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Compositional and lithological variation of the Platreef on the farm
Nonnenwerth, northern lobe of the Bushveld Complex: Implications
for the origin of Platinum-group elements (PGE) mineralization

By

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Fig. 8.2 contd: Photomicrographs of (g & h) Pyrite enclosing fragmented pentlandite and intergrown with disseminated chalcopyrite. Note the rim of fine chalcopyrite intergrown with pyrite around the coarse, fragmented, composite sulphide

(sample MOX10), (i & j) Pyrite in fractures within altered plagioclase (alt. plag). Disseminated chalcopyrite is intergrown with secondary silicates (sample MOX9 and 10, respectively). (k) Magnetite (mt) intergrown with ilmenite (ilm). Magnetite contains pyrrhotite along cleavage planes (sample MOX12). In reflected light, plane polarised light, i and j in air and g, h and k in oil.

Fig. 8.3: Photomicrographs of (a) Chalcopyrite intergrown with amphibole (am) laths along its margin, and enclosing subhedral zircon (sample MOX29). (b) Aggregate of pyrrhotite rimmed by chalcopyrite which is in turn rimmed by pyrite (sample MOX32). (c) Chalcopyrite intergrown with minor pentlandite at its margin and rimmed by pyrite. Note streaks of pyrite in adjacent altered plagioclase (Sample MOX32). (d) Pyrrhotite enclosing an intergrowth of pentlandite, pyrite and chalcopyrite. The corona around pyrrhotite consists of pyrite intergrown with minor chalcopyrite (sample MOX32). (e) Pyrrhotite enclosing vaguely round blebs of an intergrowth of pyrite and chalcopyrite. Chalcopyrite is concentrated towards the rims whereas pyrite is concentrated in the core. Pyrrhotite additionally contains flame-like exsolutions of pentlandite (sample MOX32). (f) Intergrowth of pyrrhotite (po) pyrite (py), minor chalcopyrite (cpy), and pentlandite (pn). (sample MOX27). opx = orthopyroxene. In reflected light, plane polarised light, in oil.

Fig. 8.3 continued: (g) Interstitial pentlandite intergrown with chalcopyrite. Disseminated chalcopyrite replaces adjacent altered plagioclase (alt. plag) along cleavage planes (sample MOX27). (h) Violarite (viol) rimming pentlandite and intergrown with pyrite and chalcopyrite sample (MOX29). (i) Violarite with minor relictic pentlandite is intergrown with pyrrhotite and chalcopyrite (sample MOX29). (j & k) Pyrite occurs interstitial to plagioclase and clinopyroxene (cpx) and replaces the silicates along fractures (sample MOX32). (l) Interstitial pyrite replaces clinopyroxene along cleavage planes (sample MOX 32). In reflected light, plane polarised light, in oil.

Fig. 8.4: Photomicrographs of (a) Chalcopyrite (cpy) and pyrite (py) intergrown with acicular amphibole actinolite (am) (sample P7). (b) An aggregate of intergrown anhedral magnetite (mt) and chalcopyrite in altered plagioclase (alt. plag) (sample P7). (c & d) Coarse pyrite intergrown with magnetite that encloses millerite (mil). Magnetite is also intergrown with anhedral, disseminated chalcopyrite (sample P7). (e & f) Coarse pyrite cut by veinlets of intergrown chalcopyrite and millerite (sample P7). In reflected light, in oil, (a, b & e) plane polarised light and (d & f) cross polarised light.

Fig. 8.4 continued: g & h) Chalcopyrite cut by covellite (cov) veins and rimmed by magnetite. Note minor pentlandite in h (sample P2). (i & j) Patches of violarite intergrown with pentlandite, minor chalcopyrite, covellite and cut by magnetite veinlets (sample P2). (k & l) Intergrowth of orthopyroxene (opx) and ilmenite, as well as granular, subhedral and anhedral ilmenite (ilm), orthopyroxene (opx) and minor anhedral hematite (hem) (sample P4). (m & n) Pentlandite and

chalcopyrite show extensive alteration to covellite and magnetite along irregular fractures (sample P2). In reflected light, plane polarised light except l, in oil.

Fig. 8.5: Photomicrographs of (a) Plagioclase (plag) containing vermicular network of pyrite. Pyrite also forms coronas around chalcopyrite (sample P19). (b) Skeletal pyrite and pyrite replacing plagioclase along cleavage planes (sample P19). (c) Pyrite cut by pentlandite-rich veins. Also note fine disseminated chalcopyrite in pyrite (sample P19). (d) Pentlandite replacing plagioclase along cleavage planes. Matrix is pyrrhotite with disseminated fine chalcopyrite (sample P19). (e) Pyrite enclosing millerite. Note fine disseminated chalcopyrite intergrown with pyrite (sample P15). (f & g) Millerite replacing chalcopyrite along fractures. Minor pyrite (py) grains occur at the contact between chalcopyrite and millerite, or are enclosed in millerite (sample P14). (h) Magnetite (mt) is intergrown with chalcopyrite, with minor chalcopyrite being remobilised into adjacent silicates (sample P11). In reflected light, cross polarised light, in oil.

Fig. 8.5 continued: (i) Anhedral chalcopyrite intergrown with anhedral pyrite (sample P11). (j) Massive, twinned, subhedral millerite (mil) intergrown with interstitial chalcopyrite (cpy) (sample P106). (k) Anhedral, twinned chalcopyrite intergrown with, and enclosing, vaguely round millerite (sample P106). (l & m) Fragmented pyrite intergrown with millerite and chalcopyrite (sample P15). (n) Subhedral magnetite with ilmenite lamellae (sample P15). (o & p) Radiating, skeletal ilmenite vaguely round chromite (cr) and enclosing an intergrowth of chalcopyrite and millerite (sample P15). In reflected light, plane polarised light (except i, l, n and o), in oil.

Fig. 8.6: Variation of a) Pd, b), Se with depth in pentlandite, and Se versus Pd. MP = Middle Platreef (from Townlands), anor = anorthosite, rx gn = recrystallized gabbroite (both from Nonnenwerth).

Fig. 8.7a: Cr # versus Fe # of the analysed Cr-bearing spinels from serpentinised peridotite (MO 26) and from melagabbroites (MO 27).

Fig. 8.8. fO_2 vs fS_2 (a) diagrams for the Fe-S-O system at 1270C, after Holland (1959). (b) fO_2 vs fS_2 diagram for the Fe-Ni-S-O system at about 1270C. Reaction boundaries for the Fe-S-O sub-system are shown as solid lines; others for which thermodynamic data are unavailable or unreliable are shown in dashed lines. (c) Approximate fO_2 vs fS_2 diagram for the Fe-Ni-S-O system under conditions of common hypogene equilibrium in altered ultramafic rocks, probably less than 2000C. Assemblages noted in the Platreef on Townlands are shown by circled numbers on the appropriate field of the boundary. Assemblage 1 is composed of pyrrhotite, chalcopyrite, pentlandite \pm magnetite, assemblage 2 is characterized by pyrite, pentlandite, chalcopyrite and minor pyrrhotite and assemblage 3 is characterized by pyrite, millerite, chalcopyrite \pm pentlandite \pm galena, molybdenite and magnetite. Figures modified after Eckstrand (1975).

Fig. 9.1: Back-scattered electron images showing various textures and associations of PGM and gold. Rectangle (where present) represents area enlarged in the image to the immediate right. (a) PGM (in rectangle) enclosed in plagioclase (plag) that has been altered to amphibole (am), in the vicinity of chalcopyrite (cpy). The other highly reflective phase at the top of the image is Pb derived from polishing. Sample MOX9. (b) Enlarged rectangle from a). Anhedronal moncheite (mon) is associated with disseminated anhedronal kotulskite (kot) in amphibole (black). Sample MOX9. (c) Kotulskite and moncheite enclosed in altered portions of plagioclase. Moncheite is in contact with pyrite. orth = orthoclase, alb = albite. Sample MOX9. (d) Euhedral to subhedral kotulskite and moncheite. Altered plagioclase is shown in black. Sample MOX9. (e) Composite grain of pyrrhotite (po), pentlandite (pn) and chalcopyrite, with PGM (in rectangle) situated in the periphery of the grain. Sample MOX10. (f) Enlarged rectangle from e). Subhedral to anhedronal moncheite and associated kotulskite occur included in altered plagioclase (black background). Sample MOX10. (g) A composite grain of kotulskite, gold (Au) and sperrylite in altered plagioclase (black background). Sample MOX9

Fig. 9.1 continued: Back-scattered electron images showing various textures and associations of PGM and gold. Rectangle (where present) represents area enlarged for image to the immediate right. (h) Chalcopyrite and PGM associated with quartz (qtz) and chlorite (chl), interstitial to plagioclase. Anhedronal moncheite is highlighted by rectangle. The other PGM are subhedral kotulskites (kot) Sample MOX9. (i) Enlargement of rectangle from h). Anhedronal moncheite is enclosed in chlorite (black background). Sample MOX9. (j) Subhedral moncheite forming a trail from the margin of chalcopyrite (cpy) into adjacent quartz and amphibole (after plagioclase). Sample MOX9. (k) Enlargement of rectangle from j. (l) Intergrown pyrrhotite and pentlandite, with braggite (in rectangle) occurring near margin of sulphide. Sample MOX10. (m) Enlargement of rectangle from l). Zoned subhedral grain of braggite. Increase in brightness corresponds to increase in Pt content. The numbers correspond to analyses e.g. 11 represents 11_MOX10 in Table 6 (Sample MOX10). (n) Grain of gold (Au) (in rectangle) located near fracture in orthopyroxene (opx). Sample MOX12. (o) Enlargement of rectangle from n). Subhedral grain of gold is partly corroded. Sample MOX12. (p) Gold (in rectangle) located at the contact between quartz (qtz) and chalcopyrite (cpy). Sample MOX9. (q) Enlargement of rectangle in p). Sample MOX9.

Fig. 9.2: Mineral chemistry of (Pt,Pd)-bismuthotellurides from Nonnenwerth and Townlands. a) Pd-dominated (Pt,Pd)-bismuthotellurides in the triangular plot (Pt+Pd)- (Bi+Sb)-Te (at. %). b) Pt-dominated (Pt,Pd)-bismuthotellurides in the triangular plot (Pd+Pt)-(Bi+Sb)-Te (at. %). c) (Pt,Pd)-bismuthotellurides in the triangular plot (Bi+Te+Sb)-Pt-Pd (at. %).

Fig. 9.3: Mineral chemistry of braggite from Nonnenwerth (sample MOX10).

Fig. 9.4: Back-scattered electron images showing various textures and associations of

PGM. (a) Merenskyite (mer) enclosed in pyrrhotite (po) and occurring as thin lamellae in chalcopyrite. Note also calcite enclosed in chalcopyrite. Sample MOX29. (b) Merenskyite lamellae in chalcopyrite. Sample MOX29. (c) Merenskyite (in rectangle) intergrown with amphibole, quartz and chalcopyrite within plagioclase. Sample MOX29. (d) Enlargement of rectangle in c). Subhedral merenskyite grains in amphibole and quartz after plagioclase. Sample MOX29. (e) Merenskyite (in rectangle) enclosed in chalcopyrite that is intergrown with acicular amphiboles (actinolite). Chalcopyrite also encloses subhedral zircons (zr). Sample MOX29. (f) Enlargement of rectangle in e). Subhedral merenskyite enclosed in chalcopyrite. Sample MOX29. (g) PGM (in rectangle) in amphibole peripheral to a composite grain of chalcopyrite, pyrrhotite and pentlandite. Sample MOX27. (h) Enlargement of rectangle in g) Anhedral moncheite and merenskyite in amphibole. Sample MOX27. (i) Back scattered electron image of kotulskite enclosed in chalcopyrite, close to a fracture. Sample MOX29.

Fig. 9.5: Back-scattered electron images of isomertieite and its textural setting. Isomertieite (iso) enclosed in chalcopyrite, near contact with pyrite. Sample P7. (b) Enlargement of isomertieite shown in a). Sample P7.

Fig. 9.6: Back-scattered electron images showing various textures and associations of PGM. Rectangle (where present) represents area enlarged for image to the immediate right. (a) PGM (in rectangle) enclosed in chalcopyrite (cpy) adjacent to the margin of the sulphide. Magnetite (mt) is also enriched in the border zone of the sulphide. po = pyrrhotite, pn = pentlandite, opx = orthopyroxene. Sample P13. (b) Enlargement of rectangle in a). Subrounded michenerite (mich) intergrown with merenskyite (mer). Sample P13. (c) Subrounded merenskyite enclosed in millerite. Sample P106. (d) A subrounded and an elongate merenskyite grain are enclosed in pyrite (py), associated with a fracture. Sample P15. (e) PGM (in rectangle) enclosed in pyrite along internal cracks. The PGM are associated with amphibole (am) that is intergrown with pyrite, also along cracks. Sample P15. (f) Enlargement of rectangle in e). Anhedral merenskyite intergrown with hessite (hes). Sample P15. (g) Kotulskite (kot) (in rectangle) enclosed in millerite (mil). Note chalcopyrite that is interstitial to millerite. Sample P106. (h) Enlargement of rectangle in g). Subrounded kotulskite enclosed in millerite. Sample P106.

Fig. 9.6 continued: Back scattered electron images showing various textures and associations of PGM and Bi-,Te- phases. Rectangle (where present) represents area enlarged for image to the immediate right. (i) Sperrylite (sp) (in rectangle) located at the contact between pyrrhotite and orthopyroxene (opx). Pyrrhotite is intergrown with pentlandite and also contains minor flame-like exsolutions of pentlandite. Sample P13. (j) Enlargement of rectangle in c). Subhedral sperrylite and smaller anhedral sperrylite at the contact between pyrrhotite and orthopyroxene. Sample P13. (k) Pyrite enclosing intergrowths of tetradymite-type (tet) minerals and chalcopyrite. Sample P15. (l) Pyrite enclosing a composite grain of chalcopyrite, pyrrhotite, pilsenite (pil), Fe-emplectite? (Fe-emp?) and the

unnamed phase UN 1133 with a calculated chemical formula $[\text{Bi}_4\text{Te}_2\text{Se}]$. Sample P15. (m) Altaite (alt) grains (in rectangle) are enclosed in secondary amphibole adjacent to pyrrhotite showing rims of magnetite. Sample P13. (n) Enlargement of rectangle in m). One grain of altaite is intergrown with galena (gal). Sample P13. (o) Gold (Au) grains (in rectangle) enclosed in pyrite or located near the contact between pyrite and enclosed chalcopyrite. Sample P106. (p) Enlargement of rectangle in o). Anhedral gold grains in pyrite. Sample P106.

Fig. 10.1: Regional geological map of the northern limb with results of S isotope analyses superimposed. Data from Townlands are from Manyeruke *et al.* (2005), data from Macalakaskop, Rietfontein and Turfspruit are from Sharman-Harris *et al.* (2005), data from Tweefontein are from Buchannan *et al.* (1981), data from Rooipoort are from Maier *et al.* (2007), data from Uitloop are from Tuovila (in preparation), data from Overysel are from Holwell *et al.* (2005) and data from Zwartfontein are from Liebenberg (1968). (Map modified after Ashwal *et al.*, 2005).

Fig. 10.2: $\delta^{34}\text{S}$ values of sulphidic rocks and sulphides in selected mafic/ultramafic intrusions (modified from Ripley, 1999). Kabanga and Kunene data are from Maier (unpublished), Uitloop data are from Touvila, (personal communication) and Townlands data are from Manyeruke (2003).



ABSTRACT

The present study documents the nature of the Platreef on the farm Nonnenwerth, northern Bushveld Complex and compares the lithologies and composition of the mineralized interval to those on the farm Townlands. The Platreef on Townlands was the subject of a previous study (Manyeruke 2003, MSc thesis, University of Pretoria), but in the course of the present investigation, additional data were collected. Nonnenwerth is located more than 70 km to the north of the well characterized occurrences of the Platreef at Sandsloot, Overysel and Drenthe. At Nonnenwerth, the Platreef rests on Archaean granite gneiss floor rocks whereas at Townlands, the Platreef rests on pelitic rocks of the Transvaal Supergroup.

At Nonnenwerth, the basal rocks of the Bushveld Complex may be sub-divided into two lithologically and compositionally distinct units. At the base is a relatively heterogeneous sequence of gabbro-norite with minor amounts of norite, anorthosite and igneous ultramafic rocks containing several calc-silicate xenoliths. It is some 110 m thick and is enriched in Platinum-group element (PGE)-Cu-Ni bearing sulphides (<ca. 3 modal %). Layering is mostly weakly defined and discontinuous. The mineralized interval is overlain by the Main Zone that is made up of some 170 m of relatively homogenous gabbro-norite, containing several large dolomite xenoliths. The two units are separated by an up to 25m thick dolomite xenolith. In many aspects, the composition of the Platreef and the Main Zone broadly overlap ($Mg\#_{\text{opx}}$ 57 – 72, An_{plag} 40 – 75, $MgO_{\text{whole rock}}$



7 – 15 wt. %, similar incompatible trace element patterns). However, the Platreef has distinctly higher Cr contents ($Cr_{\text{whole rock}}$ up to 1813 ppm as opposed to 280 ppm in the Main Zone) as well as concentrations of chalcophile elements (N, Cu, PGE) and sulphur.

The Platreef and the Main Zone have relatively unfractionated REE patterns with Ce/Sm between 5.7 and 10.6 (averaging 8). This suggests that the Platreef on Nonnenwerth is genetically related to Bushveld tholeiitic magma (B2/B3 of Sharpe, 1981). In contrast, Platreef rocks on the farm Townlands, south of Mokopane, are more primitive in terms of mineral and whole rock composition (Mg# opx 77, An plag 68, presence of olivine) and have higher and more fractionated REE contents (Ce/Sm 8 – 14.2, averaging 11.6). They show certain similarities to Upper Critical Zone cumulates and appear to have crystallised either from B1 – B2 hybrid magmas, or from B2 magma contaminated with crust upon emplacement. This implies that Platreef PGE mineralization cannot be correlated with specific stratigraphic units or magma types, but that it formed in response to several different processes.

Platinum-group element (PGE) contents of Platreef samples from Nonnenwerth reach 10 ppm, whereas PGE contents in the Platreef at Townlands reach 4.4 ppm. PGE distribution patterns at Nonnenwerth are more fractionated than at Townlands, with Pd/Ir mostly $\gg 100$ at Nonnenwerth compared to < 100 at Townlands. At both localities, there is a broad positive correlation between the



concentrations of 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) and between individual PGE and S (for samples with > 0.1 % S), suggesting that sulphides were the primary PGE collector. At Nonnenwerth, this model is supported by a typical magmatic sulphide assemblage composed mostly of pyrrhotite, chalcopyrite and pentlandite and the close spatial relationship between platinum-group minerals (PGM) and base metal sulphides. However, at Townlands, the presence of pyrite and millerite attests to some secondary mobility of sulphur due to assimilation of floor rock shale.

Pd, Pt and Rh are below the detection limits of the electron microprobe in the sulphides analysed from Nonnenwerth and Townlands except for pentlandite from Nonnenwerth which hosts Pd in solid solution. Pd in pentlandites from Nonnenwerth constantly contain appreciable amounts of Pd (range from ~ 140 – 700 ppm). This finding is in accordance with literature data (e.g. Gervilla *et al.*, 2004) that pentlandite may carry even up to some % of Pd (substituting for Ni) in its crystal lattice. Accordingly, the Pd contents in Nonnenwerth pentlandite probably reflect a primary magmatic signature. The lack of measurable Pd contents in pentlandite on Townlands may be due to (ii) mobilization of Pd-bearing PGM during replacement of 'primary' sulphides by pyrite dominated assemblages into the surrounding silicates (Prichard *et al.*, 2001), (iii) syn-



post-magmatic modification of the 'primary' sulphides or (iii) the results may not be representative as Pd in pentlandite was analysed in one sample only.

The platinum-group minerals (PGM) on Nonnenwerth are dominated by Pd-rich followed by Pt-rich bismuthotellurides and rare braggite and sperrylite. In contrast, mineral proportions of the PGM on Townlands are dominated by Pd-rich bismuthotellurides, minor sperrylite, rare stibiopalladinite and isomertieite. One obvious difference, however, is the wide compositional range of Pt-Pd bismuthotellurides and the presence of Pt-rich bismuthotellurides at Nonnenwerth only, whereas at Townlands, only Pd-rich bismuthotellurides are present. The significance of this finding cannot be evaluated conclusively. The variability may be related to local factors like different host rocks; footwall lithologies, down-temperature re-equilibration, activity of fluids, and other possible causes. The PGM at Nonnenwerth occur predominantly at the contact between sulphide (mostly chalcopyrite, minor pyrrhotite and rare pyrite) and secondary silicate (mostly chlorite and albite after plagioclase) or enclosed in sulphides. Importantly, Pd-rich PGM (Pd-bismuthotellurides) are mostly enclosed in silicates. However, even these PGM enclosed in silicates retain a strong spatial relationship with the base metal sulphides, mostly chalcopyrite, and are associated with secondary minerals (mostly chlorite and albite which replace plagioclase, or rarely amphibole which replaces orthopyroxene and base metal sulphides). The above observation may result from dissolution of the base metal sulphides hosting Pd, and leaving isolated insoluble Pd-PGM behind (Barnes *et*



al., 2007), or Pd may have been remobilized from the sulphides into the surrounding silicates. Based on textural evidence, the latter model is preferred. In contrast, on Townlands the PGM occur predominantly enclosed in sulphides (mostly pyrite and minor chalcopyrite and millerite), or locally at the contact between sulphide and secondary silicate (amphibole after orthopyroxene).

Sulphur isotopic ratios on Nonnenwerth range from $d^{34}\text{S}$ 0 to +2 ‰ suggesting that the sulphur in the Platreef is of mantle origin or that any S that may have been assimilated from the floor rocks was unfractionated. A similar value of $d^{34}\text{S}$ has been found by previous workers in the Platreef at Overysel which is equally located above granite gneiss. As both the basement granite and the Transvaal dolomites contain little sulphides, these results suggest that most of the S in the Platreef is of primary magmatic derivation. In contrast, Townlands sulphides have $d^{34}\text{S}$ between +4 and +8 ‰ suggesting addition of crustal sulphur. These data indicate that the formation of the PGE mineralisation in the Platreef was not controlled by assimilation of external sulphur. Instead, sulphide saturation may have been reached due to assimilation of dolomite, and/or due to differentiation and cooling of the magma upon emplacement. Subsequently, assimilation of S may have merely modified already existing sulphide melt particularly in areas where the floor rocks consisted of sulphidic shales e.g. at Townlands.

The study therefore indicates i) that contact-style PGE mineralization extends along most of the strike length of the northern lobe of the Bushveld Complex



despite variable floor rocks of different composition underlying the northern Bushveld Complex from south to north, ii) that contact-style PGE mineralization in the northern lobe of the Bushveld Complex cannot be correlated with specific stratigraphic units i.e. the Upper Critical Zone that hosts the Merensky Reef and the UG2 Reef or magma types, but that it formed due to several different processes, iii) that base metal sulphides were the primary PGE collector, iv) that Pd and Pt occur mostly as PGM with close spatial relationship with base metal sulphides. At Nonnenwerth, Pd additionally occur dissolved in pentlandite, v) that they was minimal S assimilation from floor rocks at Nonnenwerth compared to localities further south i.e. at Townlands, and vi) a dominant Bushveld B2/B3 magma source/lineage for the Platreef at Nonnenwerth.