in tholeiites + komatiites, alkaline magmas, and Bushveld B1 + B3 parental magmas.

In addition to variation in Pt/Pd, Figures 1b and 2b illustrate that there is also a trend of the alkaline magmas having lower Pd/Ir ratios at comparable MgO contents than the komatiites and tholeiites. Therefore, the processes responsible for generating alkaline magmas in the mantle source appear to fractionate both Pt and Ir from Pd.

In the following, we will first briefly review the nature of possible host phases to the PGE in the mantle before evaluating how these phases may behave during partial melting of the mantle and thereby influence PGE fractionation.

PGE hosts in the mantle

Recent work by Bulanova *et al.* (1996), Alard *et al.* (2000), Lorand and Alard (2001), and Lugué *et al.* (2001) suggests that the individual PGE are hosted by different types of sulfides in both the primordial and the lithospheric mantle. The IPGE and Rh are mainly hosted by Mss that is often included in silicate minerals, whereas Pd is mainly hosted by interstitial Cu-rich sulfides. Evidence for the existence of refractory metal phases that may additionally accommodate Os, Ir, Ru, Rh, and Pt has been summarized by Lorand *et al.* (1999). A discrete Pt rich phase has also been postulated by

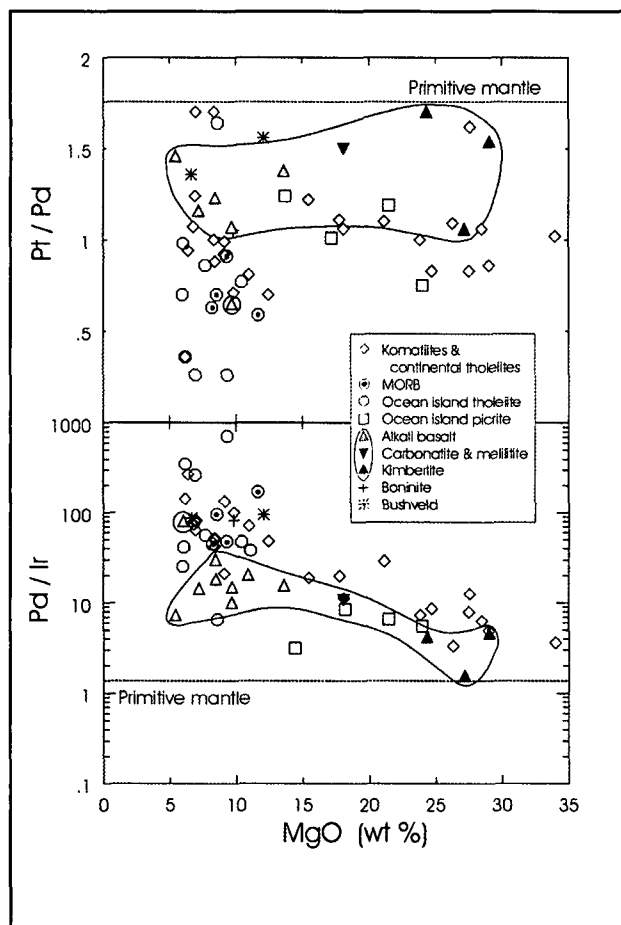


Figure 2. (a) Pt/Pd ratios, and (b) Pd/Ir ratios of mantle-derived magmas plotted vs MgO. See text for explanation.

Alard *et al.* (2000) and Lugué *et al.* (2001), but whether this is primary or has formed during alteration remains unclear. Andrews and Brenan (2002) suggest that in a basalt saturated with sulfide liquid the fS_2 of the sulfide liquid is positively correlated with fO_2 of the basalt. The fO_2 of most basalts is close to QFM, and at QFM the fS_2 of a base metal sulfide liquid is fairly high. At high fS_2 sulfide liquid will dissolve PGE at the percent level, thus Andrews and Brenan (2002) argue against co-existence of PGE alloys and sulfide melt in basalts at QFM. Assuming that fO_2 is close to QFM (or above) during partial melting of the mantle Andrews and Brenan's (2002) experiments rule out the co-existence of Pt-alloys and sulfides. On the other hand, Peregoedova *et al.* (2002) have shown that at low fS_2 Mss undergoes partial melting to form a Cu-Pd rich sulfide liquid, Fe-rich mss and Pt and Ir alloys and thus at low fO_2 , alloys and sulfide liquids could co-exist. Therefore, under relatively reducing conditions in the mantle the sulfides and alloys might be stable together. Haggerty and Tompkins (1983) have suggested that the lithosphere is more reduced (<magnetite-wustite buffer) than the upper portion of the asthenosphere, but Arculus and Delano (1987) presented contrasting evidence and thus the redox state of the upper mantle remains unclear.

Fractionation of platinum-group elements during partial melting

Small- to moderate-degree mantle melts (< ~25% partial melting) are thought to be S saturated at the source, as the sulfides in the mantle cannot be completely dissolved in the magma (Keays, 1982; Barnes *et al.*, 1985). Kimberlites and other alkaline magmas may form by small degrees of melting (Yoder and Tilley, 1962), possibly explaining their low PGE contents. In contrast, komatiites and many tholeiites form by larger degrees of melting at which all sulfides in the source may have been dissolved in the silicate magma. This is commonly assumed to explain their relatively higher PGE contents (Table 1). One could go on to argue that sulfide retention in the mantle during small degree melting will retain all PGE in the mantle resulting in broadly chondritic PGE ratios and thus relatively high Pt/Pd and low Pd/Ir in the alkaline magmas (Figure 1). However, tholeiites and komatiites tend to have relatively low Pt/Pd, although they span a wide range of degrees of melting. This suggests that, in addition to sulfides, another phase or other phases control(s) PGE fractionation during mantle melting. The most likely candidates are Os-Ir-Ru-Rh-Pt alloys (*e.g.* Lorand *et al.*, 1999). The data in table 1 suggest that the alloys and/or the mss may behave in a refractory manner during partial melting that produces tholeiites and komatiites, but that they are relatively fusible during the generation of alkaline magmas. A possible reason for the enhanced fusibility of refractory alloys and mss during the formation of alkaline magmas is discussed in the following.

Formation of alkaline magmas

Kimberlites and carbonatites

Kimberlites and carbonatites are generally seen to represent small-degree melts of CO_2 -bearing upper mantle garnet peridotite. Amongst other factors, this is indicated by their enrichment in incompatible trace elements. Notably, isotopic signatures of these rocks are highly heterogeneous (Harmer, 1999). Most carbonatites tend to have a strongly to moderately depleted signature, whereas kimberlites span a much wider field of isotopic compositions. South African Group-I kimberlites overlap with the field of carbonatites but South African type-II kimberlites (orangeites) have highly enriched isotopic signatures. Harmer (1999) proposed that the parental magmas to both kimberlites and carbonatites originally formed in the asthenosphere. These trace element-enriched melts then underwent fractionation at the base of the lithosphere, they metasomatized the base of the lithosphere, and they interacted with low-degree partial melts of the lithosphere, thereby producing Group-I kimberlites. Group-II kimberlites may be the result of interaction of the asthenospheric melts with lithosphere that had a prolonged history of metasomatism. If the lithosphere fractures, the kimberlites erupt. If the lithosphere does not fracture, CO_2 rich residues of the kimberlite melts

may percolate to shallower mantle levels and ultimately erupt to form carbonatites. The important role of lithospheric mantle sources in the formation of kimberlites and carbonatites could provide an explanation for their high Pt/Pd and low Pd/Ir ratios relative to most tholeiites and komatiites. We propose that under the relatively dry melting conditions applying to the tholeiites and komatiites, refractory Mss and Fe-Pt alloy could retain Ir and Pt, whereas Pd would be removed with the Cu-sulfide melt. This produces relatively low Pt/Pd and high Pd/Ir ratios in the tholeiitic and komatiitic magmas. During the fluid-rich melting regime applicable to the formation of kimberlites and carbonatites, the relatively refractory Pt alloys and the Mss may be destabilized, resulting in lower Pd/Ir and higher Pt/Pd than in the tholeiites and komatiites. While there is, as yet, little experimental data to constrain this model, the fluxing effect of volatiles on melting eutectica in multi-phase silicate systems is well established. We essentially suggest that this fluxing effect equally applies to PGM.

Alkali basalts

It is not the purpose of the present study to review the immense amount of data and the petrogenetic models relating to the formation of alkali basalts. Suffice it to say that the genesis of many alkali basalts remains controversial. According to perhaps the most popular view most alkali basalts are generated at relatively small degrees of partial melting of enriched mantle sources at high pressure, within plumes ascending from a deep-seated mantle reservoir, whereas tholeiites form at relatively larger degrees of melting at lower pressure (Yoder and Tilley, 1962; Jaques and Green, 1980). The PGE variations shown in Figure 2 are not in agreement with this model. Larger-degree melts (tholeiites and komatiites) would be expected to have lower Pd/Ir and higher Pt/Pd ratios than low-degree melts (*i.e.* the alkali basalts) particularly so if the magmas are derived from broadly similar sources.

An alternative view on the formation of some alkali basalts has been expressed by Bailey (1983) and Francis and Ludden (1990, 1995). Based on LILE and high field strength element systematics, Francis and Ludden (1995) suggested that alkali basalts in the northern Canadian Cordillera formed from metasomatized portions of the lithospheric mantle enriched in amphibole, at depths > 12kbar. The depleted isotopic signature and simultaneous enrichment in incompatible trace elements of alkaline end member magmas from Hawaii (Roden *et al.*, 1984) is analogous to that observed in Group-I kimberlites and carbonatites. Further, individual Hawaiian volcanoes and lava flows are characterized by contrasting isotopic compositions (Leeman *et al.*, 1977), apparently requiring mixing of different end-member magmas derived from different mantle sources. These observations suggest an extremely heterogeneous mantle source for Hawaiian basalts, consistent with derivation from mantle lithospheric sources that have been

metasomatized shortly before melting. Melting could have been triggered by lithosphere-plume interaction, fracturing of the lithosphere in extensional regimes, *e.g.* in rift- or back arc environments, or isostatic adjustment of the lithosphere beneath growing oceanic island volcanoes. The PGE data reviewed in the present paper are in agreement with this model. The elevated Pt/Pd ratios and low Pd/Ir ratios of the alkali basalts relative to the examined tholeiites could be the result of magma generation and/or equilibration in the "wet" metasomatized lithosphere.

Formation of continental flood basalts

Many continental flood basalts have a distinct crustal component, as expressed by enriched isotopic compositions (high initial Sr ratios, low $\epsilon\text{Nd}(T)$), enriched and strongly fractionated incompatible trace elements, and negative Nb-Ta anomalies. In the case of the Kaapvaal flood-type basalts the available information has been summarized by Harmer and von Gruenewaldt (1993) and Maier *et al.* (2000). Two genetic models to explain the crustal signatures may be distinguished: (i) Contamination of mantle-derived magmas by continental crust during ascent. (ii) Derivation of the magmas from a source in the "wet" continental lithospheric mantle (*e.g.*, Turner *et al.*, 1996). Both mechanisms may produce similar geochemical signatures and thus the origin of the crustal component remains controversial. Maier *et al.* (2003b) investigated the PGE contents of Kaapvaal flood-type basalts and MORBs and found that the flood-type basalts tend to have higher Pt/Pd ratios than the MORBs. Their data are incorporated in Figure 2 and it is evident that there is a trend of the continental tholeiites to overlap with the field of the alkali basalts. These results could be interpreted to indicate the presence of a lithospheric mantle component in the flood-type basalts.

Formation of komatiites

Arndt *et al.* (1998) have reviewed and assessed models of komatiite formation. Most workers feel that komatiites are large-degree melts of a depleted and dry mantle source. An alternative model invoking melting of a hydrous mantle source has recently gained some support (*e.g.* Parman *et al.*, 1997). However, the PGE data presented in Figure 2 show that most komatiites have relatively low Pt/Pd ratios, in the range of most tholeiites. Based on the interpretations presented in the proceeding chapters, these data would seem to be in support of komatiite formation from relatively dry mantle.

The origin of Bushveld magmas

The Bushveld Complex is by far the largest layered intrusion on Earth and Bushveld magmas have amongst the highest Pt/Pd ratios observed in large-volume magmatic events. This is also reflected in the composition of Bushveld cumulates and most Bushveld ores (*i.e.* the Merensky Reef, Barnes and Maier, 2002,

and references therein), which have significantly higher Pt/Pd ratios than most other large layered intrusions and associated ores. A number of authors (e.g., Hamlyn and Keays, 1986; Hatton and Sharpe, 1988; Harmer and von Gruenewaldt, 1993) suggested that Bushveld magmas formed from metasomatised sub-continental lithospheric mantle (SCLM), raising the possibility of similarities in the formation of Bushveld and alkaline magmas. In contrast, Barnes (1989) and Maier *et al.* (2000) proposed that Bushveld magmas are contaminated komatiites. As was mentioned in the case of flood-type basalts, the two processes have been difficult to distinguish (see review by Lassiter and de Paolo, 1997). The data and interpretations presented in the present paper may support a model involving an SCLM component in the Bushveld magmas. One could go on to suggest that other layered intrusions, most of which are Pd dominated, contain a smaller lithospheric component. An alternative possibility is that the Kaapvaal lithosphere was more pervasively metasomatised than other cratonic roots elsewhere, but the accumulating mantle xenolith data from, e.g., Finland (Peltonen, 2003) provides no support for this model.

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