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Petrogenesis of contact-style PGE mineralization in the northern lobe of the Bushveld Complex: comparison of data from the farms Rooipoort, Townlands, Drenthe and Nonnenwerth

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Abstract In the present study, we document the nature of contact-style platinum-group element (PGE) mineralization along >100 km of strike in the northern lobe of the Bushveld Complex. New data from the farm Rooipoort are compared to existing data from the farms Townlands, Drenthe, and Nonnenwerth. The data indicate that the nature of the contact-style mineralization shows considerable variation along strike. In the southernmost portion of the northern Bushveld, on Rooipoort and adjoining farms, the mineralized sequence reaches a thickness of 700 m. Varied-textured gabbronorites are the most common rock type. Anorthosites and pyroxenites are less common. Chromitite stringers and xenoliths of calcsilicate and shale

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are largely confined to the lower part of the sequence. Layering is locally prominent and shows considerable lateral continuity. Disseminated sulfides may reach ca. 3 modal % and tend to be concentrated in chromitites and melanorites. Geochemistry indicates that the rocks can be correlated with the Upper Critical Zone. This model is supported by the fact that, in a down-dip direction, the mineralized rocks transform into the UG2-Merensky Reef interval. Between Townlands and Drenthe, the contact-mineralized sequence is thinner (up to ca. 400 m) than in the South. Chromitite stringers occur only sporadically, but ultramafic rocks (pyroxenites, serpentinites, and peridotites) are common. Xenoliths of calcsilicate, shale, and iron formation are abundant indicating significant assimilation of the floor rocks. Sulfides may locally form decimeter- to meter-sized massive lenses. PGE grades tend to be higher than elsewhere in the northern Bushveld. The compositions of the rocks show both Upper Critical Zone and Main Zone characteristics. At Nonnenwerth, the mineralized interval is up to ca. 400 m thick. It consists largely of varied-textured gabbronorites, with minor amounts of igneous ultramafic rocks and locally abundant and large xenoliths of calcsilicate. Layering is mostly weakly defined and discontinuous. Disseminated sulfides (<ca. 3 modal %) occur throughout much of the sequence. Geochemistry indicates that the rocks crystallized mainly from tholeiitic magma and thus have a Main Zone signature. The implication of our findings is that contact-style PGE mineralization in the northern lobe of the Bushveld Complex cannot be correlated with specific stratigraphic units or magma types, but that it formed in response to several different processes. At all localities, the magmas were contaminated with the floor rocks. Contamination with shale led to the addition of external sulfur to

the magma, whereas contamination with dolomite may have oxidized the magma and lowered its sulfur solubility. In addition to contamination, some of the magmas, notably those of Upper Critical Zone lineage present at the south-central localities, contained entrained sulfides, which precipitated during cooling and crystallization.

Introduction

The Bushveld Complex of South Africa contains the world's largest mafic-ultramafic intrusions, measuring ca. 65,000 km^2 (Eales et al. 1993; Eales and Cawthorn 1996). The cumulate package is up to ca. 8 km thick and shows a broad trend of progressive differentiation from magnesian ultramafic rocks at the base to relatively siliceous dioritic rocks at the top. The sequence is generally subdivided into five major "zones." An impersistantly developed noritic Marginal Zone is overlain by the ca. 1-km-thick Lower Zone that consists predominantly of harzburgite and orthopyroxenite. The Lower Critical Zone is ca. 500 m thick and contains orthopyroxenites and several massive chromitite layers. The Upper Critical Zone is equally ca. 500 m thick and shows prominent interlayering of orthopyroxenite, norite, anorthosite, and chromitite. The Main Zone forms a ca. 3-km package of relatively homogenous gabbronorite. The Upper Zone is ca. 2 km thick and consists of gabbronorite, anorthosite, and diorite, containing more than 20 massive magnetite layers.

The platinum-group element (PGE) mineralization of the Bushveld Complex is mainly hosted in two types of deposits. The first type consists of relatively narrow (up to ca. 1 m wide) stratiform layers (so-called reefs) that occur towards the top of the Upper Critical Zone, typically some 2 km above the base of the intrusion. The Merensky Reef sulfide-bearing pyroxenite–melanorite and the UG2 chromitite are the most notable examples. They contain consistently high PGE grades (5–8 ppm) over hundreds of kilometers of strike, mainly within the eastern and western lobes of the Complex (Barnes and Maier 2002a, b; Cawthorn et al. 2002). The second type of PGE deposit comprises contact-style mineralization at the base of the intrusion, often referred to as Platreef. It occurs mainly in the northern lobe (Viljoen and Schürmann 1998), with possible correlatives in the Mineral Range (Sharpe et al. 2002). The thickness of the mineralized package can reach several hundred meters, but the mineralization is laterally much less continuous than the internal reefs, and PGE grades are mostly lower (<1–4 ppm). Because of this, exploration for contact-style mineralization has intensified only relatively

recently, in the aftermath of an important upsurge in PGE prices starting in the 1990s. As a result, at many localities in the northern limb of the Bushveld Complex, the geological and compositional characteristics of the contact-style mineralization remain poorly known. The present study reexamines the compositional and lithological variation of the PGE mineralization along >100 km of strike in the northern lobe, notably on the farms Townlands, Drenthe, and Nonnenwerth, and presents new data from the farm Rooipoort. In particular, we aim to place the mineralization into the broad lithostratigraphic framework of the Bushveld Complex, constrain the composition of the magmas from which the sulfides crystallized, and evaluate the role of floor contamination in triggering sulfide segregation from the magma.

Nature of the contact-style PGE mineralization

Sulfide mineralized rocks of considerable, but variable thickness (several tens to hundreds of meters) occur near the base of the mafic–ultramafic layered sequence in much of the northern lobe of the Bushveld Complex (Fig. 1). The main area where the mineralization does not seem to be developed comprises a ca. 10-km sector to the south of Nonnenwerth where the Upper Zone has transgressed through the Main Zone and directly overlies the floor of the intrusion (Fig. 1). The absence of sulfide mineralization in this area is indicated by a stream sediment survey conducted by the Geological Survey of South Africa. The survey failed to identify a pronounced positive Cu anomaly that is typical of the base of the remainder of the northern lobe.

At many localities, the sulfide mineralization is largely hosted by mela-, meso-, and leucogabbronorites, as well as norites and anorthosites (Fig. 2a,b). Ultramafic rocks including pyroxenites, serpentinites, and peridotites are less common and are largely, but not solely, confined to the south-central portion of the northern lobe, from Macalacaskop (Kinnaird et al. 2005) to the area around Sandsloot (McDonald et al. 2005; Fig. 1). In many cases, the ultramafic rocks are calcsilicates formed during metamorphism of dolomite xenoliths. However, igneous peridotites also occur (e.g., on Macalacaskop, Kinnaird et al. 2005, and Nonnenwerth, Manyeruke 2007). Chromitite layers and lenses up to several decimeters in width are common on Rooipoort and neighboring farms (Fig. 2a). They may also occur on Sandsloot, Turfspruit, and Tweefontein, but there, they tend to be thinner and more sporadic. Xenoliths of the floor rocks (Fig. 2b) and inclusions of various intrusive phases (Fig. 2d–e) are abundant and range in size from a few centimeters to tens of meters in height and up to hundreds of meters in width, e.g., on Drenthe (Kinnaird et al. 2005) and Nonnenwerth (Manyeruke
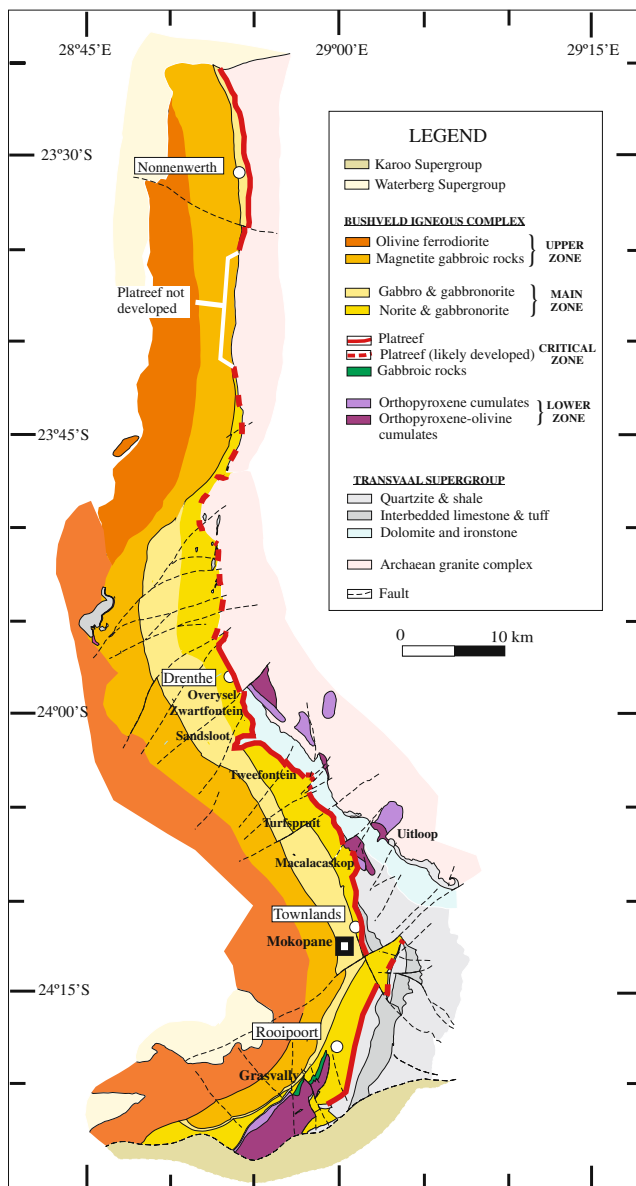
Fig. 1 Geological map of the northern lobe of the Bushveld Complex, indicating localities mentioned in the text (figure adapted from Ashwal et al. 2005)

2007). Some of the xenoliths may be attached to the floor, in which case, the sulfide-mineralized intrusions have been interpreted to form sills (e.g., Manyeruke et al. 2005).

The mineralized rocks are often described as being varied-textured because they show heterogeneity in grain size, grain shapes, and mineral modes on a scale of centimeters to meters. The bulk of the rocks are medium grained, but there also occurs a fine-grained contact phase (as, e.g., exposed on Rooipoort, Sandsloot, Drenthe, and Nonnenwerth) and, locally, pegmatitic pods, schlieren, and veins. Layering and banding may be well developed on a local scale, but is laterally much less persistent than in the remainder of the Bushveld making lithostratigraphic correlations difficult.

Sulfide contents mostly range from trace amounts to a few percent, but in some cases, massive concentrations of sulfide several meters in thickness may occur (e.g., on Turfspruit and Tweefontein, Kinnaird et al. 2005; Fig. 2c). PGE grades are mostly <1–2 ppm, but higher grades are found in individual samples throughout the northern limb and, in particular, at Sandsloot and surrounding farms where average grades are ca. 4 ppm over 10 m (Vermaak 1995). Even higher grades have recently been described from Akanani, 5 km to the north of Sandsloot (http://www. Afriore.com).

The nature of the floor rocks to the mineralized intrusive rocks shows considerable variation. In the southern portion of the northern lobe, on Rooipoort and adjoining farms, the mineralized sequence mostly rests on the Magaliesberg quartzite. The latter occurs midlevel within the up to ca. 15-km-thick Transvaal Supergroup and also forms the floor rocks of much of the western and eastern lobes of the Bushveld Complex. Towards the north, the intrusion transgresses stratigraphically progressively lower members of the Transvaal Supergroup (Fig. 1). On Townlands and Macalacaskop, the floor consists largely of shales of the Timeball Hill Formation (Manyeruke et al. 2005; Kinnaird et al. 2005). On Turfspruit and Tweefontein, the floor rocks are sulfidic shales and limestones of the Duitschland Formation (Kinnaird et al. 2005). In the southern parts of Tweefontein, the floor is formed by Penge iron formation (Buchanan et al. 1981). From northern Tweefontein to Zwartfontein, the intrusion rests on dolomite of the Malmani subgroup (White 1994; Harris and Chaumba 2001) that constitutes the basal member of the Transvaal Supergroup in the studied area. In the remainder of the northern lobe, from Overysel to Nonnenwerth, the floor rocks consist of Archean granite gneiss that forms the basement to the Transvaal Supergroup (Stevens 2004; Manyeruke 2007).

The xenoliths within the mineralized sequence consist mainly of dolomite/calcsilicate and less abundant hornfels, quartzite, and ironstone. The xenolith population thus broadly reflects the spectrum of the floor rocks to the intrusion, with the notable exception of granite gneiss that forms >50% of the exposed floor (Fig. 1), but appears to be poorly represented in the xenolith population (e.g., Cawthorn et al. 1985, but see Stevens 2004, who described some examples at Drenthe). There is an imperfect correlation between the nature of the floor rocks and that of the xenoliths. Shale, quartzite, and ironstone xenoliths mainly occur in the south. In contrast, calcsilicate xenoliths occur throughout the northern lobe (Manyeruke 2003; Kinnaird et al. 2005). They are particularly abundant where the intrusion overlies dolomite of the lower Transvaal Supergroup (e.g., on Sandsloot and adjoining farms), but they also occur further to the north where the exposed floor consists of
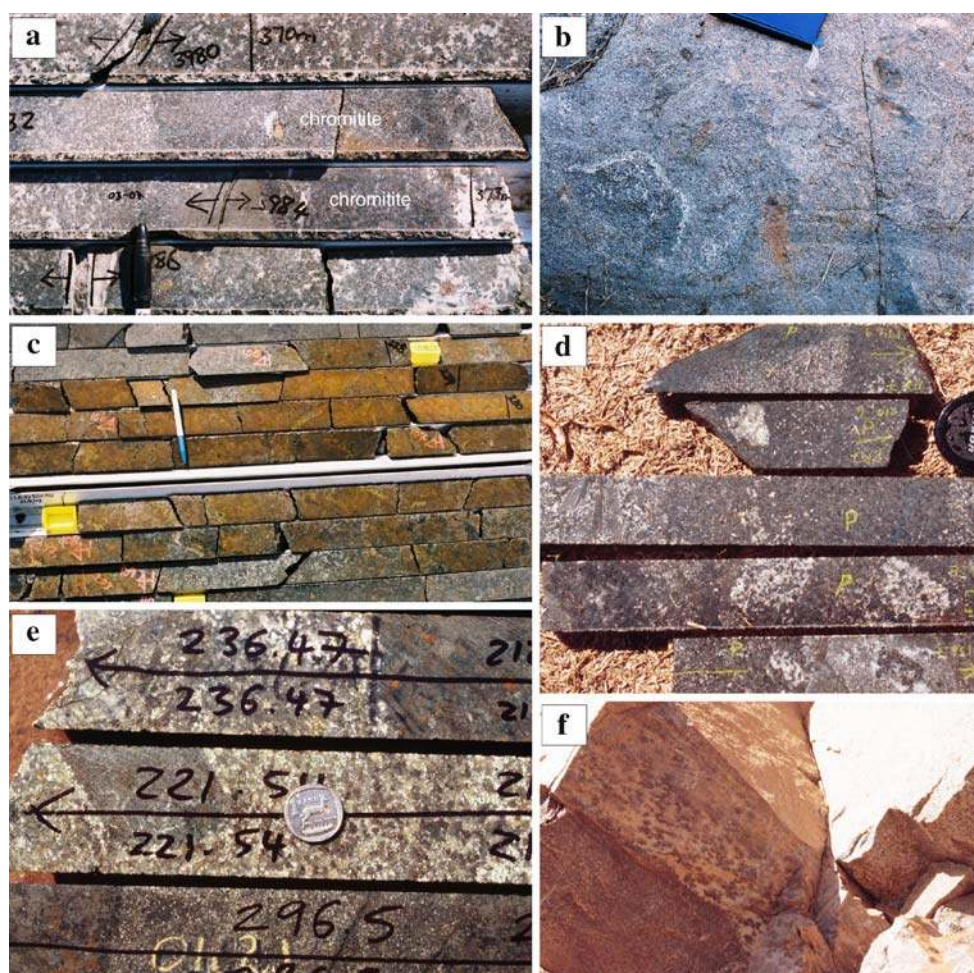
Fig. 2 Platreef lithologies in the northern lobe of the Bushveld Complex. **a** Varied-textured gabbronorite containing chromite-rich layers as well as a fragment of fine-grained (chilled?) gabbronorite, lower portion of LMF, Rooipoort, borehole 03–07. **b** Varied-textured gabbronorite containing xenoliths of calcsilicate and shale, as well as subangular domains of coarse-grained gabbronorite with pegmatoidal felsic margins, Turfspruit. **c** Massive sulfide near base of Platreef, Turfspruit. **d** Varied-textured gabbronorite from different stratigraphic levels of the Platreef at Drenthe (borehole PR7). Mesogabbronorite containing subangular inclusions of different phases of leucogabbronorite (medium to fine grained) as well as irregular pegmatoidal domains. **e** Leucogabbronorite showing variable grain size and containing inclusions of meso- to melagabbronorite. Note that disseminated sulfides are concentrated in melanocratic phase. Nonnenwerth, borehole 2121. **f** The uppermost Platreef on Zwartfontein consists of medium- to fine-grained pyroxenite/melagabbronorite that is overlain, with a sharp contact, by ca. 50 cm of mottled anorthosite followed by medium-grained gabbronorite of the Main Zone

granite gneiss basement and to the south where the floor consists predominantly of shale, quartzite, and ironstone. This suggests that some of the calcsilicate xenoliths have been assimilated upstream or down-dip of the present exposure and were entrained by the intruding magmas.

The hanging wall to the contact-mineralized sequence consists mostly of compositionally and texturally relatively homogenous gabbronorites that are generally correlated with the Main Zone (e.g., Gain and Mostert 1982; Harris and Chaumba 2001; Kinnaird 2005). The contact between the Main Zone and the underlying Platreef is often difficult to delineate because the two units may contain similar rock types. At Sandsloot, the contact is relatively sharp and often defined by a mottled anorthosite (Fig. 2f). A similar relationship has been described from Turfspruit (Kinnaird 2005). Based on microscopic and outcrop-scale textural and structural observations, Holwell et al. (2005) suggested that there may have been a significant hiatus between the formation of the Platreef and the intrusion of the Main Zone.

To the south of Mokopane, on Rooipoort and Grasvally, sulfide-mineralized contact-style rocks are overlain by sulfide-bearing, interlayered, pyroxenite-, gabbronorite-, norite-, anorthosite-, (chromitite-) bearing cyclic units that have been correlated with the Merensky Reef and associated rocks of the Upper Critical Zone (Hulbert 1983).

Previous lithogeochemical work on the contact-style mineralization

Soon after the discovery of the Merensky Reef in the eastern and western Bushveld Complex, Wagner (1929) highlighted certain lithological similarities between the Merensky Reef and rocks occurring along the base of the northern lobe, including the occurrence of PGE-rich disseminated sulfides hosted by pyroxenites and melagabbronorites of variable but often coarse-grained texture. Wagner (1929) went on to suggest that the two layers are essentially correlatable. Subsequent workers have questioned this correlation pointing out important differences between the contact-style mineralization and the Merensky Reef. The contact-mineralized interval is much thicker than the Merensky Reef, it contains abundant xenoliths that are lacking in the Merensky Reef, and it occurs at the base of the intrusion, whereas the Merensky Reef mostly occurs several kilometers above the base. Recognizing these differences, van der Merwe (1976) proposed to use the term "Platreef" for the contact-style mineralized rocks in the northern lobe of the Bushveld Complex. Many present workers (e.g., Kinnaird et al. 2005) apply the term exclusively to mineralization that is hosted by predominantly pyroxenitic rocks, which would restrict the occurrence of the Platreef sensu stricto to the sector between

Macalacaskop and Overysel. Although being somewhat arbitrary on petrogenetic grounds, this definition has the merit of delineating the most highly mineralized areas.

From the 1980s onwards, a considerable amount of compositional data on the contact-style mineralization began to appear in the public domain, initially on Platreef rocks at Sandsloot and adjoining farms (Tweefontein, Overysel, Drenthe). These data showed distinct compositional differences between the Merensky Reef and the Platreef, notably higher initial Sr isotope ratios and more variable $\delta^{34}S$ in the latter (Liebenberg 1970; Buchanan et al. 1981; Cawthorn et al. 1985; Barton et al. 1986). To many authors, this confirmed that the contact-style sulfide mineralization is not equivalent to and did not form in the same way as that in the Merensky Reef. Instead, the model mostly applied is one whereby the basal sulfides segregated in response to contamination of either the Upper Critical Zone or Main Zone magma with the sedimentary floor rocks (Buchanan et al. 1981; Gain and Mostert 1982; Kruger 2005).

During the last 5 years, a significant amount of additional data was published. These data confirm important compositional differences between the Upper Critical Zone and the contact-style mineralization at some localities, but they also indicate that the latter shows considerable variation along strike and, in places, bears important similarities to the Upper Critical Zone (Table 1). A summary

Table 1 Composition of minerals and rocks in the Platreef and the Merensky Reef

	Minerals				Whole rocks			
	Opx Mg#	Olivine Fo	Plag An	Chromite Cr_2O_3	Cr	Pd/Ir	Pt/Pd	Cu/Ni
Platreef								
Rooipoort[a]								
LMF					7,743	87	0.88	0.87
MANO					1,129	149	0.56	0.78
Townlands[b]	80	83	84		978	111	0.69	0.93
Turfspruit/Macalacaskop[c]		71						
Tweefontein[d]	78	76						
Sandsloot[e]	81	72						
Overysel[f]	74							
Drenthe[g]			81	46	834	92	0.92	0.45
Nonnenwerth[h]	75		75		291	380	0.72	2.03
Merensky Reef[i]	81	81	82	44	7,160	17	2.72	0.35

[a] This study
[b] Manyeruke (2003)
[c] Buchanan and Rouse (1984)
[d] Buchanan et al. (1981)
[e] Harris and Chaumba (2001)
[f] Cawthorn et al. (1985)
[g] Stevens (2004)
[h] Manyeruke (2007)
[i] De Klerk (1992), Maier and Eales (1997)

of some of the most important studies and results is given in the following.

Lithophile whole rock data were presented by Harris and Chaumba (2001, from Sandsloot), Manyeruke (2003) and Manyeruke et al. (2005, both from Townlands), Stevens (2004, from Drenthe), McDonald et al. (2005, from Sandsloot), and Manyeruke (2007, from Nonnenwerth). The studies by Manyeruke (2007), Stevens (2004), and McDonald et al. (2005) also provide comprehensive incompatible trace element data showing that, at different localities, the contact rocks contain a varying amount of crustal component. The Townlands rocks are characterized by fractionated incompatible trace elements, an enrichment in large ion lithophile elements, and pronounced negative Nb–Ta–Ti anomalies. These features are characteristic of the Upper Critical Zone of the Bushveld Complex (e.g., Maier and Barnes 1998), but some samples contain concentrations of rare earth elements (REE) and other incompatible trace elements far in excess of most other mafic–ultramafic Bushveld rocks, indicating localized assimilation of crust. At Sandsloot, Drenthe, and Nonnenwerth, trace element patterns are relatively unfractionated. They resemble, in many regards, those of the Main Zone and tholeiitic B2/B3 Bushveld magmas (Stevens 2004; McDonald et al. 2005; Manyeruke 2007). This could either suggest less contamination of the basal magma in the central and northern sector of the northern lobe or contamination with rocks that have low concentrations of incompatible trace elements, e.g., dolomites.

Comprehensive noble metal data on the contact-mineralized rocks were presented by Vermaak (1995), Armitage et al. (2002), Manyeruke (2003, 2007), Stevens (2004), Naldrett (2004), and Manyeruke et al. (2005). The studies by Manyeruke (2003, 2007) and Stevens (2004) also provide matching sulfur data. Several other studies (e.g., Gain and Mostert 1982; White 1994; Kinnaird 2005; Kinnaird et al. 2005; Holwell and MacDonald 2006) presented PGE data in diagrammatic form. One of the most notable results of these studies is that the Platreef appears to contain more PGE and sulfides than the Upper Critical Zone of the western and eastern limbs of the Bushveld Complex. For example, there are up to 23 m of mineralized rocks at 2.07-ppm PGE at Nonnenwerth, up to 100 m at 1.11 ppm at Drenthe, and up to 44 m at 4.1 ppm at Akanani. In contrast, the UG1 of the western and eastern Bushveld has 1- to 2-ppm PGE over ca. 1 m, the UG2 has ca. 6 ppm over 1 m, the Pseudoreefs have 1- to 2-ppm PGE over 1–5 m, the Merensky Reef has 6-ppm PGE over ca. 1 m, and the Bastard Reef has up to ca. 1-ppm PGE over a few centimeters (Barnes and Maier 2002a, b, and references therein). Some of the host rocks to these reefs also contain elevated PGE contents (notably the UG2 pyroxenite), but this has little influence on the total PGE budget.

Analogous to the lithophile data, the available PGE data from the contact mineralization show considerable variation between localities. Relatively low metal grades (mostly <1 ppm) and fractionated PGE patterns (Pd/Ir~100) occur at Townlands (Manyeruke et al. 2005), higher grades (often >3 ppm over thick intervals) with less fractionated patterns (Pd/Ir~50–100, Vermaak 1995) occur at Sandsloot, and low to intermediate grades (commonly 1–2 ppm) with highly fractionated patterns (Pd/Ir > 100) occur at Nonnenwerth (Manyeruke 2007). Pt/Pd ratios of the sulfide-rich rocks vary mostly between ca. 0.3 and unity (Kinnaird et al. 2005). Notably, the Merensky Reef and its associated rocks in the western and eastern Bushveld Complex have distinctly different noble metal patterns, with Pd/Ir ca. 20 and Pt/Pd mostly ca. 2.5 (Potts et al. 1992; Barnes and Maier 2002a, b).

The isotope database on the contact-mineralized rocks remains relatively small. The most comprehensive data set comprises sulfur isotopes. Townlands rocks have $\delta^{34}S$ +4 to +8 (Manyeruke et al. 2005), those at Turfspruit and Macalacascop have $\delta^{34}S$ +3 to +5 (Sharman-Harris et al. 2005), Tweefontein rocks have $\delta^{34}S$ +3 to +6, Zwartfontein has $\delta^{34}S$ +2 (Liebenberg 1970), and Nonnenwerth has $\delta^{34}S$ mostly +1 to +2 (Manyeruke 2007). In contrast, the Merensky Reef and the UG2 have $\delta^{34}S$ around mantle levels (Liebenberg 1970). There is a tentative, yet imperfect, correlation between the sulfur isotope and the lithophile trace element data. For example, in some of the southern localities (e.g., at Townlands), fractionated trace element signatures occur together with relatively heavy sulfur isotopic signatures, whereas, at Nonnenwerth, the mineralized rocks are characterized by unfractionated trace element patterns and mantle-like S isotopes. Thus, if the basal magma at the northern localities was contaminated with crust then the contaminant contained either few sulfides or sulfides with mantle-like isotopic signatures.

Harris and Chaumba (2001) conducted a detailed oxygen and hydrogen isotopic study of the Platreef at Sandsloot, and of Main and Upper Zone rocks further to the north. Their data indicate that the Main and Upper Zones have a homogenous crustal component possibly derived from the assimilation of lower crust. In contrast, the Platreef crystallized from a magma that was significantly more contaminated with isotopically heavy crustal oxygen. Much of the heavy oxygen was proposed to be derived from assimilated dolomitic floor rocks during emplacement. Sharman-Harris et al. (2005) also found oxygen isotopic evidence for floor assimilation by the Platreef magma on Turfspruit.

Osmium and Nd isotope data provide less evidence for local assimilation. Re/Os isotopic data on Platreef rocks from Sandsloot and Turfspruit indicate a significant crustal component, but broadly in the range of Lower and Critical Zone rocks from elsewhere in the Bushveld Complex

(Chaumba et al. 1998; Ruiz et al. 2004). Nd isotopic data on the Platreef at Drenthe indicate crustal values similar to the Main Zone of the western Bushveld Complex (εNd −6.9 to −7.7; Stevens 2004).

Several recent studies focused on the composition of sulfides and platinum-group minerals (PGM) in the contact-style mineralization, notably the work of Hutchinson and Kinnaird (2005) at Turfspruit and Macalacaskop, Holwell et al. (2006) at Sandsloot, and Manyeruke (2007) at Nonnenwerth. These studies suggest considerable mobility of S in syn- and postemplacement fluids and felsic melts resulting in both S loss and gain and the formation of secondary sulfides (chalcopyrite, pyrite, millerite) and PGM.

Geology and stratigraphy of the Bushveld rocks on Rooipoort and adjoining farms

The local geology on the farm Rooipoort has been summarized by De Klerk (2005, Fig. 3). The sulfide-bearing sequence at the base of the intrusion is up to ca.
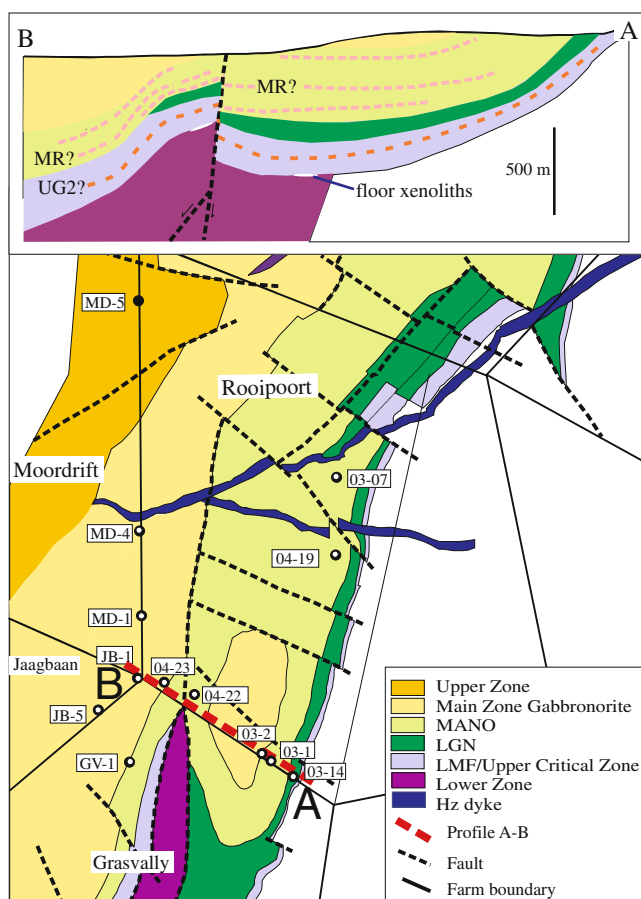
Fig. 3 Simplified geological map of the farm Rooipoort and adjoining farms showing locality of boreholes mentioned in the text (modified after De Klerk 2005). Insert shows profile along B-A
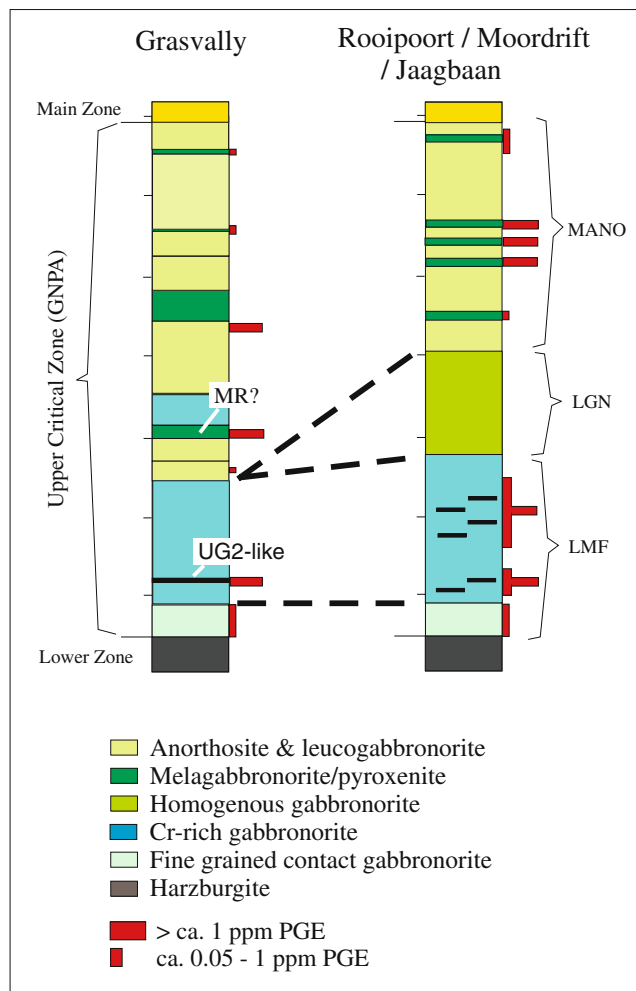
Fig. 4 Schematic stratigraphy of mineralized interval in the western portion of Rooipoort (this work), compared with Upper Critical Zone/GNPA on Grasvally (from Hulbert 1983). Note that, on Grasvally, mineralized intervals (red bars) tend to be thinner, but more metal rich

700 m thick and contains three main subunits (Fig. 4). At the base is the 50- to 200-m-thick mineralized LMF (lower mafic subunit). This is overlain by the unmineralized 50-to 100-m-thick LGN (lower gabbronorite subunit) and, at the top, the 200- to 400-m-thick mineralized MANO (mottled anorthosite subunit). Notably, this sequence occurs in essentially unchanged form across the property, i.e., it may overlie ultramafic rocks of the Lower Zone in the west and quartzitic rocks of the Transvaal Supergroup in the east (Fig. 3).

At the base of the LMF is an interval of mostly fine-grained gabbronorite, up to ca. 20 m in thickness that may represent a chilled contact facies. The rocks may locally grade into medium-grained gabbronorite and contain traces of fine disseminated sulfides with PGE contents up to a few tens of parts per billion. Xenoliths of calcsilicate and quartzite, up to several meters in thickness, may occur along the contact with the Lower Zone or the quartzitic

floor and within the overlying fine-grained gabbronorite (e.g., in boreholes 03–07, 03–14, 04–23, and 05–49). These observations have several petrogenetic implications. Firstly, the presence of the chilled contact at the base of the gabbronorite indicates that there was a significant hiatus between the crystallization of the Lower Zone and the intrusion of the LMF (e.g., Hulbert 1983; van der Merwe 1976). Secondly, the xenolith-enriched horizon between the Lower Zone and the chilled LMF may represent portions of the preserved roof rocks of the Lower Zone. Thirdly, the presence of calcsilicate xenoliths suggests that although dolomite does not form part of the immediate floor rocks to the Platreef at Rooipoort, it is probably exposed in a down-dip direction. Fourthly, the absence of gabbroic rocks at the top of the Lower Zone that may represent differences of the ultramafic rocks suggests that the Lower Zone has intruded as a crystal mush.

The fine-grained contact phase is overlain by a succession of medium-grained, varied-textured gabbronorites containing abundant metasedimentary xenoliths, and several centimeter- to decimeter-sized layers, schlieren and fragments of chromitite (Fig. 5a–c). Sulfide contents in this unit are higher than in the contact phase and range between trace amounts and ca. 3 modal %. PGE grades locally reach up to ca. 2 ppm. The highest-PGE and -sulfide contents tend to be associated with the chromitites.

The LMF is overlain by relatively homogenous gabbronorite of the LGN. The unit contains no chromitites, and sulfides are rare. Based on textural evidence, i.e., the development of a fine-grained contact phase against the LMF, De Klerk (2005) suggested that the LGN may represent a sill-like injection of Main Zone magma.

Next is the MANO, a sequence characterized by interlayering of anorthosite, mela gabbronorite, gabbronorite, and minor chromitite containing several horizons of sulfide enrichment, up to several meters in width (e.g., Fig. 5d). On Rooipoort, at least three of these layers show considerable lateral continuity (De Klerk 2005). Xenoliths of calcsilicate

Fig. 5 Lithologies of the LMF and MANO on Rooipoort and Moordrift. **a** Varied-textured gabbronorite, showing variable grain size and color index, interlayered with decimeter-wide chromitite seams and felsic veins. Borehole 03–12, upper portion of LMF. **b** Schlieren and clasts of chromitite in gabbronorite, central-upper portion of LMF, borehole 04–23. **c** Massive chromitite enriched in sulfide, central portion of LMF, borehole 04–22. **d** Melagabbronorite containing weak PGE enrichment overlying anorthosite and leucogabbronorite. Central portion of MANO, borehole 03–08. **e** Boulder-like aggregate of melagabbronorite, upper portion of MANO, borehole 03–08. **f** UG-like chromitite within gabbronorite on Moordrift, borehole MD4, 895.4–896 m

and hornfels occur in places, but are less common than in the LMF. In many, but not all cases, the sulfides occur at the base of thick (tens of m) melagabbronoritic layers (Fig. 5d). PGE grades of the sulfide-enriched layers are mostly below ca. 1–2 ppm, but may reach up to ca. 5 ppm. The MANO may also contain centimeter-sized boulder-like concretions of melagabbronorite and pyroxenite within leucogabbronorite (Fig. 5e) that are somewhat reminiscent of the boulders in the boulder bed of the western Bushveld Complex (Lee and Sharpe 1980; Maier and Barnes 2003), except that the latter tend to be larger and are hosted in a distinct, several meters-wide anorthosite layer.

A broadly similar sequence of variably mineralized rocks as that described above has previously been documented on the farm Grasvally, immediately to the south of Rooipoort (Hulbert 1983; Fig. 4) where it is known as the Grasvally norite-pyroxenite-anorthosite member (GNPA). The rocks have been correlated with the Upper Critical Zone by Hulbert (1983) based largely on stratigraphic, lithological, and compositional grounds: (1) The GNPA contains a massive chromitite referred to as the "UG2-like chromitite" in the lower portion of the sequence (Fig. 4). The latter bears certain similarities to the UG2 chromitite elsewhere in the Bushveld, notably a comparable thickness (up to ca. 1.5 m), enrichment in noble metals (up to 6 ppm PGE, average 3.3 ppm), elevated Pt/Pd (1.89), and similar Cr/Fe ratios (1.35–1.5; Botha 1985). Of all Bushveld chromitites, similarly high PGE grades and low-Cr/Fe ratios are essentially confined to the UG2. However, the UG2-like chromitite has distinctly higher-sulfide contents (ca. 1.3%) than most examples of UG2 chromitite elsewhere in the Bushveld. (2) In the hanging wall of the UG2-like chromitite on Grasvally, there occur several sulfide-mineralized pyroxenite, norite, and gabbronorite layers (Fig. 4) with peak grades of ca. 3- to 4-ppm PGE that resemble, to some degree, the Merensky Reef and associated rocks.

The GNPA at Grasvally can be correlated to the farms Jaagbaan, Moordrift, and Rooipoort (Fig. 3). For example, the UG2-like chromitite has been intersected in boreholes JB5 on Jaagbaan and MD4 on Moordrift (Fig. 3), but it appears to show less lateral continuity than on Grasvally (Botha 1985). In the easternmost portions of Jaagbaan, the chromitite begins to disintegrate, forming laterally highly impersistent schlieren and lenses similar to those observed at an analogous stratigraphic level on western Rooipoort (Fig. 5a–c). In the hanging wall of the UG2-like chromitite, there occur several sulfide-mineralized pyroxenite, norite, and gabbronorite layers with broadly similar peak PGE grades as analogous layers at Grasvally and Rooipoort (Botha 1985).

Based on the above stratigraphic, lithological, and compositional data, the possibility arises that the contact-style mineralization on Rooipoort can be correlated with the Upper Critical Zone.

New compositional data from Rooipoort and comparison to Townlands, Drenthe, and Nonnenwerth

Methods

The analytical program was designed with two main objectives in mind: (1) to compare the sulfide-mineralized rocks on Rooipoort to the Platreef and the Upper Critical Zone elsewhere in the Bushveld and (2) to examine local compositional differences at Rooipoort, between mineralized samples overlying the Lower Zone and those overlying the sedimentary floor rocks. This required major and trace element analysis of a considerable number of drillcore samples (82) from boreholes situated throughout the project area (Table 2).

The concentrations of the lithophile elements were determined at Royal Holloway University, UK. Samples were dissolved by fusion and acid digestion. A 0.2 g of sample was mixed with 1.0 g of lithium metaborate and fused in graphite crucibles at 950°C for 20 min. Ga was used as an internal standard. The mixture was dissolved in 200 ml of 5% HNO_3. This solution was used for the determination of SiO_2, Al_2O_3, and Zr by optical ICP-AES. It was also used for the determination of Cs, Nb, Rb, Ta, Th, Tl, U, Y, and the rare earth elements La, Ce, Pr, Nd, Sm, Eu, Gd, Dy, Ho, Er, Yb, and Lu by ICP-MS (mass spectrometry) after dilution (1:5). Samples were also dissolved in HF and HCl_4. A 0.2 g of sample was evaporated to dryness with 6 ml of HF and $HClO_4$ (2:1). This was then dissolved in dilute nitric acid and made up to 20 ml (10% HNO_3). This solution was used for the determination of Fe, Mg, Ca, Na, K, Ti, P, Mn, Ba, Co, Cr, Cu, Li, Ni, Sc, Sr, V, and Zn by optical ICP-AES. Laboratory standards were used for instrument calibration and drift correction. International reference materials were also used to confirm accuracy. The concentrations of the PGE were determined by ICP-MS at Genalysis, Australia. Analytical accuracy and precision were routinely checked using international standards, including SCo, BHVo, and NIMG, and by analyzing blanks and duplicates. Sulfur isotope analyses were performed at Indiana University, USA using combustion techniques.

In the following sections, the Rooipoort data are compared to our previously published and our unpublished data on contact-mineralized rocks from Townlands (Manyeruke 2003; Manyeruke et al. 2005), Drenthe (Stevens 2004), and Nonnenwerth (Manyeruke 2007).

CIPW Norms

As many of the contact-mineralized rocks are relatively altered, we have used whole rock data to calculate CIPW norms and thereby elucidate the mineralogical variation in

Table 2 Composition of Platreef and Main Zone rocks at Rooipoort

Sample	3030	3038	3054	5508	5509	5511	5510	5512	5514	5515	5516	5517	5501
Borehole	03 10	03 10	03 10	03 10	03 10	03 10	03 10	03 10	03 10	03 10	03 10	03 10	04 23
Rocktype	MANO	MANO	LGN	LGN	LGN	LGN	LGN	LMF	LZ	MZ	Dol	Dol	MZ
Depth	25.00	45.00	185.50	86.85	122.15	131.25	145.55	191.3	208.45	216.9	225.4	228.5	30.7
SiO_2 (wt%)	51.13	51.37	53.08	52.82	53.26	53.05	51.67	47.10	44.69	51.13	33.48	46.33	52.23
TiO_2	0.17	0.21	0.28	0.16	0.28	0.24	0.42	0.18	0.16	0.09	0.21	0.22	0.21
Al_2O_3	23.26	21.58	16.51	18.31	17.61	16.45	16.41	6.69	4.09	27.77	5.39	4.90	18.40
FeO	3.88	5.66	6.88	5.76	6.32	6.78	8.46	13.69	10.62	1.64	23.50	15.43	6.06
Fe_2O_3	0.68	1.00	1.21	1.02	1.12	1.20	1.49	2.42	1.87	0.29	4.15	2.72	1.07
Fe (sulf)	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
MnO	0.09	0.09	0.16	0.13	0.14	0.15	0.17	0.27	0.36	0.06	0.23	0.11	0.17
MgO	6.70	6.96	9.96	9.90	8.63	9.99	8.77	24.26	35.03	3.22	30.78	20.85	8.38
CaO	11.35	10.29	9.06	9.59	9.78	9.76	10.08	4.45	1.81	12.31	0.48	8.61	10.51
Na_2O	2.28	2.24	2.16	1.95	2.37	1.98	2.04	0.39	0.16	1.68	0.02	0.12	2.56
K_2O	0.36	0.35	0.55	0.21	0.37	0.25	0.35	0.08	0.44	1.77	1.73	0.67	0.38
P_2O_5	0.03	0.13	0.03	0.03	0.03	0.02	0.02	0.01	0.08	0.02	0.01	0.02	0.01
Cr_2O_3	0.07	0.07	0.10	0.10	0.09	0.11	0.10	0.35	0.54	0.01	0.00	0.01	0.02
Ni (sil)	0.01	0.05	0.02	0.02	0.02	0.02	0.02	0.11	0.14	0.01	0.01	0.00	0.01
Cu (ppm)	42	1388	37	242	32	70	12	22	16	11	8	136	51
Nb	1.1	1.5	1.4	0.5	1.3	0.6	0.7	0.2	1.4	1.2	0.0	0.6	1.0
Ni	164	1893	214	461	203	234	183	1159	1414	106	82	164	179
Pb	11.0	9.5	8.4	6.3	7.0	8.1	5.5	13.0	11.0	7.6	13.2	10.6	15.5
Rb	12.0	12.0	20.2	4.2	8.7	4.7	8.5	2.6	21.6	87.0	117.4	42.7	9.8
Sr	355	344	283	284	297	268	281	105	59	460	6	10	268
Y	4.9	6.1	9.5	4.5	8.4	7.7	9.3	3.5	5.9	4.7	2.1	10.6	6.8
Zn	51	65	79	60	144	74	100	164	272	38	287	96	121
Zr	26	29	34	22	31	23	27	17	41	33	55	59	24
Co	24	70	43	54	41	44	52	152	132	9	69	21	48
Cr	451	502	699	685	602	724	650	2381	3721	101	15	40	114
Sc	10	12	21	17	22	24	31	18	8	2	8	11	23
V	50	65	105	77	96	108	135	71	25	9	12	66	110
S													
Ba	130	130	183	96	162	131	149	68	127	580	213	81	157
Cs	0.64	1.24	1.47	0.73	0.52	0.34	0.91	0.62	1.51	2.68	5.17	3.34	1.60
Hf	0.63	0.69	0.82	0.39	0.72	0.37	0.56	0.17	0.68	0.57	0.88	0.99	0.59
Ta	0.09	0.14	0.12	0.04	0.10	0.05	0.08	0.02	0.10	0.12	0.00	0.07	0.09
Th	0.86	0.93	1.09	0.68	0.99	0.59	0.57	0.28	1.75	1.94	0.32	0.59	1.03
U	0.21	0.21	0.27	0.12	0.21	0.14	0.13	0.07	0.25	0.56	0.35	0.36	0.22
La	5.99	6.04	8.77	4.34	7.22	5.19	5.89	2.05	9.76	14.08	0.10	0.93	5.59
Ce	10.59	10.76	15.80	7.58	13.55	9.71	11.45	3.40	18.88	24.61	0.37	2.60	10.02
Pr	1.16	1.22	1.83	0.86	1.54	1.17	1.45	0.43	2.15	2.57	0.00	0.44	1.18
Nd	5.14	5.12	7.13	3.65	6.63	4.84	6.55	2.08	8.50	9.20	0.10	2.56	4.94
Sm	0.96	1.03	1.58	0.73	1.42	1.11	1.59	0.50	1.41	1.38	0.10	0.86	0.98
Eu	0.47	0.49	0.60	0.41	0.57	0.52	0.50	0.20	0.30	0.83	0.09	0.25	0.50
Gd	0.77	0.84	1.26	0.63	1.18	0.99	1.26	0.40	1.06	0.99	0.06	0.91	0.92
Dy	0.64	0.82	1.26	0.65	1.11	1.04	1.36	0.46	0.79	0.73	0.07	1.18	0.93
Ho	0.16	0.20	0.30	0.15	0.28	0.25	0.29	0.12	0.18	0.15	0.07	0.32	0.22
Er	0.41	0.54	0.81	0.43	0.73	0.71	0.80	0.35	0.49	0.39	0.28	0.91	0.64
Yb	0.50	0.59	0.89	0.50	0.84	0.88	0.91	0.44	0.57	0.44	0.92	1.22	0.73
Lu	0.05	0.09	0.13	0.06	0.12	0.12	0.11	0.05	0.07	0.04	0.15	0.17	0.11
Os (ppb)													
Ir													
Ru													
Rh													
Pt	<20	204.3	<20			20.0		40.0	33.3	<20	<20	<20	
Pd	20.0	296.2	<20			<20		30.0	<20	20.0	<20	<20	
Au	50.0	60.0	<20			20.0		<20	<20	<20	<20	<20	
$\delta^{34}S$													

Notes: Data are recalculated to 100% LOI free

Fe in sulfide has been estimated by multiplying S by 1.5, Fe in silicate is Fe(total)-Fe(in sulfide), FeO/Fe2O3=8,5/1.5

Ni in silicate has been estimated by assuming that Cu and Ni contents of sulfides are equivalent and by subtracting the appropriate amount of Ni from total Ni

4960	4982	4984	5038	5040	5507	5502	5110	5111	5200	5286	5363	5375	5423
04 23	04 23	04 23	04 23	04 23	04 23	04 23	04 23	04 23	04 23	04 23	04 23	04 23	04 23
MANO	MANO	MANO	MANO	MANO	LGN	LGN	LMF	LMF	LMF	LMF	LMF	LMF	LMF
73.64	122.91	123.86	163.89	186.56	227.15	263.4	300.65	300.99	333.03	362.41	388.76	393.54	412.43
53.53	54.31	53.44	49.35	52.51	51.59	52.25	49.72	53.01	47.73	52.41	52.43	52.20	47.40
0.29	0.25	0.20	0.18	0.20	0.08	0.10	0.75	0.28	0.57	0.17	0.20	0.22	0.62
17.91	8.54	20.72	9.77	26.25	22.95	20.66	11.64	18.74	14.66	14.35	11.97	12.13	10.46
6.37	10.34	4.62	7.44	2.88	3.18	4.25	11.69	6.17	10.72	8.44	9.65	10.23	14.04
1.12	1.83	0.82	1.31	0.51	0.56	0.75	2.06	1.09	1.89	1.49	1.70	1.81	2.48
nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
0.15	0.23	0.10	0.16	0.06	0.08	0.10	0.18	0.11	0.15	0.16	0.20	0.19	0.24
7.01	17.60	6.13	17.12	2.65	6.94	7.67	9.51	5.99	10.89	12.14	13.18	13.35	14.09
11.23	5.79	11.20	14.15	11.46	11.94	11.26	9.47	10.39	8.01	8.46	8.90	7.63	6.80
1.95	0.83	2.25	0.26	2.73	2.28	2.37	1.59	2.65	1.63	1.69	1.31	1.23	1.11
0.34	0.10	0.43	0.13	0.68	0.29	0.45	0.43	0.83	0.24	0.38	0.16	0.56	0.39
0.03	0.01	0.02	0.06	0.05	0.01	0.01	0.15	0.20	0.03	0.09	0.04	0.16	0.16
0.05	0.13	0.05	0.04	0.01	0.09	0.10	2.83	0.59	3.44	0.19	0.24	0.30	2.18
0.01	0.04	0.01	0.02	0.00	0.02	0.02	-0.02	-0.05	0.02	0.02	0.01	-0.01	0.04
57	36	33	99	20	12	15	1550	1962	305	913	405	1582	1453
1.4	0.2	0.5	1.5	1.1	0.1	0.3	2.5	2.1	0.8	0.6	0.3	0.8	1.2
169	426	138	283	56	166	174	1329	1427	541	1145	545	1464	1813
13.1	9.4	8.3	41.4	7.0	4.1	4.0	14.5	36.7	16.4	8.9	7.0	17.6	19.8
10.5	2.4	13.4	3.1	31.4	8.7	13.7	19.7	40.3	7.8	14.1	4.6	26.0	21.7
215	97	253	200	350	370	345	155	286	254	258	207	243	175
10.8	6.7	7.6	8.3	5.7	2.0	3.1	19.1	11.2	4.8	5.1	6.4	7.3	7.6
144	105	45	162	40	33	43	111	199	94	80	89	97	152
37	18	22	34	25	10	11	64	40	14	10	13	18	22
36	75	24	41	10	23	29	77	62	61	80	73	104	111
320	908	373	245	102	629	695	19389	4022	23528	1307	1641	2057	14945
30	31	22	12	8	13	18	38	23	24	23	33	27	30
147	154	108	67	51	54	78	528	154	465	108	121	102	429
125	59	147	81	163	95	134	119	204	96	118	71	146	121
0.94	0.25	1.47	0.42	1.77	0.50	0.47	0.82	1.24	0.41	0.60	0.33	0.97	1.40
0.84	0.34	0.47	0.66	0.54	0.10	0.19	1.56	0.95	0.22	0.17	0.25	0.38	0.44
0.17	0.02	0.06	0.15	0.09	0.02	0.04	0.19	0.16	0.02	0.03	0.03	0.04	0.05
1.56	0.30	0.56	2.86	1.08	0.20	0.37	2.46	3.04	0.35	0.22	0.27	0.57	0.58
0.31	0.04	0.10	1.02	0.23	0.05	0.08	0.54	0.61	0.05	0.00	0.04	0.11	0.08
6.82	2.39	4.98	13.83	6.42	2.03	3.06	10.77	13.33	2.25	1.97	2.11	4.00	3.70
12.87	4.58	9.49	18.54	12.22	3.28	4.51	22.87	24.38	3.95	3.27	3.81	7.49	6.47
1.55	0.58	1.18	1.83	1.41	0.39	0.54	2.91	2.65	0.52	0.47	0.58	0.93	0.78
6.60	2.60	5.54	6.89	6.13	1.64	2.67	13.00	10.30	2.46	2.35	3.01	4.48	3.40
1.58	0.68	1.29	1.26	0.98	0.33	0.48	2.89	1.93	0.60	0.57	0.77	0.96	0.83
0.49	0.27	0.56	0.34	0.64	0.38	0.41	0.66	0.73	0.42	0.42	0.35	0.45	0.33
1.43	0.70	1.11	1.23	1.02	0.30	0.44	2.59	1.71	0.59	0.58	0.72	1.03	0.81
1.57	0.86	1.16	1.12	0.82	0.25	0.41	2.77	1.61	0.67	0.71	0.95	1.05	0.92
0.38	0.21	0.27	0.26	0.20	0.08	0.11	0.57	0.35	0.17	0.17	0.22	0.24	0.22
0.91	0.61	0.91	0.70	0.51	0.23	0.28	1.61	0.95	0.50	0.49	0.64	0.69	0.65
1.01	0.84	0.78	0.83	0.54	0.25	0.35	1.82	1.02	0.56	0.62	0.76	0.87	0.76
0.14	0.11	0.11	0.10	0.06	0.02	0.04	0.25	0.15	0.07	0.07	0.10	0.12	0.10
<20	<20	20.3	<20	<20			448.0	269.4	336.4	61.2	20.2	81.5	248.1
<20	<20	<20	230.0	<20			322.9	341.9	193.7	214.3	60.6	274.9	589.1
<20	<20	<20	<20	<20			260.0	200.0	<20	30.0	<20	40.0	50.0

Sample	5431	5447	5506	5505	5459	1046	1056	1100	1114	1265	1405	1460	1724
Borehole	04 23	04 23	04 23	04 23	04 23	03 01	03 01	03 01	03 01	03 01	03 02	03 02	03 06
Rocktype	LMF	LMF	LZ	LZ	LZ	MANO	MANO	MANO	MANO	MANO	MANO	MANO	MANO
Depth	415.86	434.40	437.45	454.1	475.95	115.5	118	140.98	184.25	221	210	253.38	247.53
SiO_2 (wt%)	53.25	50.24	47.54	54.54	44.28	53.37	54.82	51.61	56.18	55.50	54.00	51.24	52.24
TiO_2	0.13	0.30	0.06	0.11	0.06	0.57	0.32	0.22	0.42	0.30	0.27	0.14	0.19
Al_2O_3	5.53	14.85	5.04	4.58	3.31	8.34	6.72	17.45	14.03	9.30	8.91	26.97	23.53
FeO	8.41	8.34	8.93	7.93	7.77	11.85	10.29	4.92	7.45	10.71	9.21	2.27	3.67
Fe_2O_3	1.48	1.47	1.58	1.40	1.37	2.09	1.82	0.87	1.31	1.89	1.63	0.40	0.65
Fe (sulf)	nd	nd	nd	nd	nd	nd	nd	2.84	0.71	0.84	0.06	0.58	1.18
MnO	0.20	0.21	0.18	0.20	0.13	0.21	0.22	0.12	0.17	0.23	0.20	0.04	0.08
MgO	26.04	10.23	32.56	26.78	39.84	16.37	19.75	10.05	10.30	15.29	18.44	2.00	3.57
CaO	4.09	12.72	3.49	3.51	1.18	3.75	4.80	9.62	6.92	4.58	5.80	13.04	10.63
Na_2O	0.21	0.99	0.12	0.24	0.01	0.97	0.69	1.83	1.79	0.95	1.04	2.72	3.13
K_2O	0.29	0.52	0.03	0.19	0.03	0.46	0.19	0.19	0.55	0.25	0.16	0.54	1.06
P_2O_5	0.02	0.03	0.01	0.01	0.01	0.22	0.05	0.11	0.08	0.04	0.03	0.03	0.07
Cr_2O_3	0.25	0.09	0.29	0.43	1.73	1.69	0.30	0.11	0.10	0.12	0.21	0.02	0.02
Ni (sil)	0.11	0.00	0.16	0.08	0.29	0.10	0.04	0.06	-0.01	0.00	0.04	0.00	-0.01
Cu (ppm)	26	295	10	31	10	384	89	2998	1329	868	32	1018	2123
Nb	0.8	0.4	0.2	0.2	0.2	5.4	3.5	2.6	5.0	4.1	2.8	1.6	2.8
Ni	1120	272	1652	831	2875	1383	511	3631	1227	913	431	1048	1981
Pb	14.5	6.1	5.9	5.2	4.5	7.1	10.7	20.5	23.0	14.5	9.0	12.9	14.8
Rb	20.3	30.2	3.0	12.4	4.0	17.2	7.1	4.2	26.0	9.2	6.2	20.4	35.9
Sr	191	286	80	98	8	186	207	257	219	140	127	399	359
Y	4.8	9.9	2.0	3.4	1.3	10.8	9.8	5.8	10.5	9.4	8.1	4.0	5.8
Zn	113	82	96	87	44	102	99	109	132	172	82	29	67
Zr	19	11	11	11	8	60	44	36	92	56	41	33	39
Co	86	54	114	79	97	105	70	139	77	100	70	19	38
Cr	1699	648	1960	2911	11835	11590	2069	727	665	805	1432	124	130
Sc	23	33	18	27	13	20	29	18	20	24	26	6	9
V	66	156	41	83	1	505	155	93	115	108	126	35	56
S								17900	4500	5300	400	3800	7500
Ba	100	143	38	74	19	169	122	87	138	91	95	201	271
Cs	2.09	1.19	0.65	1.10	0.62	1.69	0.82	0.41	1.59	0.76	0.92	0.85	1.30
Hf	0.38	0.24	0.11	0.14	0.07	1.54	1.16	0.71	2.23	1.17	0.78	0.84	0.90
Ta	0.06	0.03	0.03	0.02	0.00	0.32	0.18	0.11	0.33	0.17	0.15	0.10	0.15
Th	0.59	0.18	0.27	0.29	0.24	2.99	1.84	0.91	4.90	2.13	1.07	1.05	2.15
U	0.20	0.02	0.05	0.07	0.01	0.67	0.39	0.23	1.05	0.52	0.36	0.28	0.54
La	3.80	2.26	1.27	1.17	1.33	15.13	5.81	5.00	23.29	7.52	5.03	6.57	8.41
Ce	6.06	4.52	1.75	1.67	2.12	31.22	12.97	8.73	40.04	13.21	9.45	11.24	14.34
Pr	0.72	0.71	0.24	0.26	0.26	3.01	1.06	1.01	3.83	1.42	1.11	1.24	1.57
Nd	3.15	4.08	1.12	1.31	1.08	15.67	9.11	4.00	13.26	5.99	4.99	5.32	6.22
Sm	0.66	1.26	0.26	0.36	0.19	2.43	1.55	0.94	2.14	1.18	1.17	0.95	1.16
Eu	0.20	0.51	0.13	0.16	0.11	0.42	0.34	0.37	0.45	0.30	0.27	0.54	0.62
Gd	0.57	1.30	0.24	0.37	0.21	2.26	1.56	0.78	1.66	0.99	0.97	0.76	0.96
Dy	0.54	1.46	0.22	0.40	0.14	1.56	1.34	0.88	1.44	1.18	1.11	0.66	0.85
Ho	0.15	0.32	0.07	0.12	0.06	0.42	0.41	0.18	0.30	0.27	0.25	0.13	0.18
Er	0.42	0.80	0.22	0.34	0.16	1.03	0.98	0.49	0.86	0.80	0.72	0.34	0.49
Yb	0.60	0.94	0.30	0.43	0.21	0.88	1.05	0.59	0.99	1.11	0.89	0.37	0.60
Lu	0.08	0.13	0.03	0.05	0.01	0.16	0.16	0.15	0.20	0.25	0.19	0.12	0.15
Os (ppb)						21.01	dl	46.58	6.28	3.16	dl	dl	5.24
Ir						33.62	2.08	46.58	8.37	5.27		3.07	6.28
Ru						158.7	8.3	326.1	41.9	30.6	3.1	13.3	29.3
Rh						96.7	3.1	173.6	32.4	22.1	2.1	24.5	38.7
Pt	20.0	<20			<20	753.4	46.7	1941.6	409.3	230.9	12.4	185.0	470.2
Pd	20.0	20.0			<20	436.1	24.9	3053.3	646.9	407.1	7.2	332.1	1632.7
Au	20.0	<20			<20	33.6	0.0	261.5	71.2	68.5	13.4	50.1	151.9
dS34								3.16	3.96	4.52	3.46	4.08	3.09

1734	1805	1824	1863	1880	1907	1920	3154	3164	3180	3355	3407	3722	3735
03 06	03 07	03 07	03 08	03 08	03 08	03 08	03 12	03 12	03 12	03 14	03 14	04 19	04 19
MANO	MANO	MANO	MANO	MANO	MANO	MANO	LMF	LMF	LMF	LMF	LMF	MANO	MANO
250.17	89.08	118.3	166.64	173.59	184.41	229.17	141.38	144.86	150.26	115.5	138.5	55.47	69.25
54.55	54.51	56.49	53.14	51.82	51.81	53.00	54.00	45.47	56.80	51.15	56.25	50.99	52.12
0.30	0.37	0.29	0.28	0.25	0.14	0.18	0.43	0.30	0.33	0.43	0.18	0.19	0.19
8.92	9.30	7.98	5.67	22.23	18.05	16.39	13.01	12.89	15.89	13.18	15.16	21.75	22.10
9.42	9.34	8.72	11.63	4.83	5.77	6.00	9.08	10.95	7.39	9.59	6.23	4.13	4.37
1.66	1.65	1.54	2.05	0.85	1.02	1.06	1.60	1.93	1.30	1.69	1.10	0.73	0.77
0.03	1.50	0.22	1.65	1.93	0.05	0.14	0.06	0.51	0.07	0.14	0.95	0.11	0.76
0.22	0.21	0.19	0.34	0.10	0.12	0.13	0.17	0.15	0.09	0.15	0.19	0.09	0.09
18.05	17.21	17.84	20.56	4.63	11.84	12.76	10.67	14.09	4.94	10.48	11.13	6.07	5.92
5.30	4.63	4.84	3.63	10.27	9.39	8.46	7.82	5.26	8.88	6.45	5.97	13.52	10.67
1.11	0.75	1.02	0.52	2.39	1.46	1.49	2.04	1.36	0.79	2.01	1.87	1.96	2.36
0.18	0.22	0.31	0.07	0.60	0.19	0.18	0.65	0.39	3.36	0.60	0.70	0.31	0.44
0.02	0.07	0.02	0.02	0.12	0.01	0.02	0.05	0.04	0.00	0.07	0.05	0.06	0.08
0.20	0.17	0.49	0.30	0.03	0.14	0.15	0.40	6.59	0.15	4.03	0.14	0.08	0.07
0.03	0.08	0.05	0.13	-0.05	0.03	0.04	0.02	0.07	0.02	0.04	0.07	0.01	0.06
74	1647	218	404	3212	39	155	124	1022	9	255	1433	174	1054
2.2	3.4	2.0	0.9	2.3	0.9	1.8	3.4	2.7	11.3	4.1	2.1	1.7	2.5
415	2443	717	1705	2757	318	598	307	1678	176	614	2130	247	1657
11.2	21.5	16.4	18.8	25.6	3.7	17.2	8.8	15.5	6.3	11.3	37.0	7.7	15.0
6.7	12.7	12.5	2.6	19.4	3.6	5.4	20.3	14.9	180.9	20.2	26.0	11.8	12.9
113	119	111	58	272	238	239	241	162	32	208	253	293	354
10.5	10.6	11.7	9.0	9.0	4.1	5.4	13.4	9.5	48.0	16.0	11.4	8.5	6.7
94	140	98	142	69	57	56	85	107	26	99	132	40	52
37	127	49	25	43	22	33	57	65	70	141	61	27	26
74	125	69	121	94	43	51	58	121	7	81	74	20	53
1383	1192	3372	2050	239	942	998	2734	45066	1013	27549	956	561	498
26	24	26	37	13	16	16	28	21	5	24	17	19	12
140	121	140	211	93	76	82	202	557	89	372	60	105	86
200	9500	1400	10500	12300	300	900	400	2800	400	900	5900	700	4900
80	73	126	43	147	74	83	206	144	270	223	508	105	153
0.45	1.04	1.62	0.31	0.87	0.26	0.36	0.98	0.96	2.33	1.00	1.86	0.85	0.77
0.74	2.98	1.16	0.49	0.96	0.47	0.65	1.26	1.29	1.74	3.27	1.24	0.75	0.75
0.15	0.22	0.16	0.05	0.14	0.05	0.12	0.19	0.15	0.81	0.27	0.15	0.08	0.10
1.84	2.03	2.73	0.58	2.04	0.59	1.14	2.24	1.80	1.77	3.38	2.28	1.63	1.05
0.53	0.54	0.72	0.16	0.51	0.12	0.32	0.59	0.38	0.73	0.71	0.67	0.31	0.25
6.17	6.40	10.41	3.63	9.35	3.56	4.94	12.15	8.55	5.18	14.43	19.87	5.83	6.02
11.00	12.49	18.16	6.30	17.52	5.79	8.48	23.46	15.90	12.67	28.16	33.19	12.49	12.24
1.28	1.47	1.97	0.75	1.97	0.65	0.99	2.70	1.75	2.02	3.24	3.34	1.08	0.96
5.65	6.54	8.06	3.51	8.41	2.91	4.17	11.38	7.54	11.42	13.64	12.51	9.05	8.58
1.26	1.44	1.79	0.86	1.82	0.69	0.94	2.30	1.63	4.07	2.77	2.12	1.47	1.28
0.30	0.26	0.43	0.23	0.58	0.35	0.32	0.58	0.45	0.69	0.64	0.77	0.59	0.68
1.19	1.19	1.48	0.81	1.37	0.58	0.75	1.92	1.30	4.28	2.26	1.57	1.62	1.37
1.40	1.35	1.65	1.08	1.30	0.58	0.81	2.01	1.39	6.06	2.31	1.51	1.25	0.92
0.30	0.33	0.36	0.28	0.27	0.13	0.17	0.41	0.28	1.39	0.46	0.34	0.38	0.31
0.88	0.92	0.96	0.83	0.75	0.38	0.46	1.16	0.76	3.91	1.31	1.04	0.80	0.70
1.08	1.27	1.24	1.09	0.83	0.45	0.56	1.32	0.95	4.68	1.50	1.35	0.74	0.58
0.21	0.24	0.26	0.23	0.17	0.13	0.15	0.24	0.21	0.76	0.28	0.28	0.11	0.09
dl	6.30	dl	dl	5.23	dl	dl	dl	53.62	dl	8.35	dl		
dl	6.30	dl	dl	5.23	dl	dl	dl	110.89	dl	19.84	4.28		
dl	33.6	5.2	3.1	28.2	dl	5.1	3.1	415.5	9.0	78.3	10.7		
4.1	42.0	5.2	4.2	59.6	1.0	6.2	9.2	185.2	11.3	61.6	33.2		
3.0	389.3	26.0	35.6	502.1	5.1	66.6	45.9	1282.0	68.7	308.1	278.3	20.0	90.0
2.0	1213.1	30.1	54.4	2092.1	7.2	117.9	128.4	452.1	569.2	505.5	845.6	30.0	340.0
dl	114.4	dl	6.3	172.6	dl	54.3	9.2	65.8	7.9	34.5	116.7	<20	710.0
5.03	3.12	3.33	2.6	4.1	1.82	3.07	4.36	5.09		4.53	4.65		

Sample	3739	3748	3769	3776	3778	5504	3779	3783	3807	3813	3824	3831	5503
Borehole	04 19	04 19	04 19	04 19	04 19	04 19	04 19	04 19	04 19	04 19	04 19	04 19	04 19
Rocktype	MANO	MANO	MANO	MANO	MANO	MANO	MANO	MANO	LGN	LGN	LGN	LGN	LGN
Depth	72.05	93.4	106.21	122.9	124	171.95	221.78	223.63	246.82	258.48	292.11	297.03	322.45
SiO_2 (wt%)	53.18	53.39	53.67	53.06	53.24	53.88	55.17	54.12	55.25	55.20	55.37	55.29	54.78
TiO_2	0.22	0.23	0.34	0.24	0.24	0.41	0.47	0.41	0.52	0.50	0.61	0.54	0.58
Al_2O_3	16.78	19.73	18.12	19.77	21.00	18.35	21.49	16.89	17.36	17.49	17.98	18.09	17.59
FeO	5.88	5.42	6.48	5.49	5.08	6.20	4.68	6.88	6.90	7.18	6.54	6.62	6.81
Fe_2O_3	1.04	0.96	1.14	0.97	0.90	1.09	0.83	1.21	1.22	1.27	1.15	1.17	1.20
Fe (sulf)	0.21	0.03	0.00	0.84	0.00	0.00	0.05	0.42	0.03	0.03	0.03	0.03	0.00
MnO	0.13	0.11	0.14	0.11	0.10	0.13	0.09	0.16	0.14	0.14	0.12	0.13	0.14
MgO	9.75	7.06	7.67	7.20	6.16	6.32	3.57	7.87	6.04	5.72	5.11	5.24	5.34
CaO	10.27	10.18	9.67	9.63	10.29	10.03	9.36	8.72	8.91	9.01	9.20	9.20	9.46
Na_2O	2.00	2.42	2.16	2.21	2.39	2.78	2.88	2.29	2.56	2.51	2.69	2.65	2.91
K_2O	0.29	0.32	0.43	0.33	0.45	0.69	1.25	0.77	0.87	0.78	0.99	0.87	1.01
P_2O_5	0.07	0.07	0.09	0.08	0.08	0.06	0.12	0.10	0.12	0.12	0.13	0.12	0.10
Cr_2O_3	0.14	0.08	0.08	0.08	0.07	0.06	0.03	0.12	0.06	0.05	0.05	0.05	0.08
Ni (sil)	0.03	0.01	0.01	0.00	0.01	0.01	0.00	0.02	0.01	0.01	0.01	0.01	0.00
Cu (ppm)	367	98	45	912	44	52	41	467	49	47	55	51	53
Nb	2.0	2.0	4.2	2.1	2.3	2.7	5.0	3.9	5.1	4.5	6.5	5.8	4.3
Ni	690	181	178	875	149	142	77	664	139	128	108	114	95
Pb	5.3	6.2	8.1	11.7	9.3	9.8	13.0	9.2	9.0	8.4	8.8	11.4	7.7
Rb	8.8	7.7	16.2	8.3	11.5	19.3	44.8	22.8	26.3	23.6	31.3	27.1	28.9
Sr	251	300	275	308	320	324	332	270	309	294	309	313	337
Y	8.5	8.4	10.3	8.3	8.1	13.1	13.3	14.0	16.6	17.6	18.1	18.3	17.4
Zn	53	48	63	55	47	180	50	68	66	68	62	64	75
Zr	30	29	61	35	31	77	87	66	79	61	115	113	51
Co	44	31	32	52	25	36	18	47	33	35	31	30	35
Cr	986	524	543	521	470	412	191	801	438	361	327	362	572
Sc	22	17	19	16	14	20	15	23	22	22	21	20	23
V	135	110	115	94	90	125	109	139	146	150	152	141	150
S	1400	200		5400			300	2700	200	200	200	200	
Ba	107	130	127	150	183	242	368	257	298	324	366	299	312
Cs	0.73	0.54	1.05	0.78	0.53	0.58	1.51	1.19	1.05	1.06	0.96	0.94	0.93
Hf	0.80	0.82	1.56	0.92	0.88	1.67	2.17	1.65	1.93	1.50	2.75	2.61	1.35
Ta	0.10	0.10	0.22	0.12	0.14	0.24	0.32	0.26	0.31	0.27	0.39	0.36	0.31
Th	1.06	1.18	2.27	1.14	1.21	2.08	2.79	2.20	3.34	2.97	3.84	3.41	2.84
U	0.27	0.28	0.54	0.34	0.35	0.55	0.70	0.58	0.72	0.76	0.87	0.97	0.66
La	6.03	7.26	8.95	8.21	8.12	12.14	14.82	12.13	15.37	14.88	16.88	16.84	16.84
Ce	12.74	14.68	18.61	16.22	16.05	23.47	28.55	24.28	31.73	30.50	34.12	33.71	33.36
Pr	1.07	1.30	1.72	1.43	1.45	2.65	2.92	2.47	3.30	3.22	3.53	3.47	3.95
Nd	9.29	10.04	12.00	10.40	10.28	11.52	15.97	14.76	17.48	17.69	19.23	19.37	17.46
Sm	1.40	1.58	1.88	1.51	1.44	2.34	2.65	2.50	3.07	3.19	3.45	3.31	3.36
Eu	0.56	0.72	0.71	0.67	0.73	0.76	1.00	0.80	0.96	0.98	0.98	0.99	0.86
Gd	1.58	1.59	1.86	1.61	1.59	1.96	2.49	2.38	2.85	2.92	3.14	3.08	2.79
Dy	1.26	1.23	1.58	1.26	1.22	1.74	2.02	2.00	2.56	2.55	2.53	4.07	2.62
Ho	0.37	0.37	0.45	0.37	0.37	0.39	0.52	0.55	0.62	0.62	0.65	0.68	0.54
Er	0.86	0.83	0.97	0.85	0.82	1.12	1.20	1.28	1.45	1.51	1.62	1.64	1.41
Yb	0.78	0.72	0.95	0.78	0.72	1.17	1.04	1.23	1.36	1.43	1.49	1.53	1.63
Lu	0.13	0.11	0.15	0.13	0.10	0.16	0.18	0.18	0.22	0.24	0.24	0.24	0.24
Os (ppb)													
Ir													
Ru													
Rh													
Pt	30.0	<20	20.0	40.0	<20		<20	70.0	<20	<20	<20	<20	
Pd	70.0	30.0	<20	20.0	<20		<20	290.0	<20	<20	<20	<20	
Au	150.0	<20	<20	20.0	20.0		<20	40.0	<20	<20	<20	<20	
dS34													

| 3840	3841	3842	3843	3849	3850	3853	3864	3875	3889	3894	3895	3901	3908	3913
04 19	04 19	04 19	04 19	04 19	04 19	04 19	04 19	04 19	04 19	04 19	04 19	04 19	04 19	04 19
LMF	LMF	LMF	LMF	LMF	LMF	LMF	LMF	LMF	LMF	LMF	Dol	Dol	Hfs	LMF
356.77	357.18	357.54	358.3	367.65	367.97	369.89	376.09	383.61	388.83	391.74	392.87	397.88	402.07	405.79
53.93	50.07	51.01	54.06	69.26	54.16	57.65	54.60	55.41	53.46	53.77	52.82	50.18	71.58	57.63
0.30	0.28	0.23	0.29	0.13	0.29	0.56	0.39	0.46	0.41	0.42	0.29	0.14	0.25	0.65
16.21	14.83	16.45	16.81	13.08	10.43	10.52	15.75	15.43	16.32	18.33	8.23	6.30	14.52	15.14
6.97	9.46	8.08	6.12	3.77	9.89	10.24	7.53	6.96	6.48	6.26	3.57	7.76	2.97	8.35
1.23	1.67	1.43	1.08	0.67	1.75	1.81	1.33	1.23	1.14	1.11	0.63	1.37	0.52	1.47
0.02	0.03	0.00	0.00	0.00	0.30	0.08	0.00	0.12	2.46	0.25	0.00	0.00	0.03	0.03
0.14	0.14	0.13	0.13	0.13	0.22	0.21	0.17	0.14	0.13	0.13	0.11	0.16	0.05	0.14
9.60	10.24	9.48	9.24	5.04	13.54	10.34	7.54	8.19	7.91	7.65	12.96	14.15	2.90	5.24
7.86	6.92	7.96	9.00	5.02	7.00	6.12	9.32	8.71	8.50	8.66	20.32	19.31	2.68	7.71
1.98	1.69	1.85	2.03	1.50	1.01	1.52	2.47	2.35	2.02	1.95	0.36	0.36	2.67	1.85
0.91	0.68	0.80	0.83	1.30	0.68	0.60	0.70	0.74	0.76	1.29	0.63	0.23	1.74	1.62
0.09	0.08	0.08	0.07	0.04	0.06	0.11	0.08	0.10	0.15	0.11	0.05	0.03	0.05	0.15
0.74	3.87	2.49	0.33	0.06	0.65	0.23	0.10	0.13	0.10	0.06	0.02	0.01	0.02	0.03
0.02	0.03	0.02	0.02	0.01	0.02	0.01	0.01	0.02	0.14	0.01	0.00	0.00	0.00	0.00
72	123	52	34	50	719	148	65	116	3259	468	20	8	21	69
4.0	4.1	3.0	2.8	3.8	3.1	6.4	3.8	4.8	4.2	5.3	3.3	4.8	4.9	7.2
273	411	282	208	105	912	280	180	326	4706	523	63	35	37	105
8.0	6.0	6.8	8.6	16.8	15.0	17.2	7.5	7.8	20.6	12.1	3.6	0.4	18.8	15.1
34.0	24.4	26.6	25.0	50.9	29.2	17.3	22.0	23.9	25.3	48.2	40.0	1.3	75.9	76.2
266	231	270	266	243	161	156	294	263	257	271	97	93	330	240
12.3	11.0	9.9	9.8	16.0	16.9	17.9	14.4	15.4	14.3	13.0	13.1	11.7	10.7	22.8
50	55	49	49	47	105	103	69	67	86	77	36	69	42	65
68	60	54	48	113	46	89	61	114	79	75	102	67	245	134
42	67	49	32	15	80	65	40	46	130	40	6	14	5	39
5079	26479	17025	2246	382	4460	1576	654	907	702	428	110	45	151	194
20	20	20	20	11	31	27	27	25	21	19	7	3	6	27
130	369	244	109	43	205	166	164	158	127	99	45	32	42	197
100	200				1900	500		800	15700	1600			200	200
299	230	267	248	604	198	252	228	225	249	460	147	31	599	640
1.71	1.35	1.26	0.99	1.79	1.78	1.42	1.00	0.87	0.96	1.97	1.11	0.40	3.23	3.26
1.64	1.41	1.27	1.21	2.91	1.28	2.05	1.43	2.64	1.81	1.86	2.50	1.40	5.51	3.09
0.24	0.19	0.18	0.17	0.34	0.22	0.38	0.22	0.28	0.26	0.35	0.35	0.41	0.37	0.40
2.50	2.16	1.91	2.05	7.50	3.15	3.10	2.36	2.97	3.24	4.45	4.83	2.36	8.45	4.10
0.69	0.53	0.48	0.47	1.77	0.90	0.76	0.57	0.70	0.92	0.90	0.45	0.77	1.72	1.10
11.63	9.54	8.77	8.40	26.85	12.26	15.23	11.39	14.39	12.80	14.12	6.35	25.33	33.32	21.91
23.33	19.66	18.37	17.62	50.22	26.65	30.67	23.35	28.15	27.03	28.26	18.01	44.95	57.15	44.10
2.22	1.76	1.63	1.59	5.14	2.71	3.03	2.23	2.74	2.58	2.70	1.97	4.05	5.20	4.53
14.02	12.51	11.66	10.96	22.41	15.54	17.54	13.97	15.97	15.12	15.76	14.63	18.97	22.37	22.98
2.24	1.93	1.73	1.76	3.77	2.79	3.07	2.35	2.78	2.53	2.58	2.74	2.98	3.05	4.24
0.73	0.61	0.67	0.64	1.00	0.58	0.78	0.81	0.81	0.77	0.82	0.48	0.56	1.37	1.18
2.29	2.06	1.90	1.83	3.06	2.62	2.87	2.42	2.74	2.51	2.35	2.40	2.50	2.57	3.71
1.72	1.51	1.42	1.46	2.20	2.24	2.56	2.00	2.17	2.15	1.87	1.96	1.67	1.47	3.16
0.48	0.46	0.41	0.42	0.58	0.62	0.66	0.54	0.60	0.58	0.52	0.54	0.45	0.45	0.83
1.14	1.03	0.99	0.96	1.40	1.45	1.54	1.29	1.38	1.37	1.28	1.19	1.04	1.00	1.98
1.08	0.93	0.89	0.88	1.48	1.49	1.63	1.20	1.29	1.19	1.21	1.17	0.95	0.97	1.91
0.15	0.15	0.13	0.14	0.23	0.24	0.25	0.20	0.21	0.19	0.19	0.17	0.15	0.16	0.30
	6.22	3.10							3.14					
	17.63	10.33							6.28					
	56.0	30.0							28.3					
	37.3	24.8							82.7					
50.0	213.7	165.3	20.0	<20	110.0	30.0	<20	20.0	411.2	20	<20	<20	<20	<20
30.0	141.1	89.9	<20	<20	260.0	60.0	<20	40.0	1752.8	60	<20	<20	<20	<20
<20	8.3	7.2	<20	<20	30.0	<20	<20	<20	96.3	<20	<20	<20	<20	<20
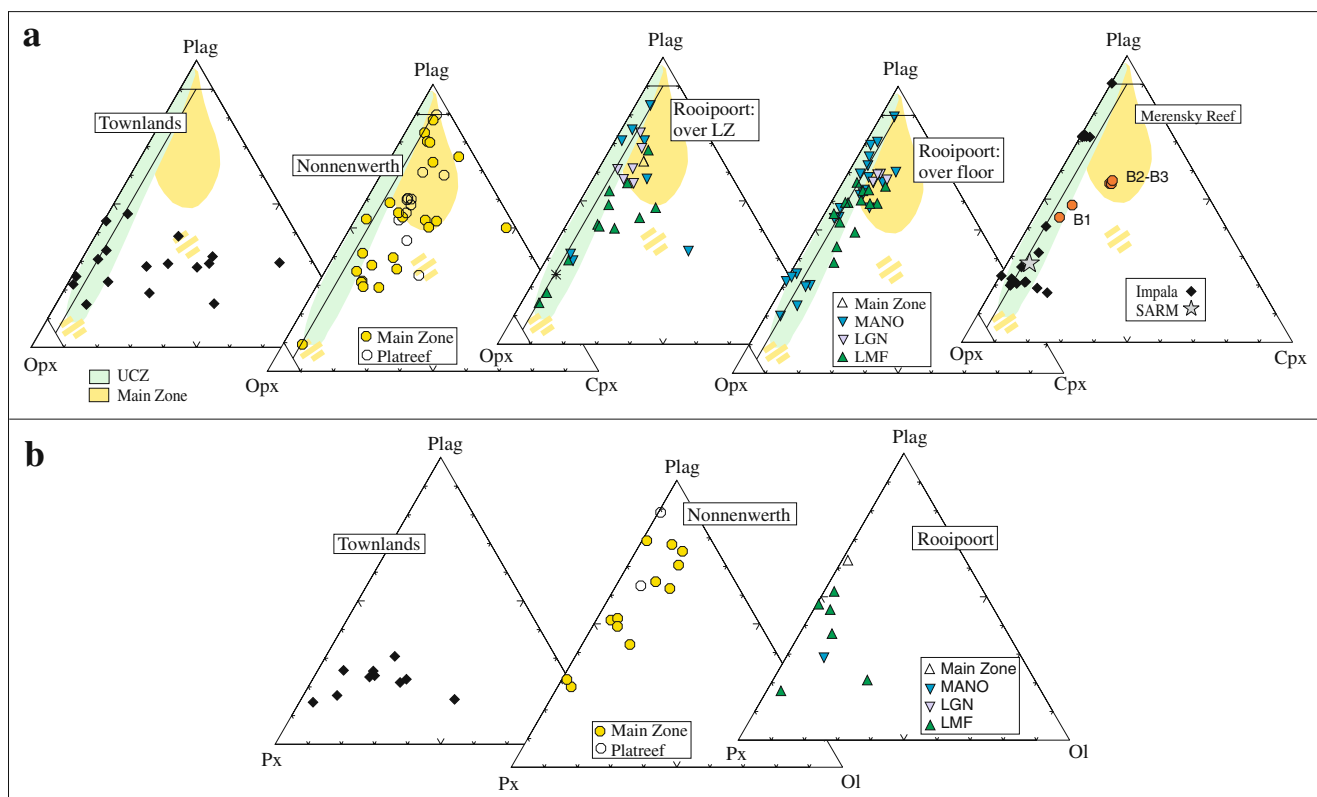
Fig. 6 CIPW normative compositions of rocks from Rooipoort, Townlands, and Nonnenwerth. **a** Plagioclase–clinopyroxene–orthopyroxene. Data from Merensky Reef (Barnes and Maier 2002a) and B1–B3 sills (Curl 2001) are shown for comparison. **b** Plagioclase–olivine–pyroxene. Only rocks containing olivine have been plotted

Fig. 7 Data from Rooipoort (this study), Grasvally (Hulbert 1983), Townlands (Manyeruke 2003), Drenthe (Stevens 2004), Sandsloot (McDonald et al. 2005), and Nonnenwerth (Manyeruke 2007) plotted into binary variation diagrams of **a** Al_2O_3 vs CaO, **b** CaO vs MgO, **c** Cr vs MgO (all whole rock data), and **d** Cr vs Mg# (orthopyroxene data). Data from the Upper Critical Zone and Main Zone are shown in colored fields (data from Mitchell 1986, Teigler and Eales 1996, Maier and Eales 1997). Mineral compositions are compiled from Manyeruke (2003, 2007), Stevens (2004), Harris and Chaumba (2001), and Hulbert (1983)
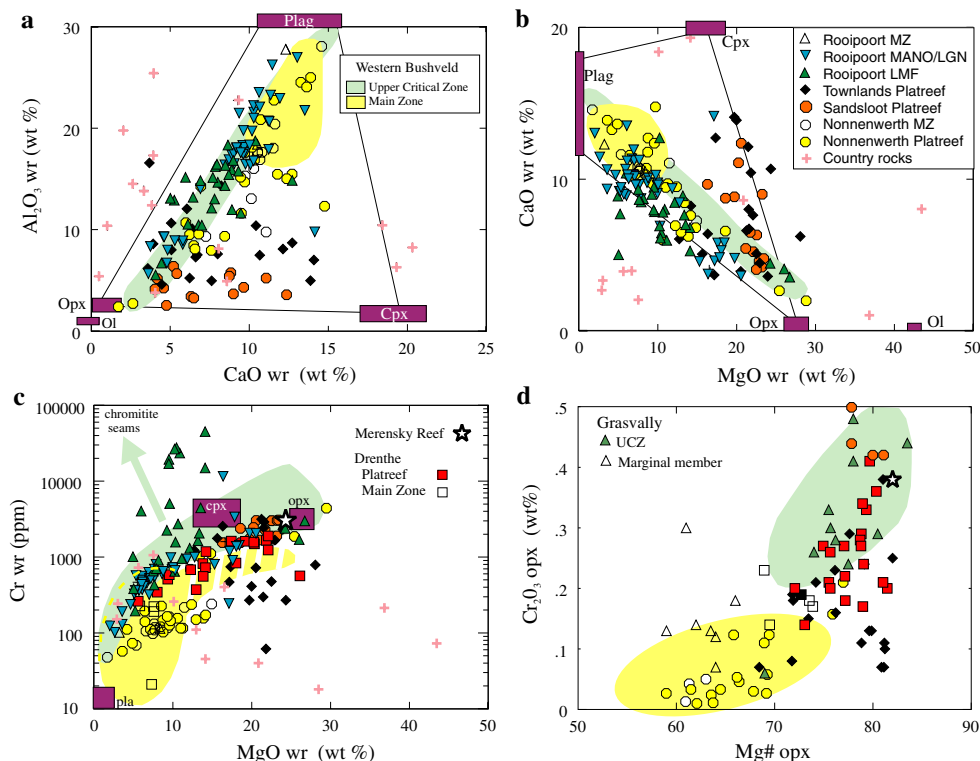
Fig. 8 Chondrite-normalized
REE patterns of Rooipoort
rocks compared to data from
Townlands (Manyeruke et al.
2005), Nonnenwerth
(Manyeruke, in preparation), and
Drenthe (Stevens 2004). Shaded
fields represent REE patterns of
Main Zone (pink) and Upper
Critical Zone (blue); western
Bushveld Complex (data from
Maier and Barnes 1998). Nor-
malization factors are from
McDonough and Sun (1995)
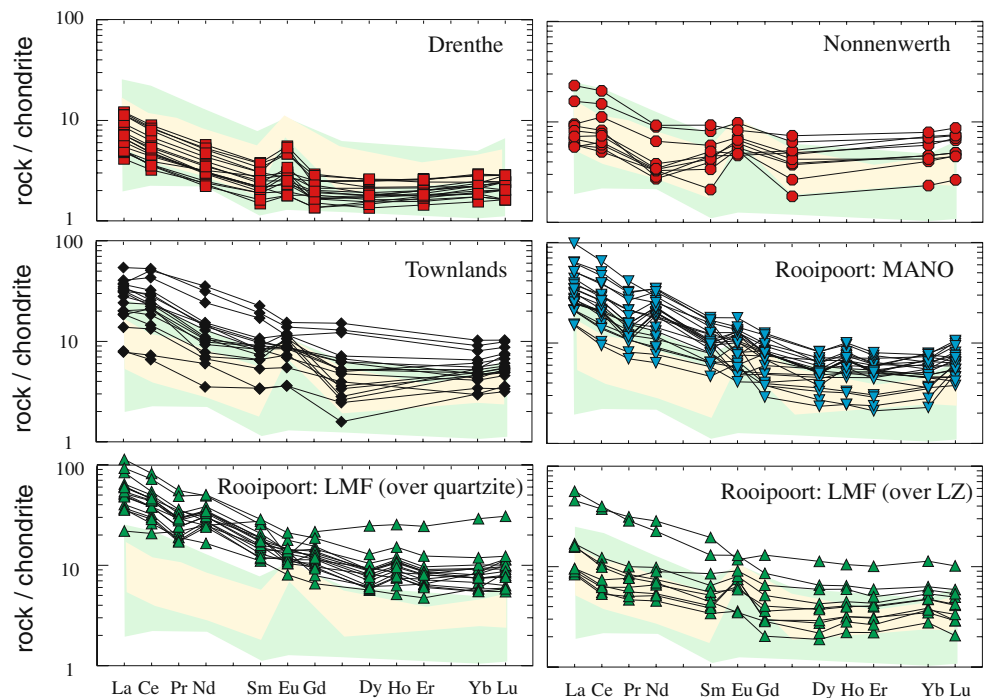
the rocks. Most of our samples from Rooipoort, and the samples from Townlands and Nonnenwerth analyzed by Manyeruke (2003, 2007), are orthopyroxene-rich gabbronorites (Fig. 6a; note that all our rock names are based on International Union for the Geological Sciences (IUGS) nomenclature, Streckeisen 1976). The cumulus phases are essentially orthopyroxene and plagioclase, with clinopyroxene mainly occurring as an interstitial phase. Norites are less abundant, gabbros are rare, and pyroxenites are absent. There is a considerable compositional variation between localities. At Rooipoort, there occur mainly norites and orthopyroxene-rich gabbronorites, with norites being particularly common in areas where the mineralization overlies quartzitic floor rocks. The rocks thus show considerable mineralogical overlap with the Upper Critical Zone of the western Bushveld Complex (e.g., Maier and Eales 1997). Rocks from Nonnenwerth are richer in clinopyroxene and consist mainly of gabbronorites. Their composition overlaps with that of the Main Zone in the western Bushveld Complex (e.g., Mitchell 1986). The samples from Townlands are on average more melanocratic than those from Rooipoort and Nonnenwerth. Rocks with more than 50 normative percent plagioclase do not occur at Townlands, whereas they are common at Rooipoort and Nonnenwerth.

As the contact-mineralized rocks are sometimes corre-lated to the Merensky Reef (Wagner 1929; White 1994), data from Merensky Reef silicate rocks at Impala mine (Barnes and Maier 2002a) and from the SARM bulk sample of Potts et al. (1992) are also plotted. Analogous to the contact-style rocks, the analyzed Merensky Reef does not contain pyroxenites, but instead consists mainly of

melagabbronorites and melanorites. The composition of the Merensky Reef shows some overlap with the mineralized rocks at Townlands and, to a lesser degree, the LMF and MANO at Rooipoort, but the Nonnenwerth rocks contain distinctly more plagioclase and clinopyroxene. The compositions of magnesium-basaltic B1 sills, representing the parental magmas to the lower and Lower Critical Zones of the Bushveld Complex, and the B2 and B3 sills, thought to represent an important proportion of the Upper Critical Zone and Main Zone magmas (data from Curl 2001), are also shown in Fig. 6 to illustrate that the B2–B3 magmas are relatively enriched in normative clinopyroxene. This explains why the Upper Critical and Main Zones of the Bushveld Complex contain more clinopyroxene than the Lower and Lower Critical Zones (Mitchell 1986; Teigler and Eales 1996), and it could suggest that many of the contact-mineralized rocks contain a significant B2–B3 component.

The rocks from Rooipoort, Townlands, and Nonnenwerth contain considerable normative olivine, with the largest olivine component (commonly 10–50%) being present at Townlands (Fig. 6b). At Rooipoort, normative olivine is essentially confined to areas where the interval overlies the Lower Zone. The presence of normative olivine in the contact-style rocks is notable because normative olivine is absent in most Merensky Reef intersections (with the exception of the northwestern Bushveld Complex). As there is no evidence that the contact-style rocks crystallized from a more magnesian magma than the Merensky Reef (Table 1), this suggests that the normative olivine (and possibly some of the normative clinopyroxene) at Townlands, Nonnen-

Fig. 9 Binary variation diagrams of Ce vs Sm showing data from **a** the Upper Critical Zone including the Merensky Reef (Maier and Barnes 1998; Barnes and Maier 2002a) and data from contact-mineralized rocks at **b** Nonnenwerth (Manyeruke 2007), **c** Drenthe (Stevens 2004) and Sandsloot (McDonald et al. 2005), **d** Townlands (Manyeruke 2003), **e** Rooipoort (samples overlying the Lower Zone), and **f** Rooipoort (samples overlying quartzitic floor rocks). Solid lines indicate Ce/Sm ratio of B2/B3 and B1 magmas (from Curl 2001). Compositional field of the Transvaal shales is from Klein and Beukes (1989)
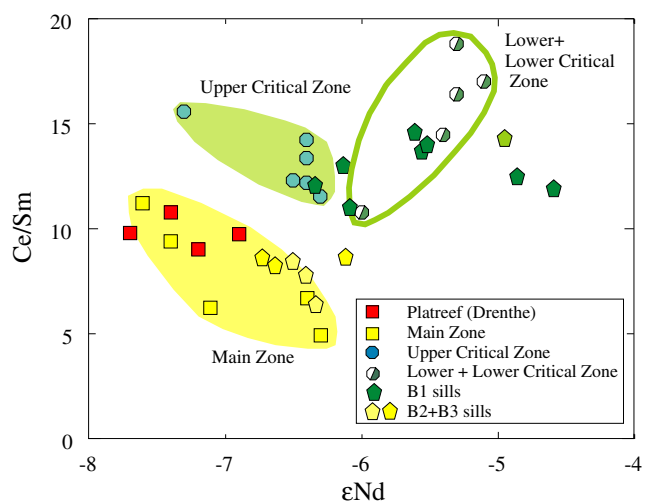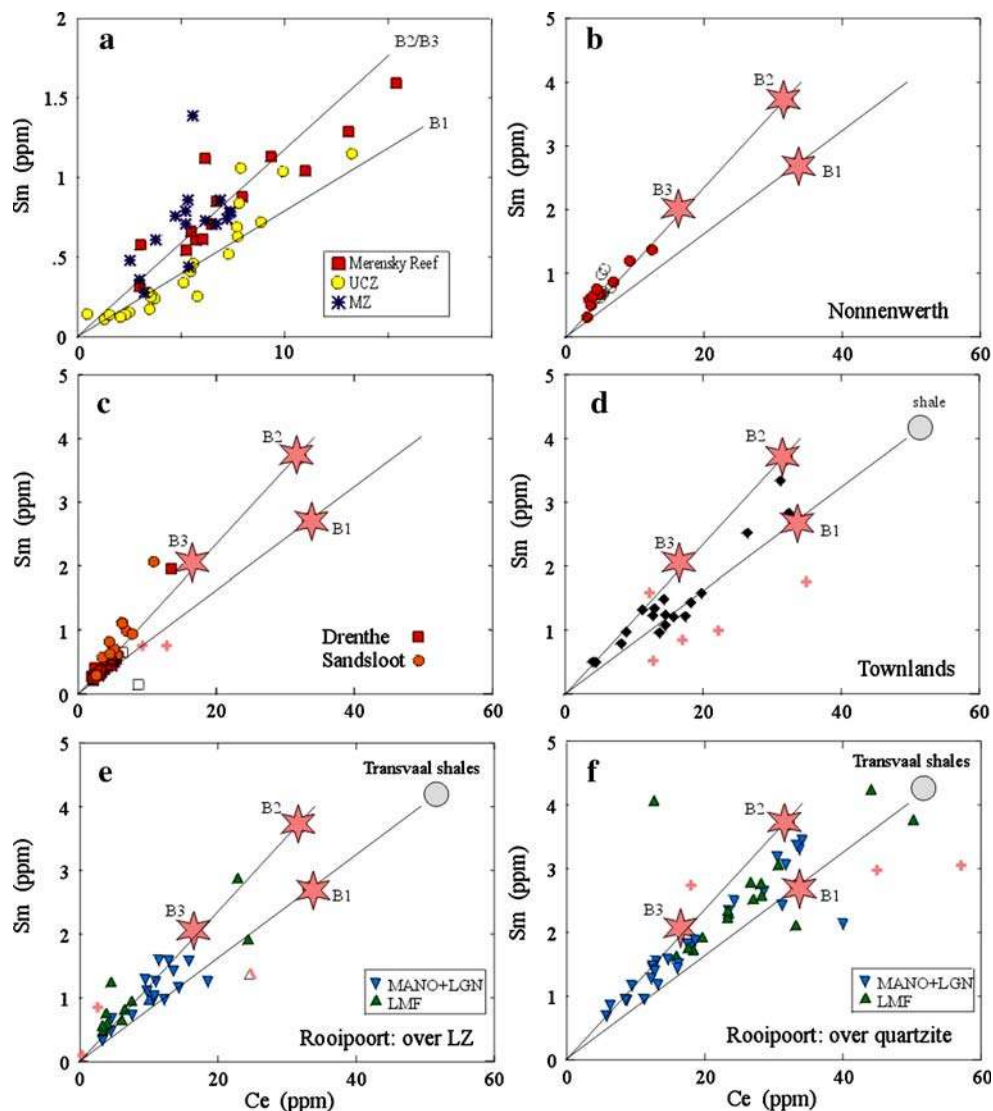
Fig. 10 Ce/Sm plotted vs εNd in Platreef samples from Drenthe (data from Stevens 2004). Also shown are data from Bushveld B1–B3 sills and cumulate rocks from the Lower, Critical, and Main Zones (data from Maier and Barnes 1998, Maier et al. 2000)

werth, and Rooipoort reflect the assimilation of a Ca–Mg component derived from either the floor rocks and/or xenoliths.

Lithophile chemistry

The compositions of the analyzed rocks from Rooipoort, as well as the samples from Drenthe (Stevens 2004), Townlands (Manyeruke 2003), Nonnenwerth (Manyeruke 2007), and Sandsloot (McDonald et al. 2005), appear to be mainly controlled by the relative proportions of plagioclase, orthopyroxene, and clinopyroxene (Fig. 7a–b). The bulk of the samples overlap with Upper Critical Zone and Main Zone data from the western Bushveld Complex, but the contact rocks show a wider compositional spread due to a larger component of either clinopyroxene or calcsilicate. This is particularly evident in the data from Townlands, Sandsloot, and Nonnenwerth.

Fig. 11 a–d Binary variation diagrams of chalcophile elements vs sulfur. Note broad positive correlations between metals and sulfur suggesting primary concentration of PGE by magmatic sulfides. **e–f** Variation diagrams of PGE. Note positive correlations between PGE that could behave mobile, e.g., Pd, and those that are immobile, e.g., Ir and Pt. **g** Pd/Ir vs S. **h** Pt/Pd vs S (Main Zone and Upper Critical Zone data from Maier and Barnes 1999)
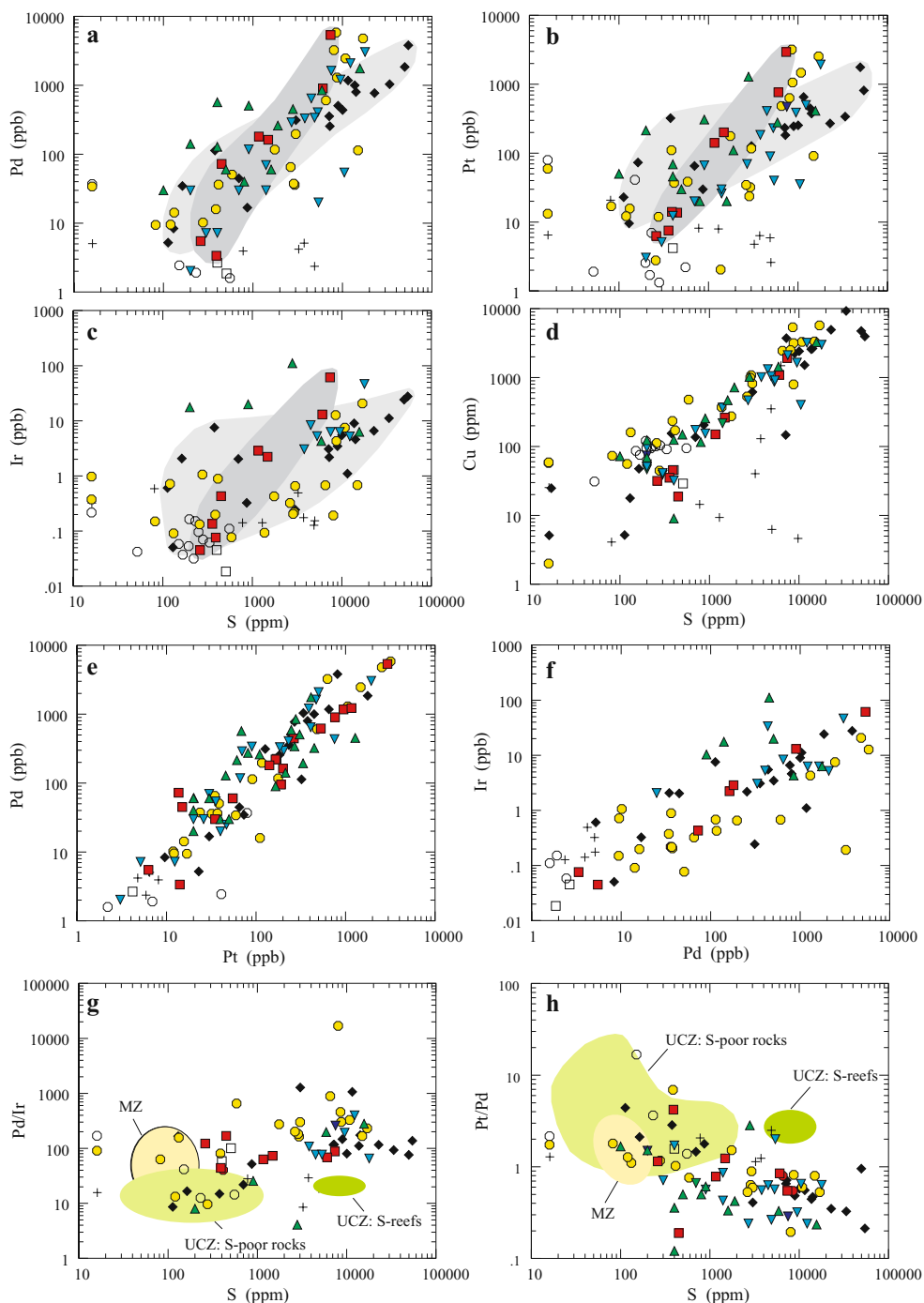
The samples from the different localities define distinct compositional fields in terms of their whole rock Cr and MgO contents (Fig. 7c). The rocks from Rooipoort have variable MgO contents and relatively high Cr contents, containing cumulus chromite in addition to the major silicates. They thus show considerable overlap with the Upper Critical Zone. The rocks from Nonnenwerth have the lowest Cr and lowest MgO contents of the analyzed Platreef samples and overlap with the Main Zone. Most of the rocks from Townlands, Sandsloot, and Drenthe have intermediate

Cr and MgO contents and plot between the Upper Critical Zone and MgO-rich samples from the Main Zone.

The composition of the orthopyroxenes shows a broadly analogous pattern (Fig. 7d). Orthopyroxenes from the south (Grasvally) and center (Sandsloot) are the most primitive and overlap with orthopyroxenes from the Upper Critical Zone, having relatively high Mg# and high Cr contents. Orthopyroxenes from Nonnenwerth are the most evolved and show overlap with the Main Zone orthopyroxenes. Samples from Drenthe show mostly intermediate compositions. The samples from

Fig. 12 Primitive-mantle-normalized concentrations of the chalcophile metals (normalization factors from Barnes and Maier 1999). Data from Drenthe are from Stevens (2004), data from Townlands are from Manyeruke (2003), Nonnenwerth data are from Manyeruke (in preparation), Merensky Reef data are from Barnes and Maier (2002a), and UG2 data from Impala mine are unpublished data of Maier and Barnes
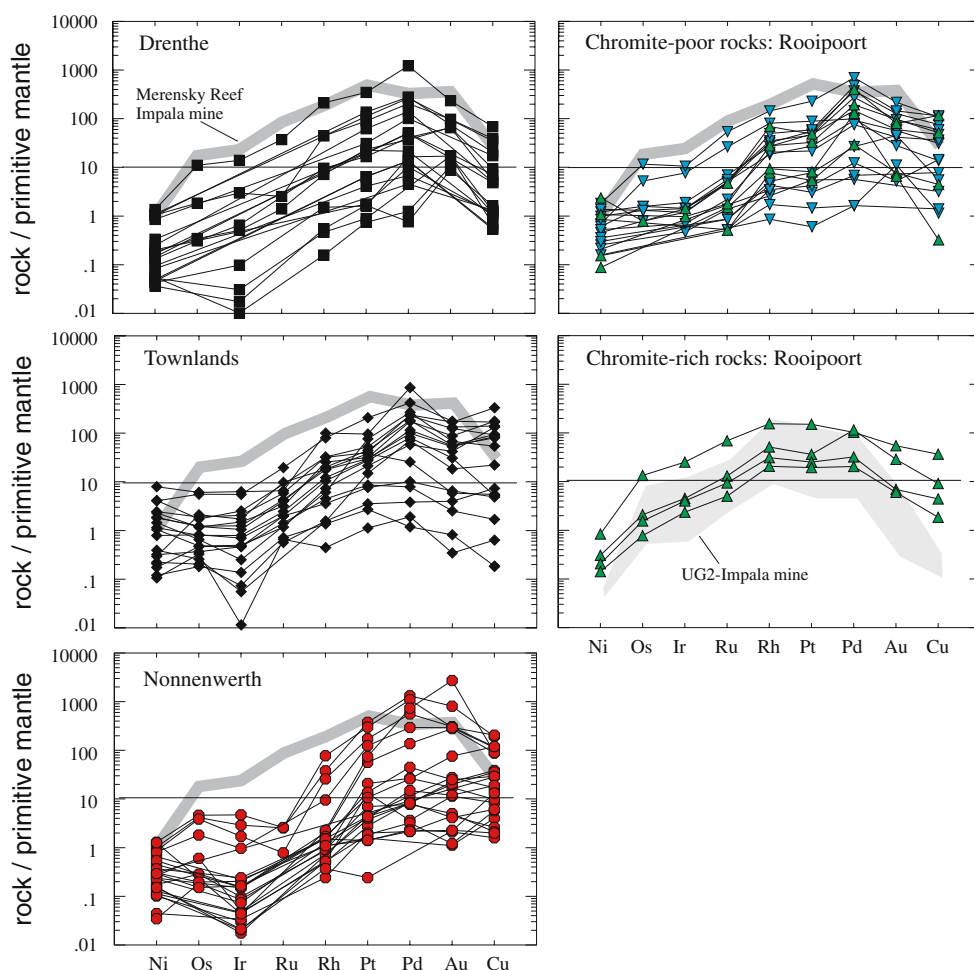
Townlands have the most variable compositions. Some orthopyroxenes overlap with those from the Upper Critical Zone, but several others have high Mg# and low Cr contents, consistent with crystallization from Upper Critical Zone magma contaminated with dolomite.

A pattern of systematic regional compositional variation is also reflected by the concentrations of the incompatible elements. Most of the rocks from Rooipoort and Townlands have relatively fractionated REE patterns (La/Lu$_N$ 4.4–6.2) and higher total REE abundances than cumulates from the Upper Critical and Main Zones (Fig. 8). Notably, among the Rooipoort samples, those that represent the LMF overlying the sedimentary floor rocks are particularly REE rich and fractionated, whereas many of the LMF samples overlying the Lower Zone have flatter patterns. The REE patterns at Nonnenwerth and Drenthe (as well as Sandsloot, McDonald et al. 2005, not shown in Fig. 8) are relatively unfractionated (La/Yb$_N$ 1.6–3.2) with relatively low total element abundances overlapping with the compositions of the Upper Critical and Main Zones (Fig. 8).

The variable crustal component of the samples from the studied localities is highlighted in plots of Ce vs Sm (Fig. 9). To illustrate that the diagram additionally provides some

constraint on the magmatic lineage of the rocks, data from the Upper Critical and Main Zones of the western Bushveld are also shown (Fig. 9a). The Main Zone has an average Ce/Sm ratio of 8.97 (Maier and Barnes 1998), broadly similar to that of B3 sills that are thought to represent the parental magmas to the Main Zone. In contrast, the Upper Critical Zone rocks have an average Ce/Sm ratio of 13.6 and plot mostly along the trend of magnesian basaltic Bushveld B1 sills that are thought to represent the parental liquids to much of the Lower and Lower Critical Zones. The Merensky Reef occurs towards the top of the Upper Critical Zone. Several authors have argued that the uppermost portion of the Upper Critical Zone formed through blending of residual B1 with intruding B2 magmas (e.g., Eales et al. 1990). This model is consistent with the scatter of the Merensky Reef data between the B2 and B1 liquid lines. Based largely on trace element data, Barnes and Maier (2002a) proposed that the parental magma of the Merensky Reef consists of a 60:40 mixture of B1 to B2 component.

The mineralized LMF and MANO rocks from Rooipoort have Ce/Sm ratios of 9.2–10.2, and the samples from Townlands have Ce/Sm 11 (Fig. 9d–f). A possible interpretation is that these rocks reflect mixing between B1 and
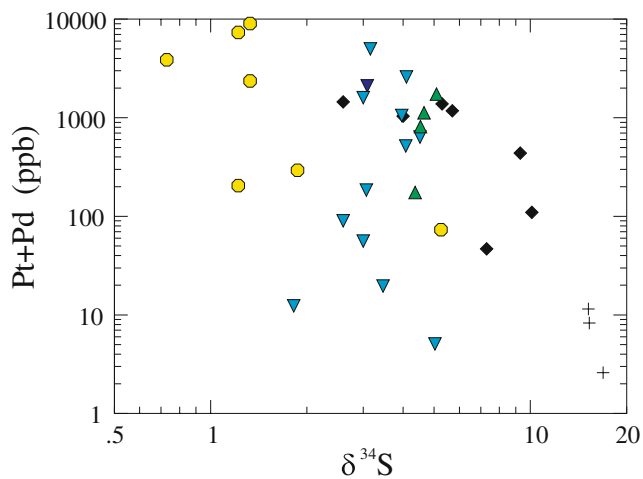
Fig. 13 Pt + Pd plotted vs $\delta^{34}S$ in rocks from Rooipoort (present work), Townlands (Manyeruke 2003), and Nonnenwerth (Manyeruke 2007). See Fig. 7 for symbols

B2/B3 magma. In some samples, the concentrations of the REE are too high to be explained by a trapped melt component of either B1 or B2/B3 Bushveld lineage. The composition of these samples is more consistent with a significant component of assimilated country rocks. As the dolomites of the Transvaal Supergroup tend to have low concentrations of most incompatible trace elements, the most likely contaminant are shales (Klein and Beukes 1989). The rocks from Nonnenwerth, Drenthe, and Sandsloot have a B2/B3 signature (average Ce/Sm 7.4 at Nonnenwerth, 9.03 at Drenthe, 7.51 at Sandsloot). An B2/B3 lineage of the Platreef at Drenthe is in agreement with the available Nd isotopic data (Fig. 10). Ce and Sm contents at Nonnenwerth and Drenthe (Fig. 9b,c) are

relatively low and can be largely explained by control of the elements in 10–30% trapped melt.

Chalcophile elements

In mafic–ultramafic igneous systems, the chalcophile metals are normally assumed to be mainly concentrated by magmatic sulfides. This model is supported by the broadly positive correlations between the chalcophile elements and sulfur in the data sets from Rooipoort, Townlands, Drenthe, and Nonnenwerth (Fig. 11a–d) and by the positive correlations between those PGE that could behave in a mobile manner (in particular Pd, Hsu et al. 1991) and those that are believed to be immobile under most conditions (e.g., Pt and Ir; Fig. 11e–f). Based on the slopes of the PGE/S data arrays, the Townlands sulfides appear to have the lowest metal tenors, with progressively higher tenors at Rooipoort, Nonnenwerth, and Drenthe.

Mantle-normalized PGE patterns of most samples are relatively fractionated (Fig. 12), with Ni/Ir_N around unity, a progressive increase from Ir to Pd (Pd/Ir ca. 10 to 1,000), and a decrease from Pd to Cu resulting in $Cu/Pd_N < 1$. These patterns indicate that the parental magmas to the rocks were fertile in terms of PGE. Compared to the Merensky Reef, the contact-style rocks tend to be less enriched in PGE relative to Cu and Ni, they have more fractionated metal patterns resulting in higher Pd/Ir ratios, and they show an enrichment in Pd relative to Pt.

Four samples from the LMF at Rooipoort that contain 10–20% chromite in the form of stringers and lenses have bell-shaped mantle-normalized PGE patterns (Fig. 13) that show increasing metal concentrations from Ni to Rh, flat
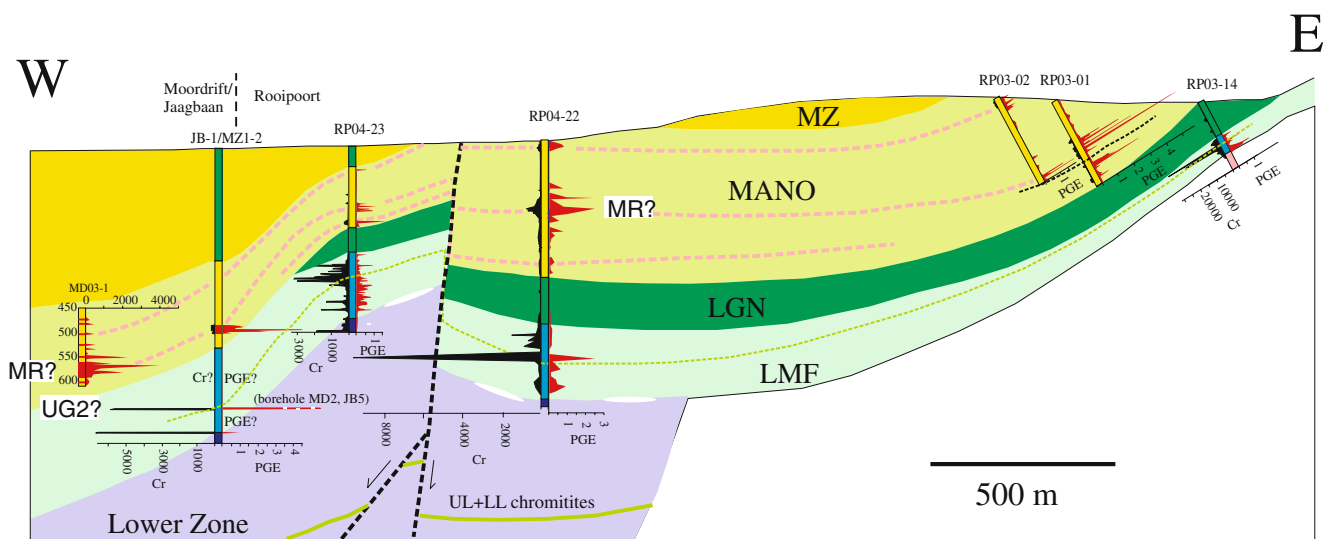
Fig. 14 Down-dip correlation of lithological units on Rooipoort and adjoining farms Jaagbaan/Moordrift. Section is based on borehole information along profile A–B (Fig. 3). Note how the putative Merensky Reef and UG2-like chromitite on Jaagbaan and Moordrift transform into wide intervals of chromite and PGE enrichment in the boreholes on Rooipoort
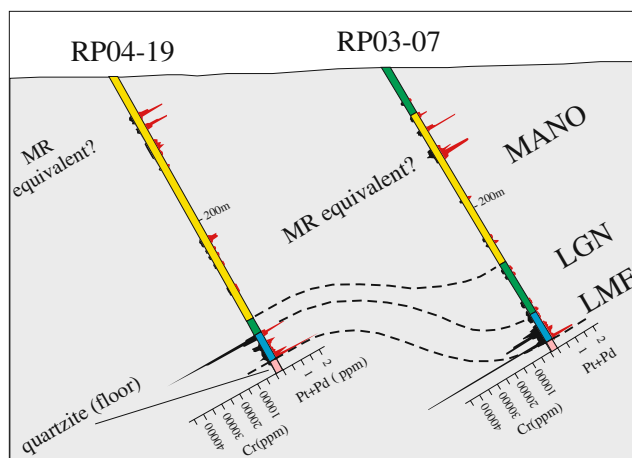
Fig. 15 Profiles of boreholes intersecting the contact-style mineralization in the central and northern parts of Rooipoort (see Fig. 3 for borehole locations)

patterns from Rh to Pd, and decreasing concentrations from Pd to Au. Pt/Pd ratios tend to be higher (up to 3) than in the remainder of the Platreef rocks. The patterns resemble those of other chromitites in the Bushveld Complex (e.g., Scoon and Teigler 1994) suggesting a common mode of formation that led to a distinct enrichment of Pt over Pd and of the noble metals over Cu and Ni.

Pd/Ir and Pt/Pd ratios of the contact-style rocks are plotted vs sulfur in Fig. 11g–h. The diagrams illustrate that (1) the data show limited compositional overlap with the Upper Critical and Main Zones and (2) the data show considerable variation in Pd/Ir and Pt/Pd. These features indicate that Pt/Pd and Pd/Ir ratios of the contact-style rocks cannot readily be used to infer magmatic lineage. The sulfide-rich rocks tend to have higher Pd/Ir ratios and lower Pt/Pd ratios than the sulfide-poor rocks. An analogous correlation is not apparent in data from the western Bushveld Complex.

S isotopic data

We analysed 16 samples from the MANO and the LMF at Rooipoort for whole rock S isotopic ratios. The samples have $\delta^{34}S$ between +1.8 and +5.1, indicating that at least some of the sulfur at Rooipoort is of crustal derivation. The MANO rocks have a slightly lower average value ($\delta^{34}S$ +3.49) than rocks from the LMF ($\delta^{34}S$ +4.66), suggesting enhanced assimilation of external S at the base of the sequence. A broadly similar compositional range in $\delta^{34}S$ and an analogous pattern of elevated $\delta^{34}S$ towards the base of the succession has been documented in contact-style rocks at Townlands, Turfspruit, Macalacaskop, and Tweefontein (Liebenberg 1970; Sharman-Harris et al. 2005; Manyeruke et al. 2005) and in the UG2-like chromitite at Grasvally ($\delta^{34}S$ + 4, Hulbert 1983). The most likely sources of some of the crustal S are shales and/or iron formation of

the Transvaal Supergroup. In contrast, contact-style rocks from Zwartfontein and Nonnenwerth have $\delta^{34}S$ values mostly between 0 and +2 (White 1994; Manyeruke 2007). These values overlap with the mantle range and are thus less indicative of an external S component. Notably, our samples indicate a lack of correlation between $\delta^{34}S$ and the concentration of sulfur (not shown) and PGE (Fig. 13).

Discussion

The contact-style mineralization within the stratigraphic framework of the Bushveld Complex

The dense spacing of relatively deep exploration boreholes on the farms Jaagbaan, Moordrift, and Rooipoort, aided by an anticlinal upwarp, has resulted in the exposure of more than 3 km of down-dip lithological variation (Fig. 14) offering a unique opportunity to constrain the lithostratigraphic relationships of the contact-style mineralization at these localities. The lithological and compositional data presented in the preceding chapters indicate that the LMF and MANO on Rooipoort progressively transform into an interval hosting the UG2-like chromitite, Merensky Reef, and associated rocks on Jaagbaan, Moordrift, and Grasvally. The present study therefore suggests that the GNPA/Upper Critical Zone at Grasvally, Jaagbaan, and Moordrift can be correlated with the LMF-MANO in the central and eastern portions of Rooipoort. This implies that, where it abuts against the margin of the intrusion, the Upper Critical Zone can transform into contact-style mineralization resembling the Platreef.

At the present time, we can only speculate on the reasons for the observed lithological changes of the Upper Critical Zone adjacent to the margin of the intrusion. The available data indicate that the Upper Critical Zone was emplaced after the Lower Zone. This explains why in internal environments, the Upper Critical Zone rocks appear to have cooled relatively slowly, allowing mixing of new magma with residual Lower Zone liquids and the accumulation of laterally extensive and relatively thin cumulate layers such as the Merensky Reef and the UG2 chromitite. In marginal environments where the Upper Critical Zone magma transgressed over the floor, it could not mix with significant amounts of residual liquids and likely cooled at a relatively faster rate. This would have prevented suspended crystals and sulfide melt to segregate and accumulate efficiently to form relatively narrow and continuous silicate-, oxide-, and sulfide-enriched layers. Instead, relatively wide PGE- and sulfide-rich zones formed, and any chromitite layers contained higher-gangue contents (e.g., the UG2-like chromitite, Hulbert 1983). Assimilation of the floor rocks led to highly variable

compositions and textures of the rocks and an abundance of xenoliths not observed in internally located Upper Critical Zone intervals. Layering was further disturbed after accumulation of the rocks, during progressive heating, partial melting, devolatization, and updoming of the floor rocks. This could have led to lateral sliding of the semiconsolidated cumulate layers and may have resulted in the brecciation of the UG2-like chromitite on eastern Moordrift and on Rooipoort.

A genetic relationship of the contact-style mineralization on Rooipoort and the Platreef elsewhere in the northern lobe of the Bushveld Complex is suggested by several lithological similarities, notably the abundance of floor xenoliths and the dispersed nature of the sulfide mineralization. A chromite-rich interval similar to the LMF has not been identified on Townlands, Drenthe, and Nonnenwerth, but chromitite stringers have been reported from Tweefontein (Viljoen and Schürmann 1998) and occur at the base of the Platreef on Sandsloot. This suggests that the Cr-rich magma correlated with the UG2-like chromitite on Moordrift, Jaagbaan, and Grasvally, and the LMF on Rooipoort, was equally present further to the north. However, it has either become less voluminous towards the north, or progressively diluted, or its crystallization products have been partly eroded by subsequent magma pulses.

The MANO and its mineralized zones can be correlated along strike at Rooipoort (Fig. 15) and to the adjoining farm Oorlogsfontein in the north (http://www.Platinum GroupMetals.net). However, on Townlands, Turfspruit, and Sandsloot, there is a little record of distinct, laterally correlatable, PGE-enriched layers within or above the typical varied-textured Platreef. This suggests that, at these localities, the MANO either remains undiscovered, that it wedges out, or that it has transformed into the Platreef, in an analogous manner as the UG2-like chromitite on Moordrift has transformed into the LMF on Rooipoort.

In summary, contact-style sulfide-mineralized rocks at the base of the northern Bushveld Complex share certain lithological, compositional, and petrogenetic similarities. However, the sequence is not correlatable along strike. On Rooipoort and adjoining farms, the contact-style rocks can probably be correlated with the Upper Critical Zone, including the UG2 chromitite and the Merensky Reef. Between Townlands and Drenthe, the contact-style rocks have a mixed Upper Critical Zone–Main Zone signature and locally contain a high component of the floor rocks, whereas at Nonnenwerth, the rocks bear more lithological similarities to the Main Zone.

Magmatic lineage of the Platreef

The compositions of the parental magmas to the Platreef have remained controversial. This is because of the considerable variation in lithology and composition of the rocks that can be partly assigned to the assimilation of the floor rocks. Contamination has resulted in an abundance of xenoliths and modification of the primary magmatic trace element and isotopic signatures.

To overcome these challenges, early workers have attempted to determine the composition of fine-grained contact rocks that might represent chilled liquids. Hulbert (1983) found that fine-grained rocks at the base of the GNPA on the farm Grasvally are essentially of tholeiitic (B2/B3) composition. However, Hulbert (1983) argued that some of the Cr-rich cumulates of the GNPA, notably the UG2-like chromitite, could not have crystallized from Cr-poor tholeiitic magma alone, but required inmixing of Cr-rich magnesian basaltic (B1) magma. This led him to propose that the GNPA crystallized from a hybrid magma consisting of residual differentiates of magnesian basaltic (B1) magma derived from the Lower Zone and newly intruding tholeiitic (B2/B3) magma. This model is analogous to that proposed for the Upper Critical Zone of the western Bushveld Complex (e.g., Eales et al. 1990).

The results of the present study are consistent with this model. In the southern portion of the northern Bushveld, at Rooipoort, the contact-style rocks have fractionated trace element patterns with Ce/Sm ratios intermediate between those of B1 and B2/B3 magmas. The orthopyroxenes have compositions overlapping with those of the Upper Critical Zone. Some rocks (notably in the LMF) are relatively Cr and MgO rich. By analogy with the Upper Critical Zone elsewhere in the Bushveld, these features could suggest mixing of magnesian basaltic with tholeiitic magma. The model is supported by the lithological correlation of the GNPA on Grasvally, Moordrift, and Jaagbaan with the mineralized sequence on Rooipoort (Fig. 14).

From Townlands to Drenthe, the limited data available also suggest a mixed Upper Critical Zone–Main Zone lineage. However, there seems to be considerable local compositional variation. At Macalacaskop and Turfspruit, there occur relatively large amounts of ultramafic rocks, possibly indicating a relatively high magnesian basaltic (B1) component in the magma. At Sandsloot and Drenthe, the tholeiitic (B2/B3) component seems to be relatively more prominent, as indicated by unfractionated REE patterns and a lower proportion of ultramafic to mafic rocks.

At Nonnenwerth, the contact-style rocks bear strong compositional resemblance with the Main Zone and thus appear to have crystallized largely from tholeiitic (B2/B3) magma, as indicated by the relatively unfractionated REE patterns with low Ce/Sm ratios, εNd values in the Main Zone range, mostly relatively low MgO and Cr contents, and high Pd/Ir.

The origin of the PGE mineralization

Several past authors have proposed that the contact-style PGE mineralization formed in response to the contamination of Bushveld magmas with the floor rocks (Buchanan et al. 1981; Gain and Mostert 1982; White 1994). This model is supported by a number of observations, notably: (1) The contact-style mineralization occurs along the base of the intrusion, although the mineralized interval can be several 100 m thick. (2) The mineralized rocks contain abundant xenoliths of dolomite and shale suggesting interaction of the magma with relatively reactive floor rocks. (3) The mineralized interval contains a higher bulk sulfide content than the Upper Critical Zone reefs, suggesting addition of external sulfur to the contact magma and/or a lower S solubility in the latter. (4) Most contact-type sulfides have lower metal tenors than those in the internal PGE reefs. Relatively low metal tenors are characteristic of basal sulfide ores in many intrusions elsewhere in the world and are normally explained by low R factors of assimilated sulfides. (5) At many localities in the northern Bushveld, the contact-mineralized rocks have distinctly crustal S isotopic signatures.

The available data suggest that the contact magmas assimilated various types of floor rocks. In the north–central sector, from Tweefontein to Nonnenwerth, the main contaminant was probably dolomite, as suggested by the predominance of calcsilicate xenoliths. Assimilation of dolomite probably did not introduce significant amounts of external sulfur to the magma, as indicated by the mantle-like S isotopic signature of the contact-mineralized rocks at Zwartfontein and Nonnenwerth and the general paucity of sulfides in the dolomitic floor rocks. Instead, assimilation of dolomite may have lowered the S solubility of the magma in response to devolatization and oxidation (De Waal 1975). The importance of dolomite assimilation in causing sulfide saturation in the Nonnenwerth contact rocks is highlighted by the concomitant paucity of sulfides in most other Main Zone rocks elsewhere in the Bushveld.

To the south of Tweefontein, the main contaminants of the contact magma probably consisted of dolomite and shale. This is suggested by the abundance of xenoliths of calcsilicate and shale in the contact rocks, and by the relatively heavy S isotopic signature of the magmatic sulfides (δ^{34}S +2 to +10) (Manyeruke 2003; Manyeruke et al. 2005; Sharman-Harris et al. 2005). However, our observations from Rooipoort and adjoining farms also suggest that contamination was not required to trigger sulfide saturation in the magma. At these localities Upper Critical Zone reefs including the UG2-like chromitite and a probable Merensky Reef analogue can be seen to transform into contact-mineralized rocks. The implication is that the magma was already S saturated before final emplacement

and thus that contact-style PGE mineralization may form when S-saturated magma abuts against refractory floor rocks.

One of the most important unresolved questions concerning the petrogenesis of contact-style mineralization relates to the apparent restriction of the high-grade mineralization to a relatively narrow corridor from Sandsloot to Overysel. Past authors have noted that the high-grade area broadly coincides with the transgression of the intrusion through dolomite floor rocks and suggested that dolomite assimilation may have caused oxidation of the magma, lowered its S solubility, and thereby triggered sulfide saturation (De Waal 1975). An evaluation of this model is currently difficult because of lack of PGE and sulfide data, but other possibilities that should additionally be considered include the following: (1) Devolatization of the floor rocks and xenoliths could have caused partial melting of semi-consolidated contact-style rocks and concentration of PGE in residual cumulates. (2) The sulfides could have formed at higher R factors than those elsewhere in the northern Bushveld. (3) The high-grade localities could have been exposed to a combination of favorable processes, including lower degrees of magma contamination with sulfidic floor rocks and thus less dilution of PGE, a lower S solubility of the magma due to enhanced assimilation of dolomite, and a high proportion of PGE-rich Upper Critical Zone sulfides entrained in the magma.

Pt/Pd ratios

Several previous authors have remarked on the fact that the contact-style mineralization shows relatively low Pt/Pd ratios (Pt/Pd mostly <1) compared to the internal reefs and silicate rocks of the western and eastern Bushveld Complex (Pt/Pd > 1; e.g., McDonald et al. 2005, and references therein). We suggest that the difference in Pt/Pd between the internal and the contact-style mineralization can largely be assigned to two processes: (1) Palladium (as well as S) may be mobilized in percolating late magmatic or hydro-thermal melts and/or fluids, particularly if the sulfides are completely resorbed (e.g., Boudreau and Meurer 1999; Peregoedova et al. 2004). This may result in particularly high Pt/Pd ratios in internal reefs that are underlain by thick packages of compacting and cooling cumulates. For example, certain intersections of UG1 chromitite at Impala mine have up to 700-ppb Pt and <20-ppb Pd (unpublished data of Maier and Barnes). The Merensky Reef apparently also underwent S and/or Pd mobility as indicated by common replacement textures of the sulfides (Li et al. 2004) and high Pt/Pd ratios of up to 11 in the chromitite stringers (Barnes and Maier 2002a). Secondary Pd mobility, comprising both localized Pd loss and gain may also have occurred in the Platreef because of the devolatization of the

floor rocks. This model is supported by low Pd/Ir and high Pt/Pd in S-poor Platreef rocks (Fig. 11g–h). (2) In the contact-style environments, Pd could show enhanced partitioning into sulfide melt relative to Pt and Ir. The contaminated Platreef magma was likely to have had a higher oxygen fugacity (e.g., De Waal 1975) resulting in the oxidation of Pt and Ir and decreased partitioning into sulfide melt. This model is supported by a trend of relatively low Pt/Pd in basal sulfide ores elsewhere in the Bushveld magmatic province, e.g., the Uitkomst Complex (Maier et al. 2004).

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