



CHAPTER SIX: WHOLE ROCK CHEMISTRY

6.1 CIPW norms

As the Platreef rocks from Nonnenwerth are relatively altered, I have calculated CIPW norms for the analysed samples (Fig. 6.1). The rocks are mostly gabbronorites and leucogabbronorites with normative orthopyroxene slightly dominating over clinopyroxene. This observation is in agreement with the petrographic data presented in chapter 4. However, what is notable is that the rocks also have a considerable normative olivine component. This is also observed in other Platreef intersections e.g. at Rooipoort and Townlands, but it is absent in most Upper Critical Zone rocks, e.g. the Merensky Reef from Impala mine (Barnes and Maier, 2002a). The enrichment in normative olivine in the Platreef could be explained in two contrasting ways: (i) Assimilation of a Si-poor and Mg-rich component derived from dolomite or calc-silicate as suggested by the abundance of dolomite xenoliths in the analysed sequence. (ii) Hydrothermal Si-loss of the rocks as suggested by the common alteration of the rocks, notably that of plagioclase to fine-grained clays.

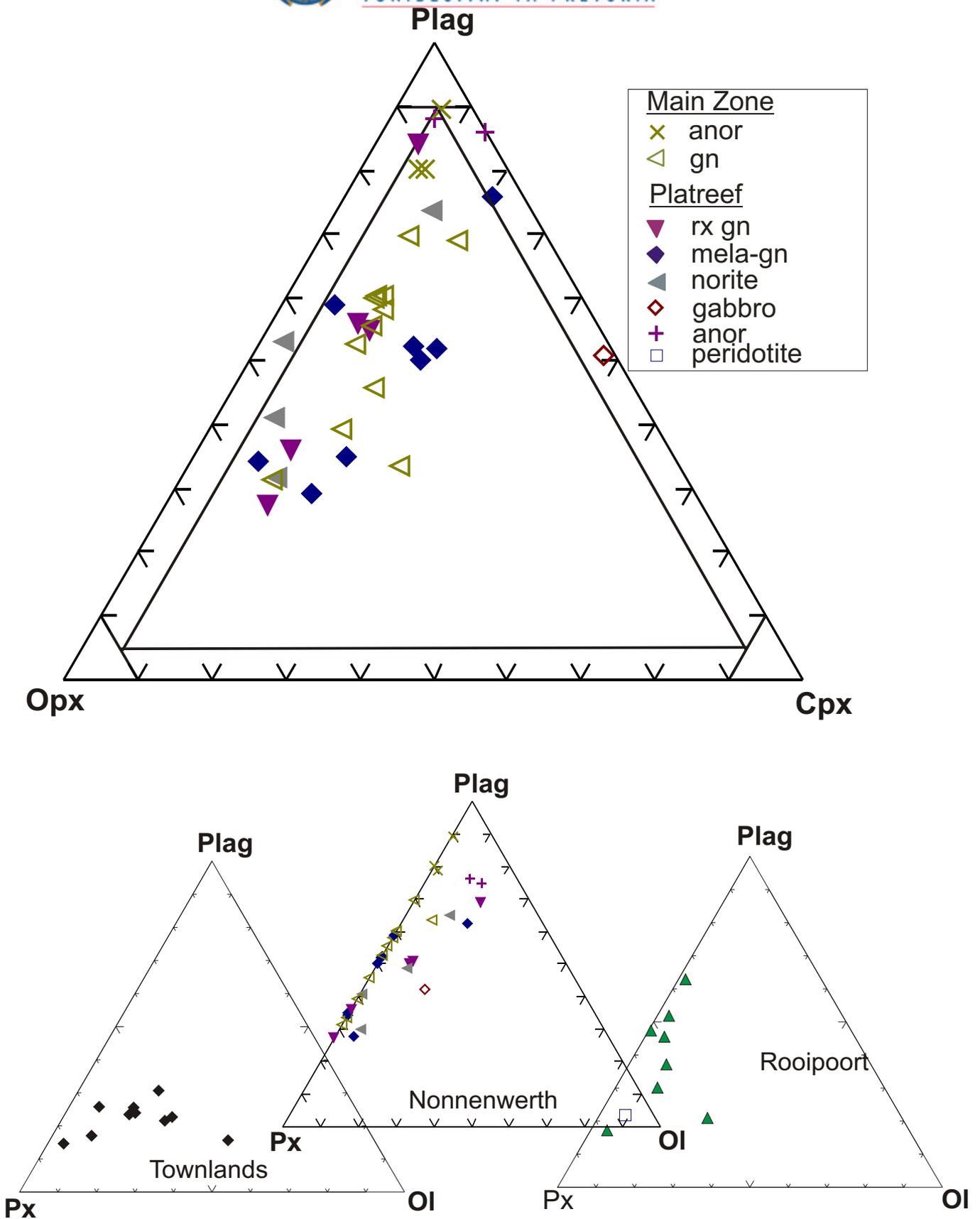


Fig. 6.1: CIPW normative compositions of Platreef samples from Nonnenwerth. gn = gabbronorite, rx = recrystallized gabbronorite, anor = anorthosite, Plag = plagioclase, Opx = orthopyroxene, Cpx = clinopyroxene, Ol = olivine. Note: Legend applies to Nonnenwerth samples only.



6.2 Lithophile geochemistry

6.2.1 Major and minor elements

Whole rock analytical results are given in Table 1. Selected major element data representing the different lithologies from the Platreef and the Main Zone at Nonnenwerth are shown in Fig. 6.2 and 6.3. The compositional fields of orthopyroxene, plagioclase and clinopyroxene, and tholeiitic (B2/B3) Bushveld parental magma (Davies and Tredoux, 1985) are also plotted. The data from both intervals (Platreef and Main Zone) essentially overlap. They define a negative correlation between MgO and Al_2O_3 , CaO and Na_2O_3 (Fig. 6.2a - f) and a positive correlation between MgO and SiO_2 , FeO, TiO_2 and Cr_2O_3 (Fig. 6.2g - l). Most samples plot near tielines joining plagioclase with orthopyroxene and clinopyroxene (except for the SiO_2 versus MgO plot) confirming that the chemistry of the rocks is controlled by the relative proportions of these phases and trapped melt. The data also show that plagioclase constitutes ca. 20 – 60 % of the rocks.

The relatively low SiO_2 contents of the samples are noteworthy (Fig. 6.2g and h). This may indicate the presence of calc-silicate component derived from dolomite or calc-silicate as suggested by the abundance of dolomite xenoliths in the analysed sequence, or alteration resulting in SiO_2 -loss as suggested by the common alteration of the rocks, notably that of plagioclase to fine-grained clays.

Cr contents in most samples are controlled by the trapped melt and the cumulus phases i.e. clinopyroxene and orthopyroxene (Fig. 6.2m and n). However,

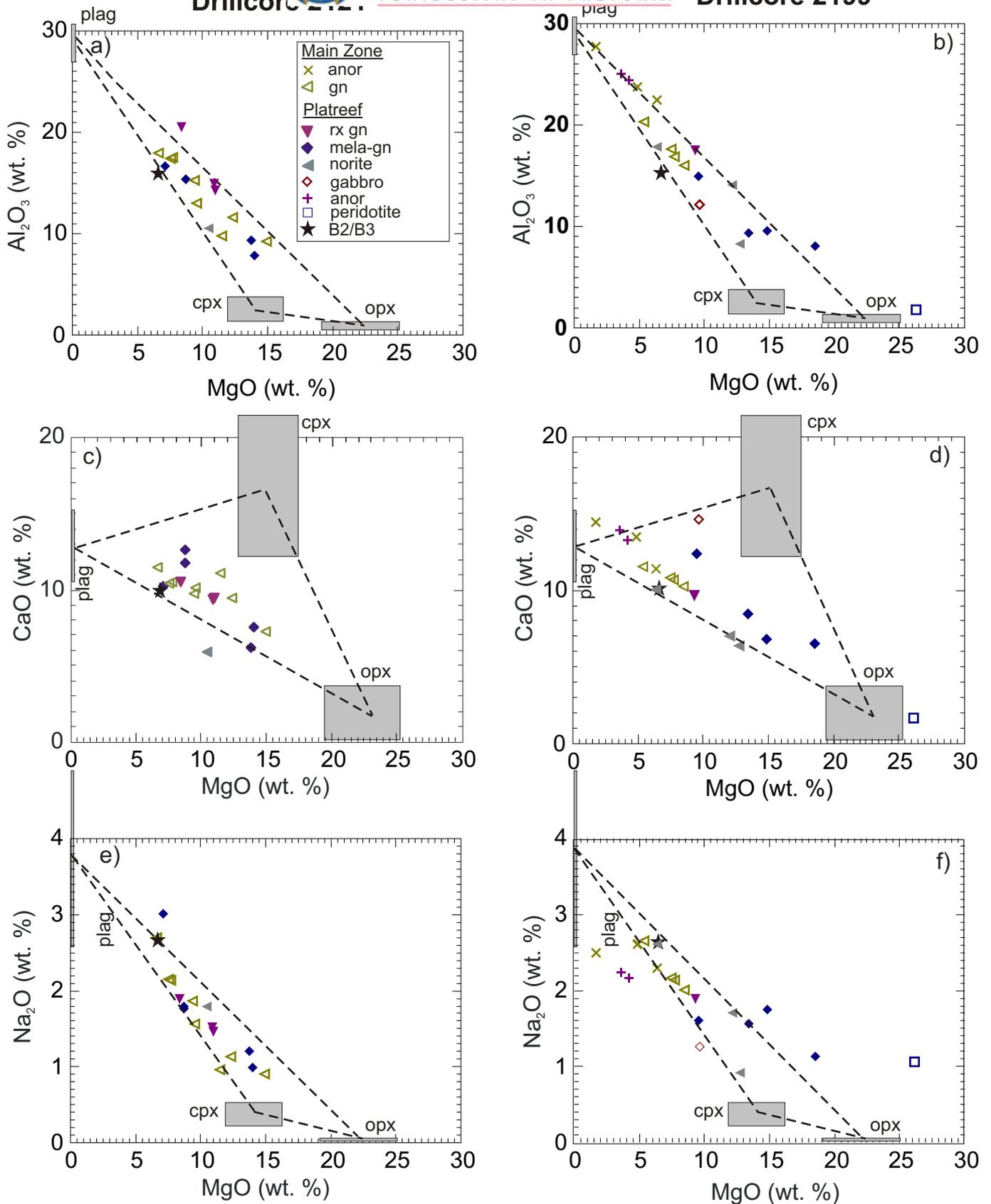


Fig. 6.2: Binary variation diagrams of (a and b) Al_2O_3 versus MgO, (c and d) CaO versus MgO and (e and f) Na_2O versus MgO in rocks from Nonnenwerth. Also plotted are compositional ranges of tholeiitic (B2/B3) Bushveld parental magma (Davies and Tredoux, 1985), and major rock forming minerals (shaded) in the Platreef on Nonnenwerth to determine which phases control the chemistry of the rocks. plag = plagioclase, cpx = clinopyroxene, opx = orthopyroxene, rx gn = recrystallided gabbronorite, gn = gabbronorite and mela-gn = mela-gabbronorite.

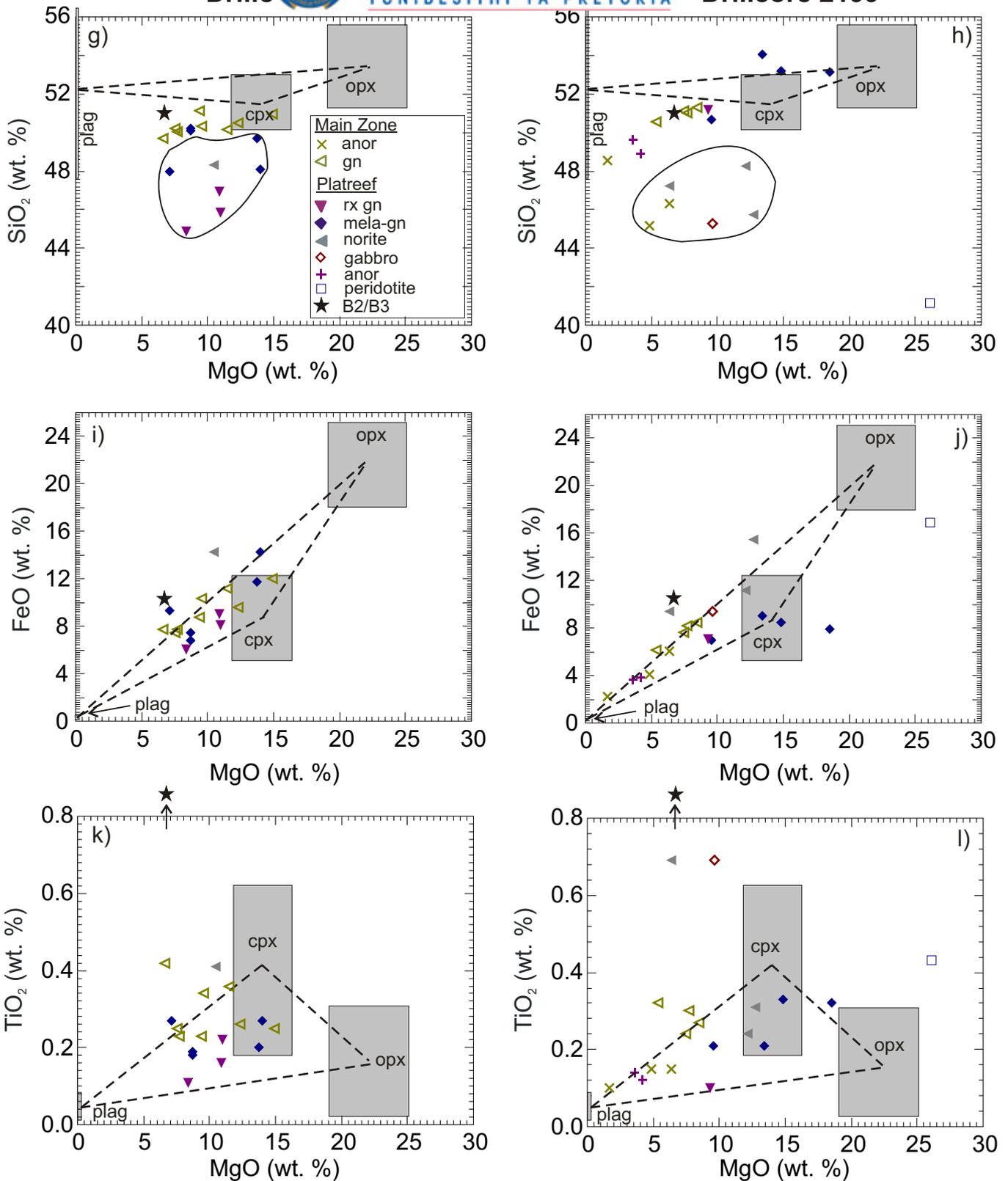


Fig. 6.2 (contd): Binary variation diagrams of (g and h) SiO₂ versus MgO, (i and j) FeO versus MgO and (k and l) TiO₂ versus MgO in rocks from Nonnenwerth. Also plotted are compositional ranges of tholeiitic (B2/B3) Bushveld parental magma (Davies and Tredoux, 1985), and major rock-forming minerals (shaded) in the Platreef on Nonnenwerth. plag = plagioclase, cpx = clinopyroxene, opx = orthopyroxene, rx gn = recrystallized gabbronorite, gn = gabbronorite and mela-gn = mela-gabbronorite.

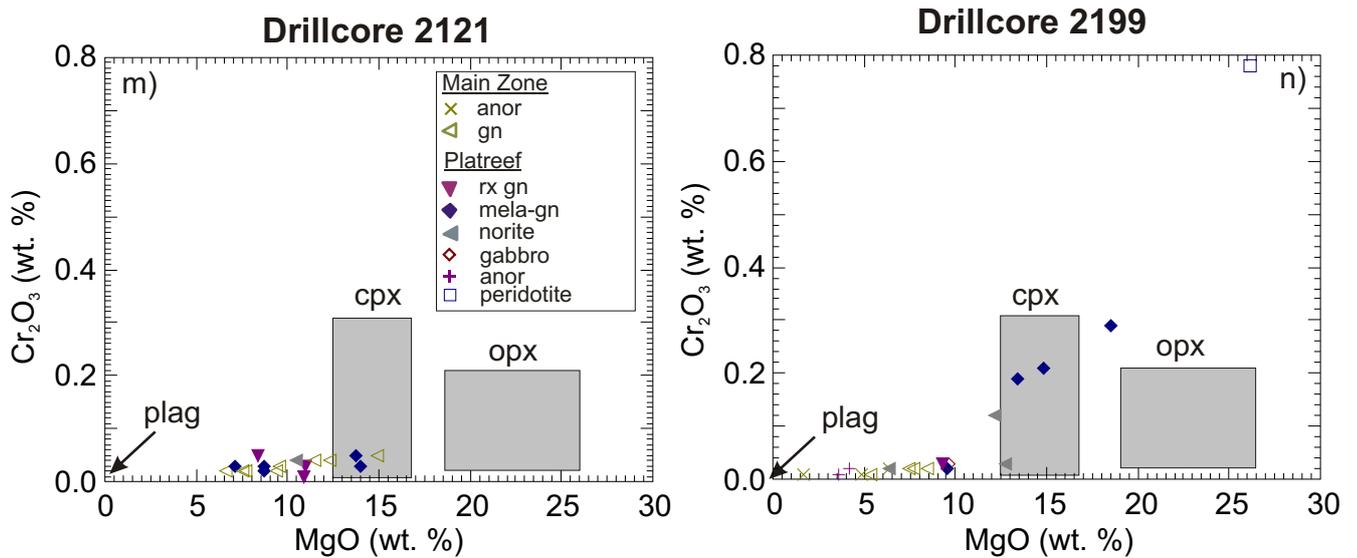


Fig. 6.2 (contd): Plot of Cr_2O_3 (m and n) versus MgO. Also plotted are major rock forming minerals (shaded). plag = plagioclase, cpx = clinopyroxene, opx = orthopyroxene, gn = gabbronorite, rx gn = recrystallized gabbronorite and mela- gn = mela-gabbronorite

serpentinised peridotite and some magnesian melagabbronorite samples from core 2199 contain cumulus chromite, as their Cr_2O_3 contents are too high to be explained by trapped melt and pyroxene alone.

MgO and Cr_2O_3 contents are plotted against depth in Fig. 6.3. The data show broadly similar MgO and Cr_2O_3 contents in the Platreef and the Main Zone, except for a distinct increase in MgO and Cr_2O_3 in some of the basal samples in drillcore 2199 with depth, and high Cr_2O_3 contents in gabbronorites towards the base of the Platreef. The data is consistent with lithological observations that the rocks become progressively more leucocratic with height.

6.2.2 Trace elements

Selected trace elements (V, Zr, Y, Sr and Sm) are plotted against MgO in Fig. 6.4. As the major rock forming minerals from the Platreef at Nonnenwerth were not analysed



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Drillcore 2199

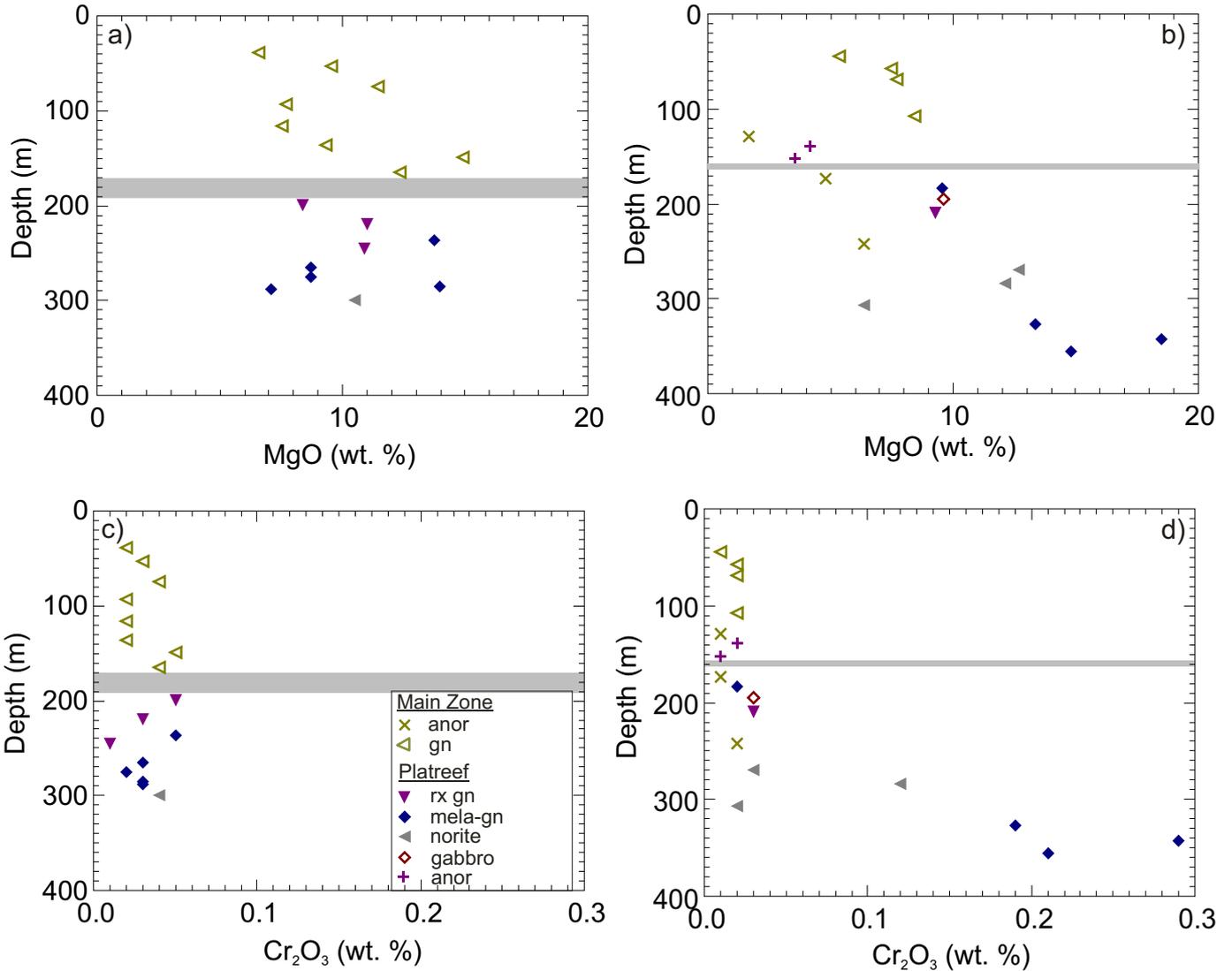


Fig. 6.3: Plot of (a and b) MgO versus depth, and Cr₂O₃ (c and d), in the Platreef at Nonnenwerth. gn = gabbronorite, rx gn = recrystallized gabbronorite and mela- gn = mela-gabbronorite



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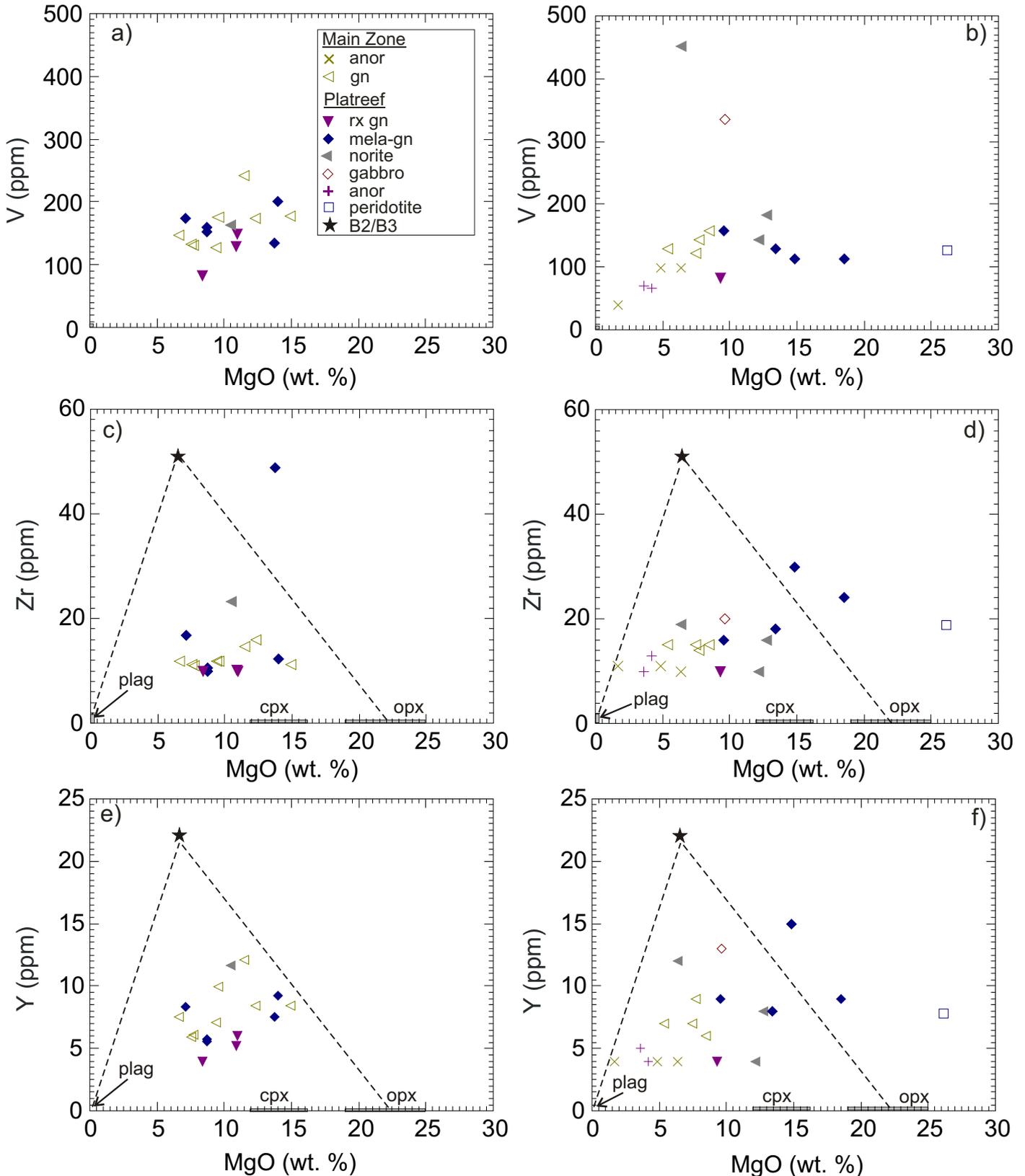


Fig. 6.4: Binary variation diagrams of (a and b) V versus MgO, (c and d) Zr versus MgO and (e and f) Y versus MgO in rocks from Nonnenwerth. Also plotted are compositional ranges of tholeiitic (B2/B3) Bushveld parental magma (Davies and Tredoux, 1985) and major rock forming minerals assuming they have 0 ppm incompatible trace elements. plag = plagioclase, cpx = clinopyroxene, opx = orthopyroxene, rx gn = recrystallized gabbro-norite, gn = gabbro-norite and mela-gn = mela-gabbro-norite.



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Drillcore 2199

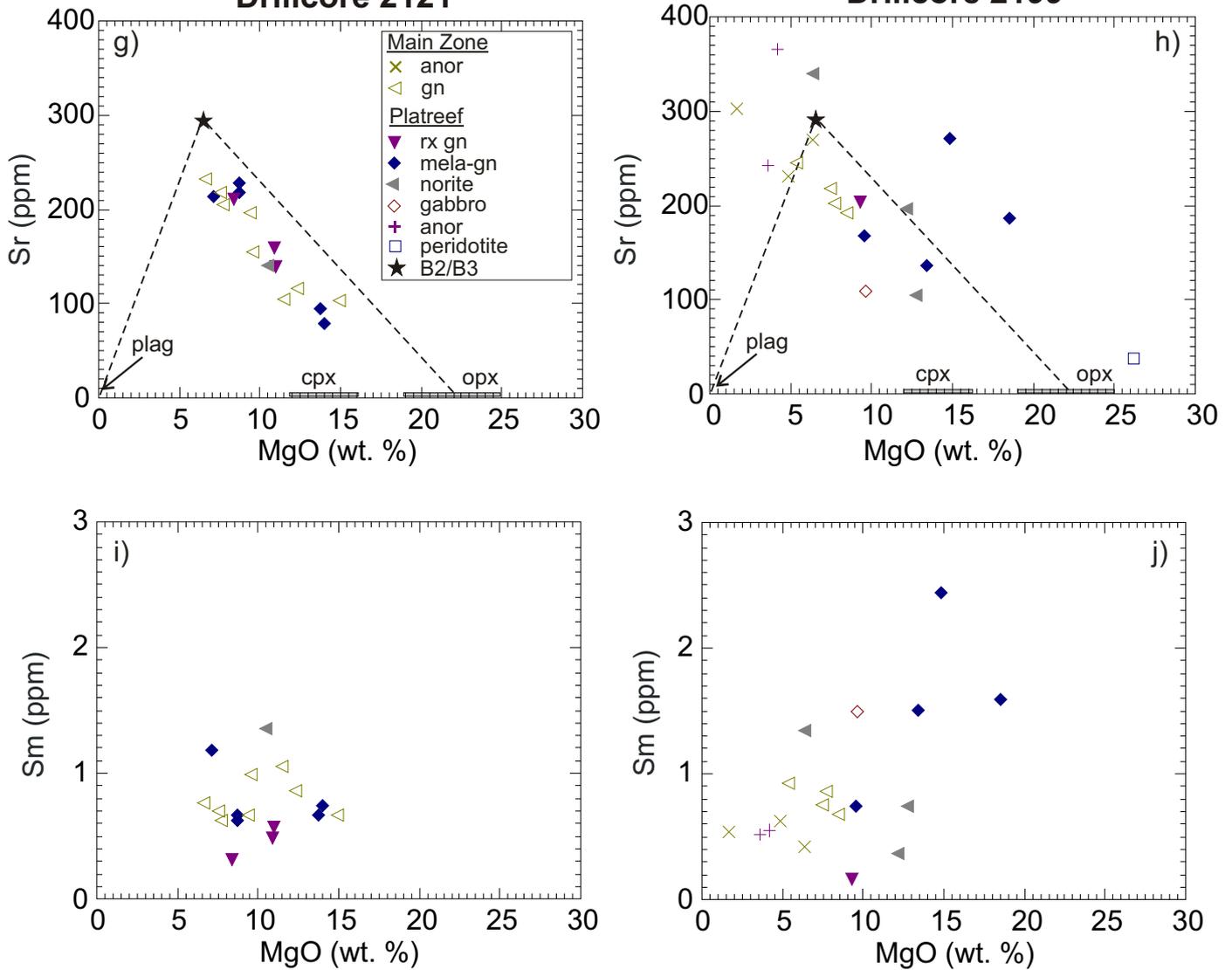


Fig. 6.4 (contd): Binary variation diagrams of (g and h) Sr versus MgO, (i and j) Sm versus MgO in rocks from Nonnenwerth. Also plotted are compositional ranges of tholeiitic (B2/B3) Bushveld parental magma (Davies and Tredoux, 1985) and major rock forming minerals assuming they have 0 ppm incompatible trace elements. plag = plagioclase, cpx = clinopyroxene, opx = orthopyroxene, rx gn = recrystallized gabbronorite, gn = gabbronorite and mela-gn = mela- gabbronorite.



for these elements, the minerals were not plotted onto the diagrams. It is evident that the concentrations of the elements show broad overlap in the Platreef and the Main Zone.

Vanadium shows a broadly positive correlation with MgO, suggesting that it is largely hosted by pyroxenes ($D_V^{\text{opx/melt}} = 0.6$, $D_V^{\text{cpx/melt}} = 1.35$; Rollinson, 1993). Two samples show markedly elevated V contents, suggesting they contain some cumulus magnetite.

The diagrams of Zr and Y against MgO show that Zr and Y apparently behave in a compatible manner. The trend may be due to the elements concentrations of the two elements being close to the detection limits (see Appendix 1b) except for one melagabbronite (MOX11) which has 49ppm Zr (Fig. 6.4c) suggesting the presence of zircon. No zircon was identified in the sample. However, since Zr, Y and Sm are incompatible with regard to the major rock forming minerals, their concentration should thus be largely controlled by the trapped melt. Assuming that the Platreef largely crystallized from B2/B3 magma, as indicated by the compositional overlaps with the Main Zone (Chapter 6), one can estimate that the rocks contain ca. 20 – 30% trapped melt.

Strontium is compatible with regard to plagioclase ($D_{\text{Sr}}^{\text{plag/melt}} = 1.83$; Rollinson, 1993) explaining the negative correlation between Sr and MgO seen in Fig. 6.3g and h.



Chondrite-normalized rare earth element patterns of the analysed rocks are considered in Fig. 6.5. In general, the analysed Platreef and Main Zone rocks have broadly similar patterns as the Main Zone of the western Bushveld Complex (Maier and Barnes, 1998). This suggests a genetic link between the Platreef and the Main Zone.

One of the principal differences between the Platreef and the Main Zone is the less pronounced positive Eu anomaly in many of the Platreef rocks. This is particularly apparent in those samples with relatively high REE contents and probably reflects a relatively higher liquid component in the Platreef. The lowest REE concentrations occur in the recrystallized rocks, suggesting expulsion of the liquid component during recrystallization and explaining the positive Eu anomaly in the recrystallized rocks.

The REE patterns of the Platreef on Nonnenwerth are distinct from those of the Platreef on the farms Townlands and Rooipoort which show higher REE concentrations and more fractionated REE patterns (Fig. 6.5). Thus La/Lu_N ratios for the Platreef on Nonnenwerth are 0.82 – 6.26 (averaging 2.08) whereas the Platreef at Rooipoort has La/Lu_N 0.71 – 7.41 (averaging 3.96) and at Townlands it has 2.19 – 5.49 (averaging, 4.09). The contrasting concentration patterns of the REE at the individual localities may be due to variable contamination with different floor rocks. In the Mokopane area, the floor rocks consist of hornfels, quartzite and calc-silicates of the Pretoria Group (Manyeruke, 2003). In contrast, at Nonnenwerth the floor rocks are granitic gneisses, and probably included calc-silicate and dolomite. The latter lithologies contain low levels of incompatible trace elements (Klein and Beukes, 1989)

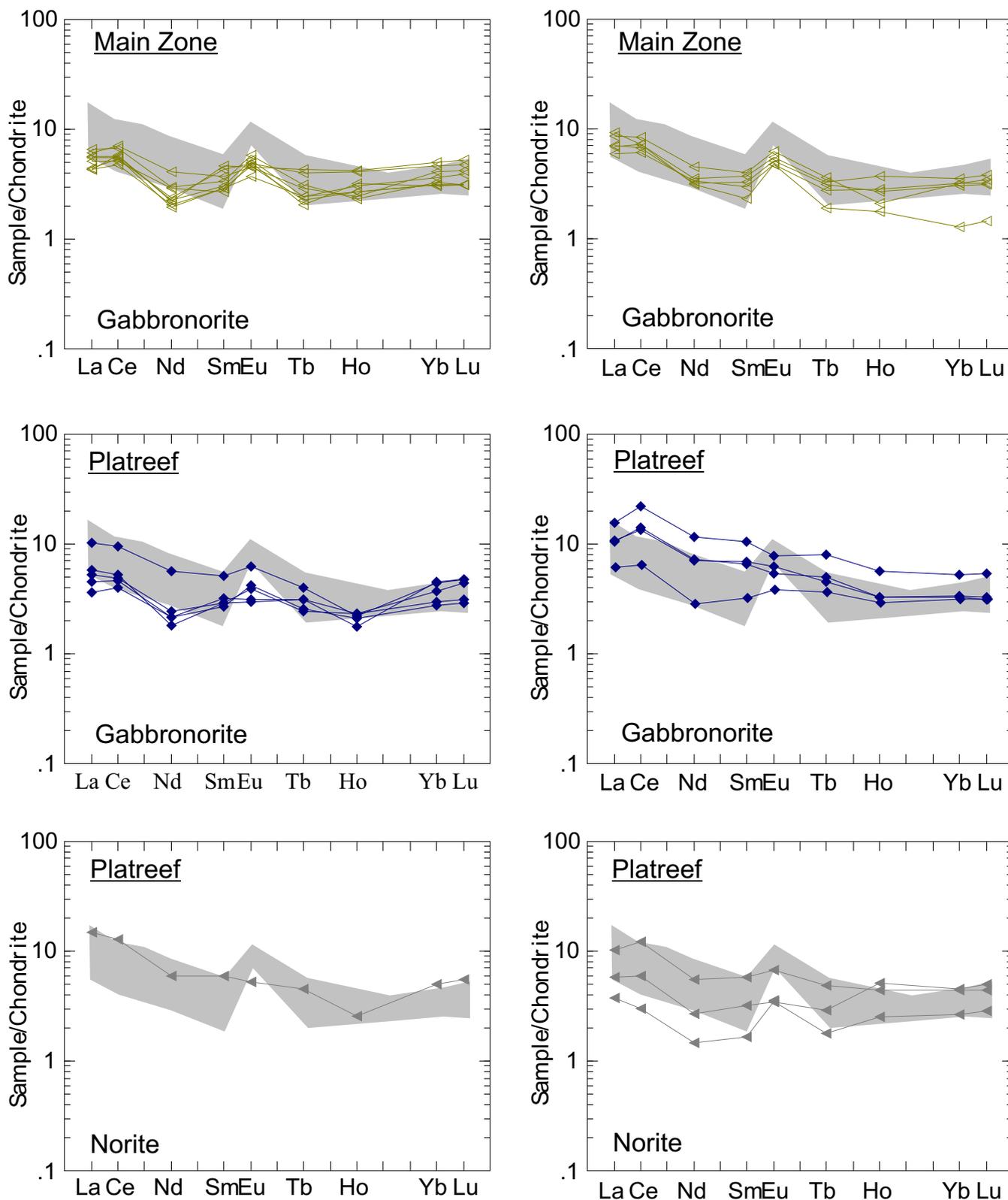


Fig. 6.5: Chondrite-normalized REE diagrams for Platreef lithologies on Nonnenwerth and from the Main Zone in the western Bushveld Complex (shaded; Maier and Barnes, 1998). Normalization values are from Taylor and McLennan (1985).



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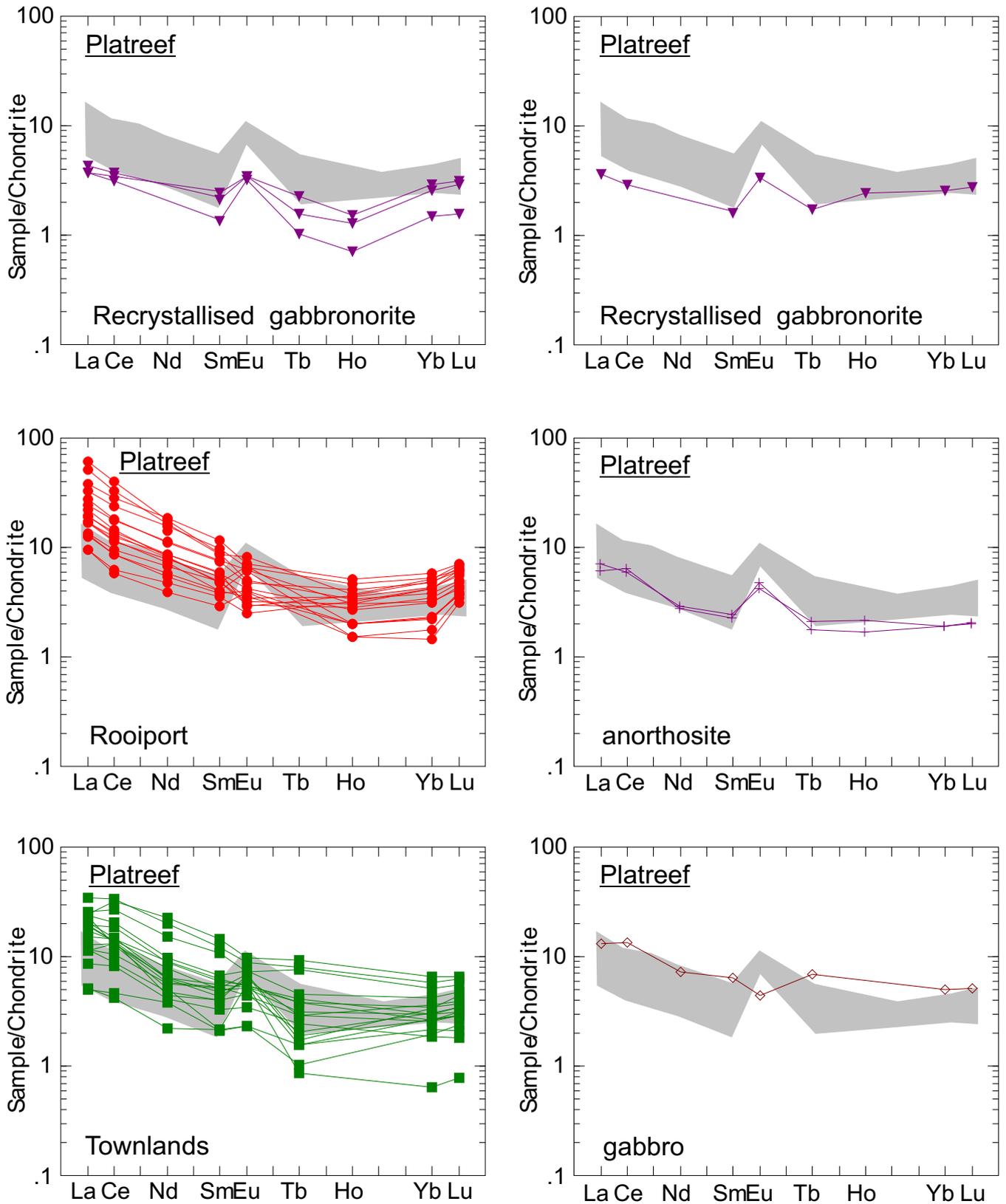


Fig. 6.5 contd: Chondrite-normalized REE patterns for Platreef lithologies on Nonnenwerth and from the Main Zone in the western Bushveld Complex (shaded; Maier and Barnes, 1998). Also shown are data from Townlands (Manyeruke et al, 2005) and Rooiport (Maier et al., 2007). Normalization values are from Taylor and McLennan (1985).



(Fig. 6.5) and thus would not contribute significant amounts of these elements to the magma.

Mantle normalized trace element patterns on Nonnenwerth are weakly fractionated, but show negative Nb and Ti anomalies and strong positive Sr and Pb anomalies (Fig. 6.6). The positive Sr anomalies are due to the presence of cumulus plagioclase in most of the rocks, whereas the positive Pb suggests the presence of a crustal component. However, it remains unclear whether this crustal component is derived from contamination during emplacement or whether it reflects contamination of B2/B3 liquids prior to emplacement, in a staging chamber.

Mantle normalised trace element patterns for Platreef samples from Rooipoort and Townlands are more fractionated than those from Nonnenwerth, and show stronger positive Pb and negative Nb and Ti anomalies, suggesting a larger crustal component. This could be due to more enhanced crustal contamination in the southern portion of the northern lobe of the Bushveld Complex, or it could reflect a more important B1 liquid component.

In an attempt to better constrain the derivation of the crustal component, and the magmatic lineage of the rocks, the REE data have been plotted in binary variation diagrams (Fig. 6.7). It is evident that the Nonnenwerth rocks have Ce/Sm ratios similar to B2/B3 liquids (average 8.2 at Nonnenwerth, 7.9 in B2/B3 liquids; Curl, 2001) and that the influence of B1 liquid is minor. Furthermore, the rocks were evidently not significantly contaminated with shale, as shale has similar Ce/Sm ratios as B1



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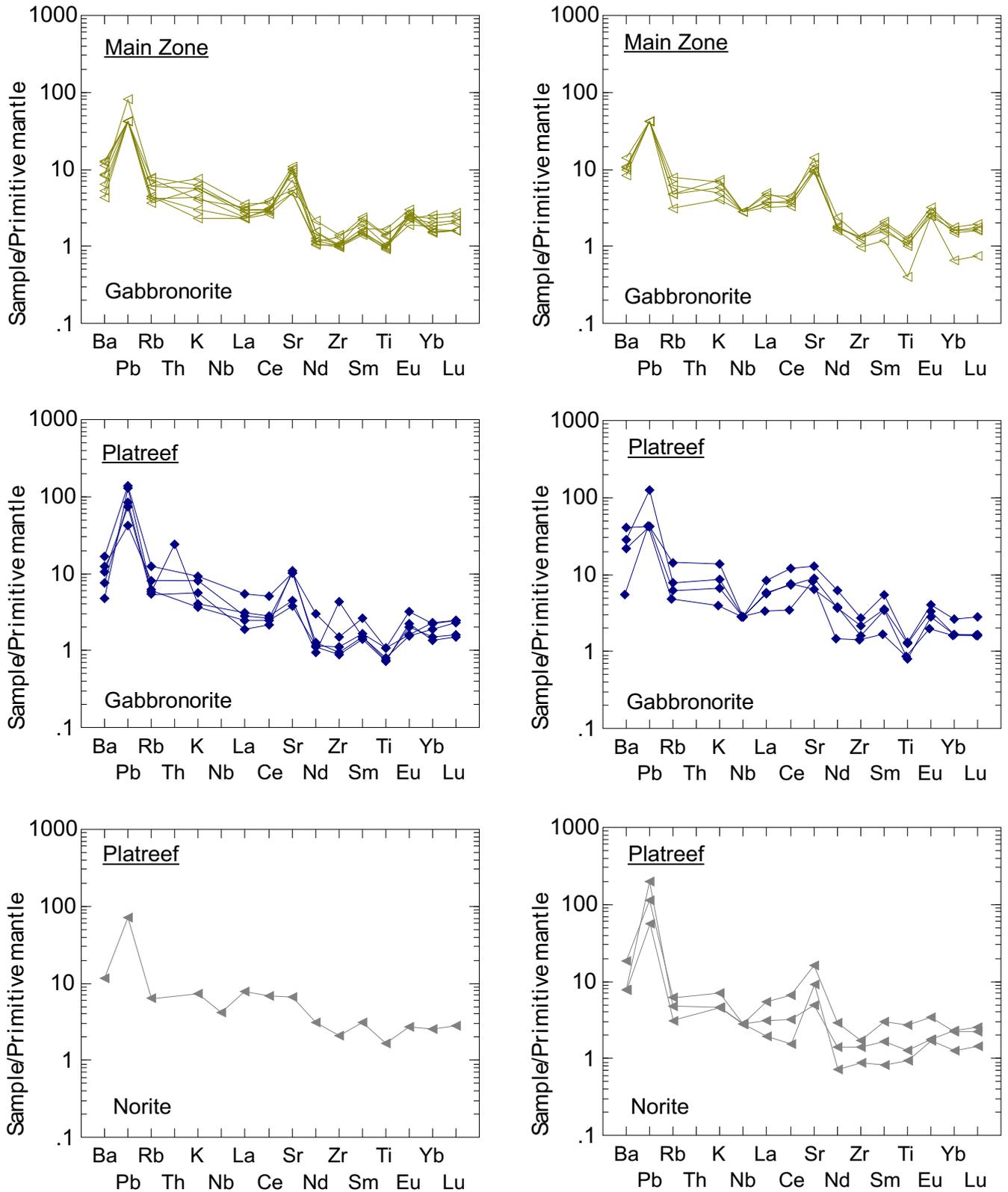


Fig.6.6: Primitive mantle normalized incompatible trace element patterns for Platreef rocks on Nonnenwerth (drillcores 2121 and 2199). Normalization values are from Sun and McDonough (1989).

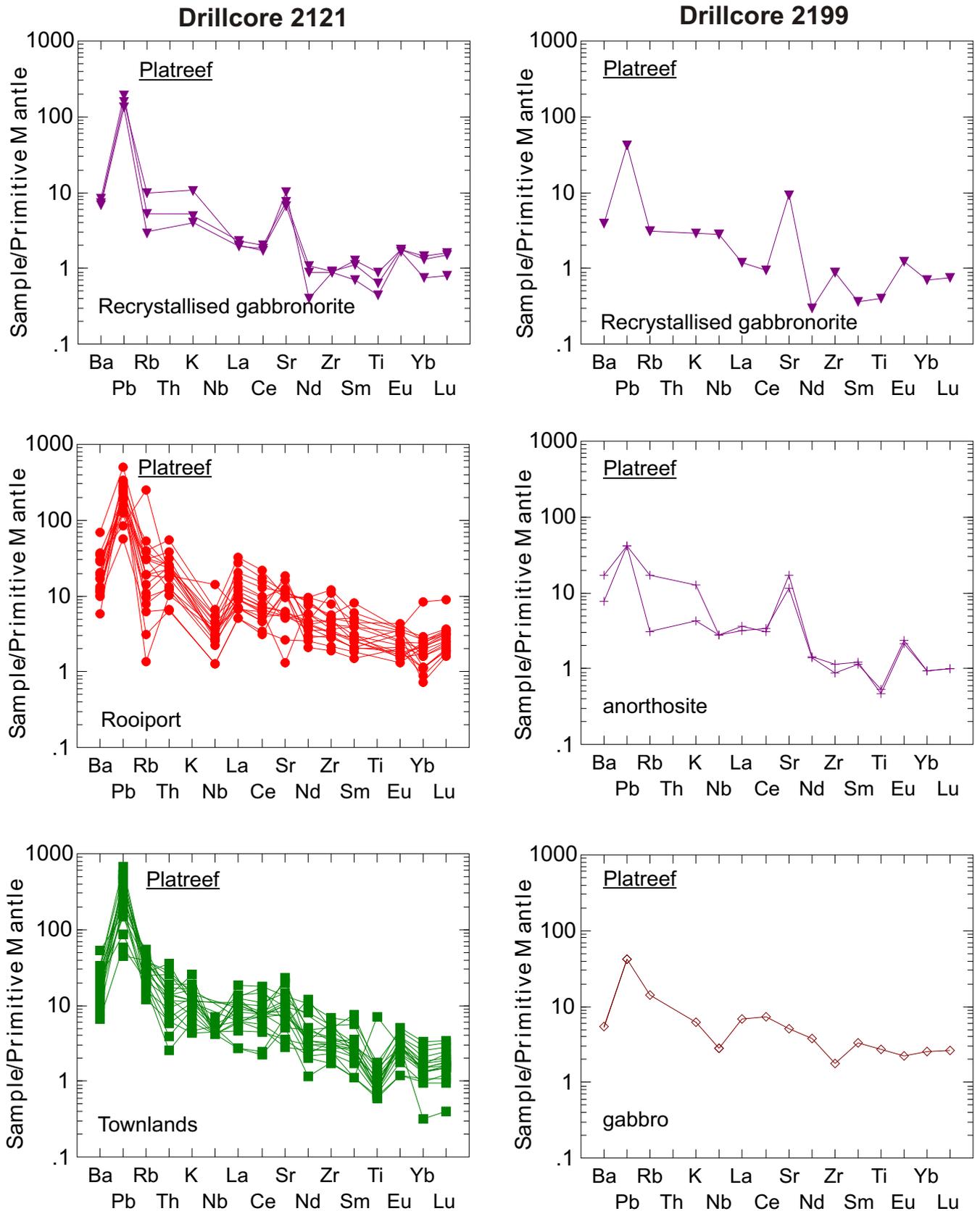


Fig. 6.6: contd: Primitive mantle normalized incompatible trace elements for Platreef rocks on Nonnenwerth from (2121 and 2199). Also included are the patterns of Platreef rocks from Townlands (Manyeruke et al., 2005) and Rooiport (Maier et al., 2007). Normalization values are from Sun and McDonough (1989).

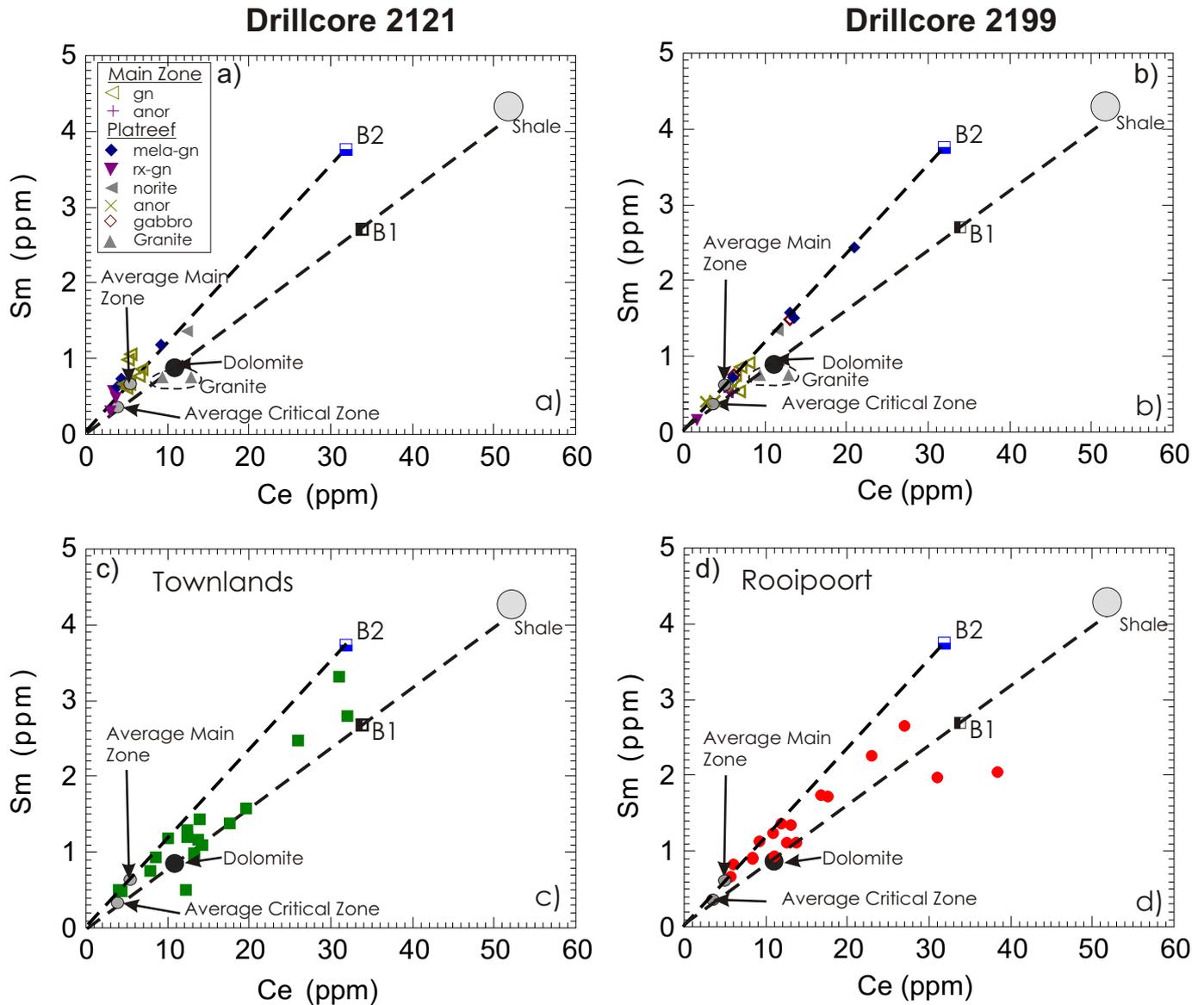


Fig. 6.7: Sm versus Ce for Platreef rocks on (a) Nonnenwerth, drillcore 2121. (b) Nonnenwerth, drillcore 2199. (c) Townlands (Manyeruke, 2003; Manyeruke et al., 2005). (d) Rooipoort (Maier et al., 2007). Also shown are the compositions of Bushveld B1 and B2 parental magmas (Curl, 2001), average Critical Zone and Main Zone rocks (Maier and Barnes, 1998), shales and dolomite (Klein and Buikes, 1989). gn = gabbro, anor = anorthosite, rx gn = recrystallized Gabbro, mela gn = melagabbro.



Bushveld parental magma, as well as high Ce and Sm contents. In contrast, contamination with dolomite cannot be excluded as dolomite has low concentrations of Ce and Sm as well as most other incompatible trace elements. Platreef rocks from Townlands and Rooipoort have Ce/Sm ratios between B2 and B1 liquids (Fig. 6.6). This could indicate a larger B1 component, but the trace element contents in many samples are too high to be solely explained by a trapped liquid component and require addition of a contaminant, most likely shale.

6.3 Concentrations of sulphur and chalcophile elements

Sulphur contents in the analysed rocks are plotted against MgO in Fig. 6.8. The tholeiitic (B2/B3) and Mg-basaltic (B1) parental magmas of the Bushveld Complex are plotted for comparison. The tholeiitic B2 magma has ca. 400 ppm S (Davies and Tredoux, 1985; Barnes and Maier, 2002b). Since S is an incompatible element, the S-saturation boundary would be around 400 ppm S. Platreef rocks (except one recrystallized gabbronorite sample and two melagabbronorite samples from drillcore 2199) have S contents mostly significantly above 400 ppm. This suggests that the Platreef rocks crystallized from a S-saturated magma and contain cumulus sulphides. The Main Zone rocks from Nonnenwerth have between 120 and 300 ppm S indicating that the Main Zone magma was probably S-undersaturated during crystallization of the rocks and is supported by the absence of sulphides in the Main Zone rocks.

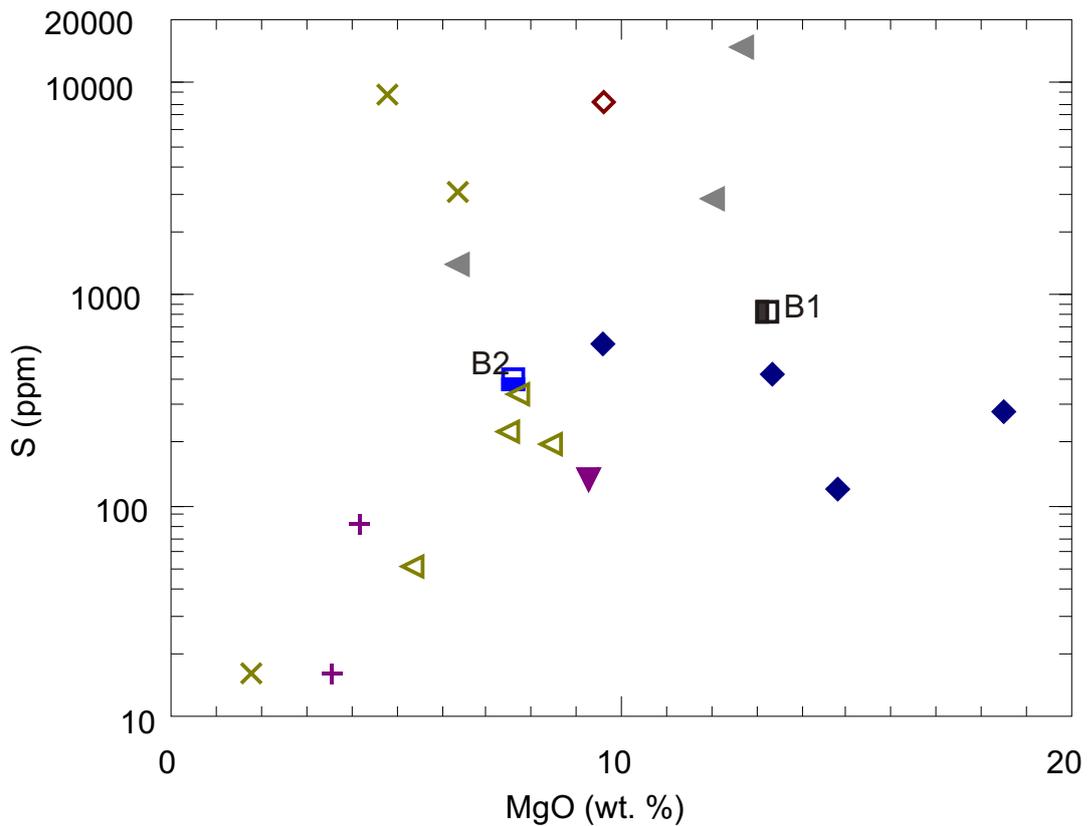
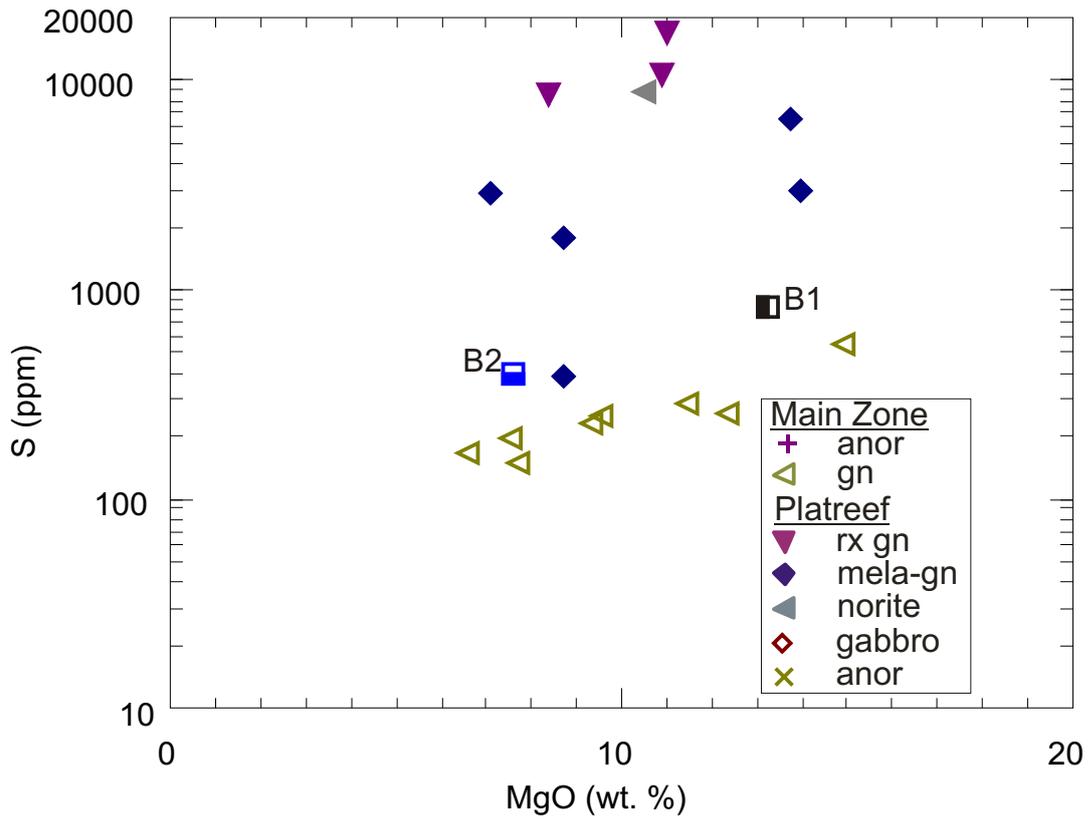


Fig. 6.8: Plot of MgO versus S in drillcore 2121 (top) and 2199 (bottom). Also plotted are compositions of Mg-basaltic and tholeiitic Bushveld parental magmas (Davies and Tredoux, 1985). gn = gabbronorite, rx gn = recrystallized gabbronorite, anor = anorthite, and mela-gn = mela-gabbronorite



Drillcore 2121

Drillcore 2199

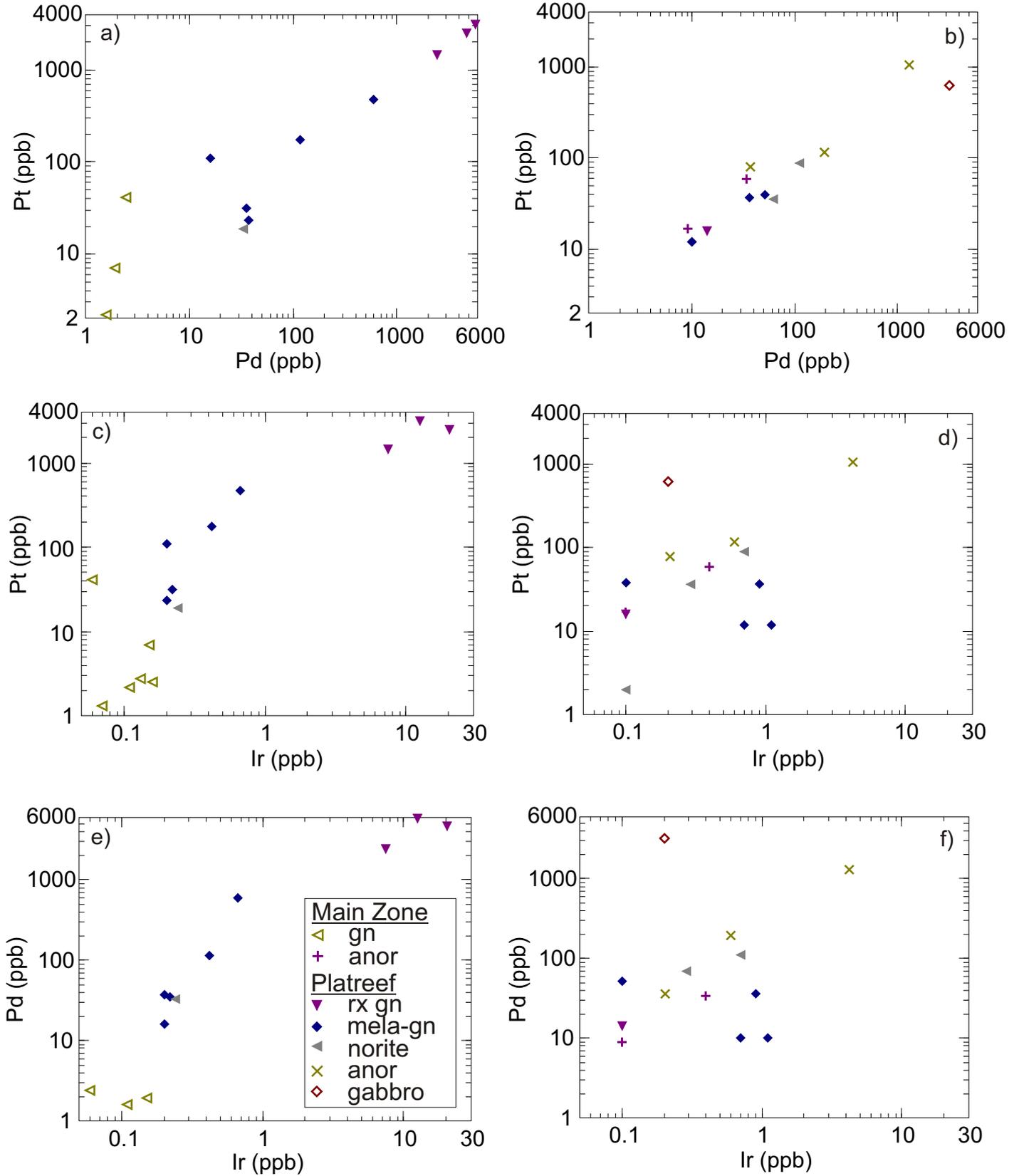


Fig. 6.9: PGE binary plots of the Platreef on the farm Nonnenwerth. rx gn = recrystallized gabbronorite, gn = gabbronorite, mela-gn = mela-gabbronorite, anor = anorthosite.



Drillcore 2121

Drillcore 2199

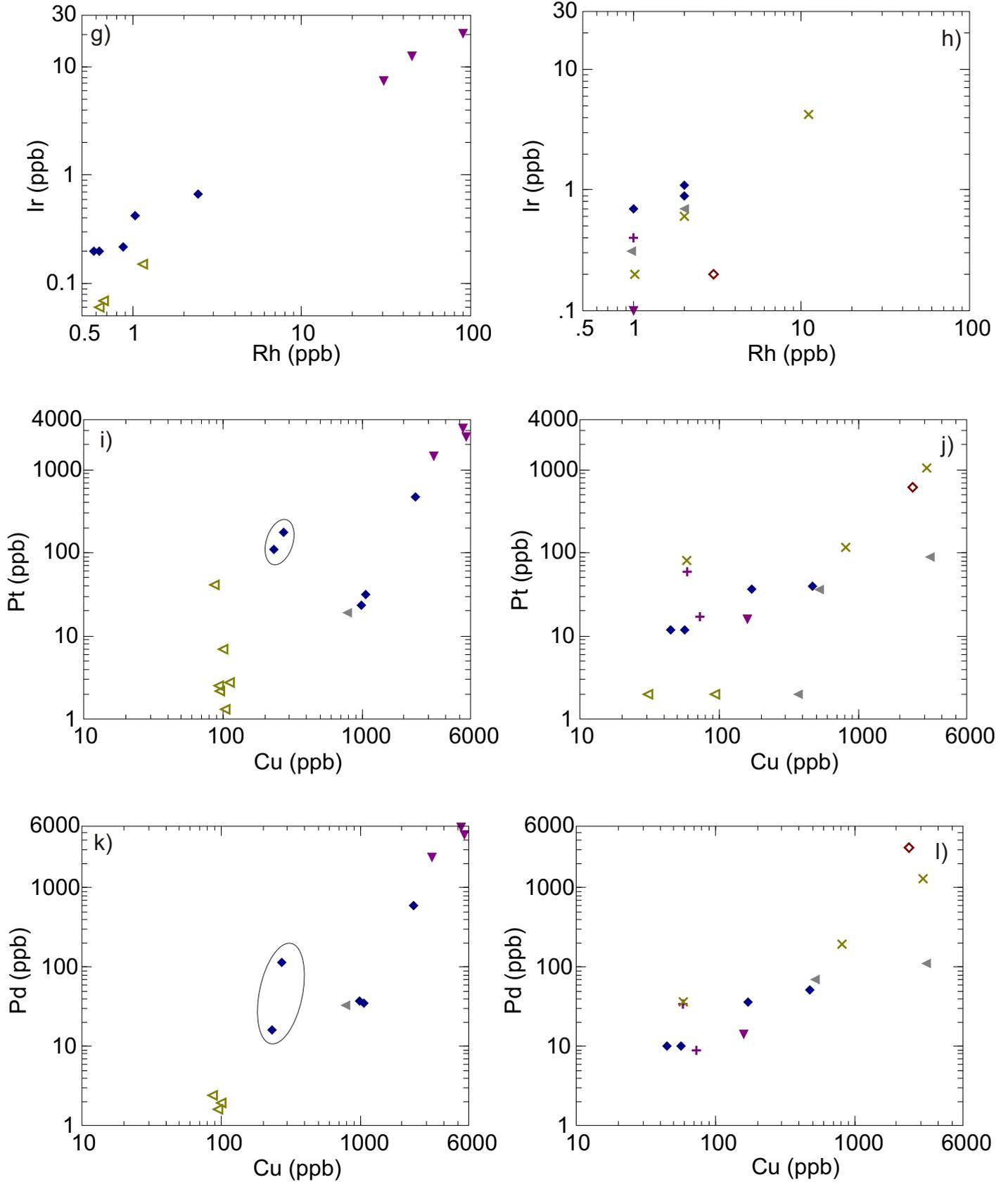


Fig. 6.9: (contd) PGE binary plots of the Platreef on the farm Nonnenwerth. rx gn = recrystallized gabbronorite, gn = gabbronorite, mela-gn = mela-gabbronorite, anor = anorthosite.



To assess the nature of the phases controlling the PGE, the PGE are plotted against each other in Fig. 6.9. 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 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. 6.9b and e). The broad positive correlation between these elements thus suggests that in most samples the PGE were concentrated by magmatic sulphides. However, in drillhole 2199, the correlations between Pt and Pd on the one hand and Ir on the other hand are relatively poor, suggesting that in some samples from this locality Pt and Pd behaved in a mobile manner.

Further support for the model of primary sulphide control is shown by the broadly positive correlations between PGE, Ni and Cu with sulphur in samples containing > ca. 1000 ppm S (Fig. 6.10). By extending best-fit tie-lines through the data to 38 % S (i.e. the approximate S content of the sulphide), one can estimate the metal content of the sulphide at ca. 12 % Cu, 6 % Ni, 40 ppm Pt and 80 ppm Pd. These values are comparable to those of the Platreef on Townlands. Assuming D values between sulphide melt and silicate melt of ca. 1000 for Cu and 500 for Ni (Francis, 1990). The metal tenors suggest that the Platreef magma had ca. 120 ppm Cu and Ni, values that are normal for tholeiites but different to those of Mg-basaltic B1 magma which has ca. 70 ppm Cu and ca. 400 ppm Ni.

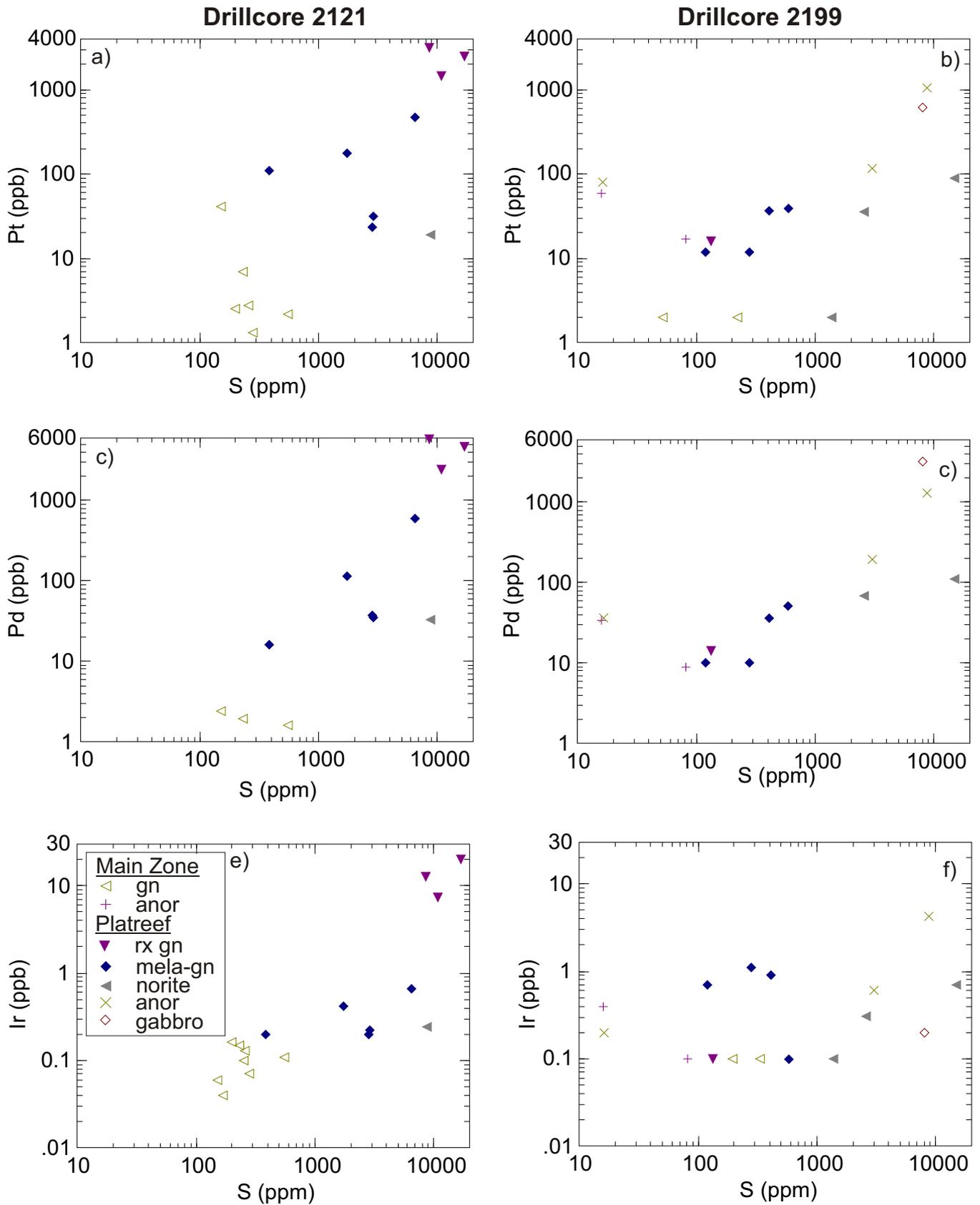


Fig. 6.10. Plots of a) Pt, b) Pd and c) Ir versus S. rx gn = recrystallized gabbronorite, gn = gabbronorite, mela-gn = mela-gabbronorite, anor = anorthosite.

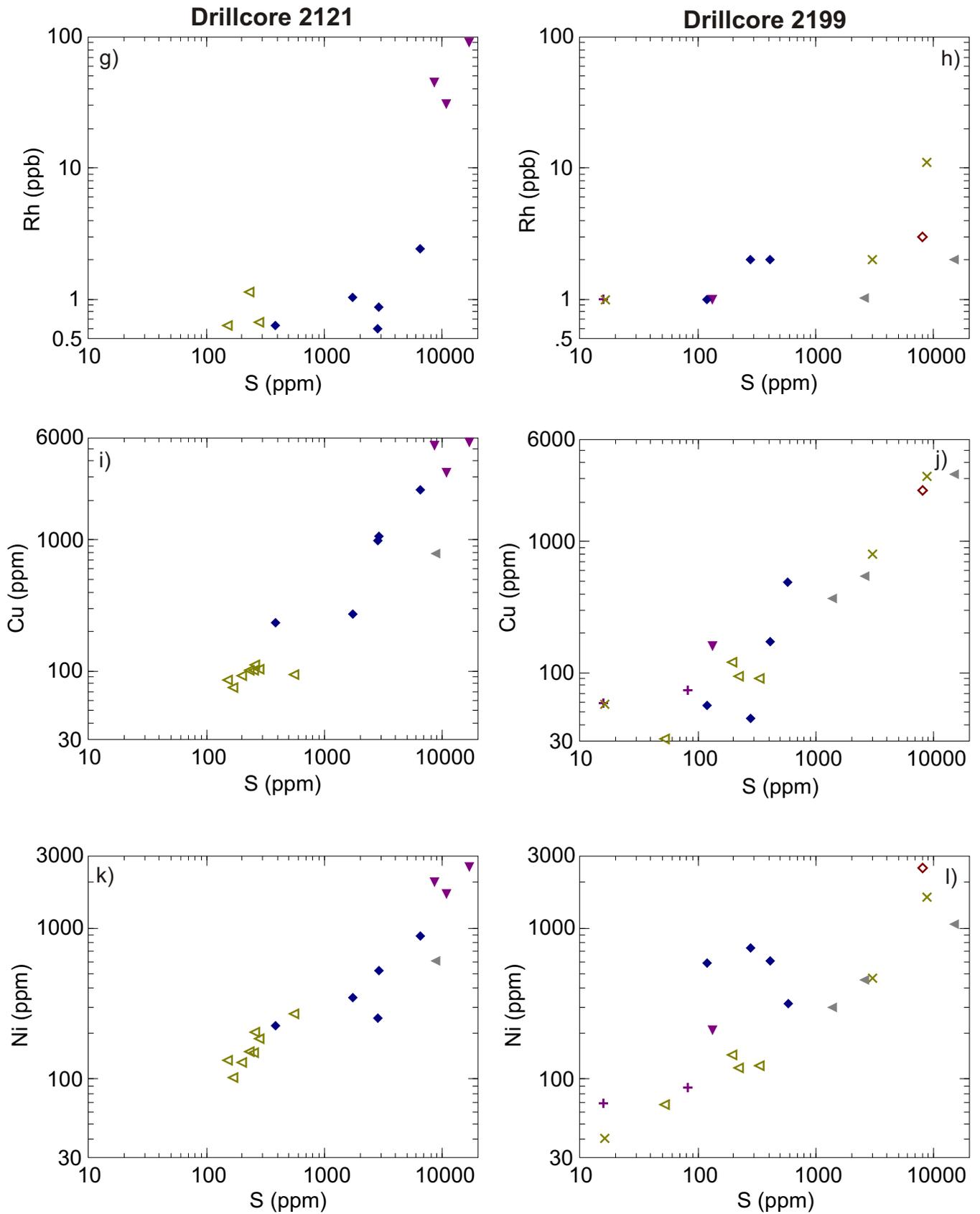


Fig. 6.10. (contd) Plots of d) Rh, e) Cu and f) Ni versus S. rx gn = recrystallized gabbronorite, gn = gabbronorite, mela-gn = mela-gabbronorite, anor = anorthosite.



In Fig. 6.11, the metals and S are plotted versus stratigraphic height. The sharp compositional break between the Platreef and the Main Zone that was evident in the mineral compositional data is again visible. The Platreef has relatively high PGE contents (between 0.002 and 8.865 ppm Pt + Pd) whereas the Main Zone mostly has PGE contents approaching the detection limit (< 0.2 ppb). In the Platreef, PGE and sulphur contents increase with height. This includes Ir which is normally separated from Pt and Pd during fractionation and crystallization of sulphide liquid (Kullerud et al., 1969; Naldrett, 1989). However, the observation that S also increases with stratigraphic height suggest a sulphide control for the PGE and that if Ir was fractionated from Pt and Pd, it was not transported far from the sulphide liquid (probably cm scale). The highest PGE concentrations occur in the recrystallized gabbro in drillcore 2121 (average 6.6 ppm Pt + Pd). In drillcore 2199, the highest concentrations occur in one anorthositic sample and a gabbro which have 2.3 and 3.8 ppb Pt + Pd, respectively. It is presently not known why the highest PGE values occur in different lithologies in the different boreholes. This may be due to the heterogeneity of the Platreef.

The noble metal concentrations have been normalised to primitive mantle and plotted in order of decreasing melting temperature in Fig. 6.12. Noble metal concentrations of the Merensky Reef and the Main Zone are shown for comparison. Ni is included in the plots to the left of Os, and Cu (as well as Au) to the right of Pd due to their broadly similar behaviour to Os and Pd, respectively, during fractionation (Barnes and Naldrett, 1987).



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Drillcore 2199

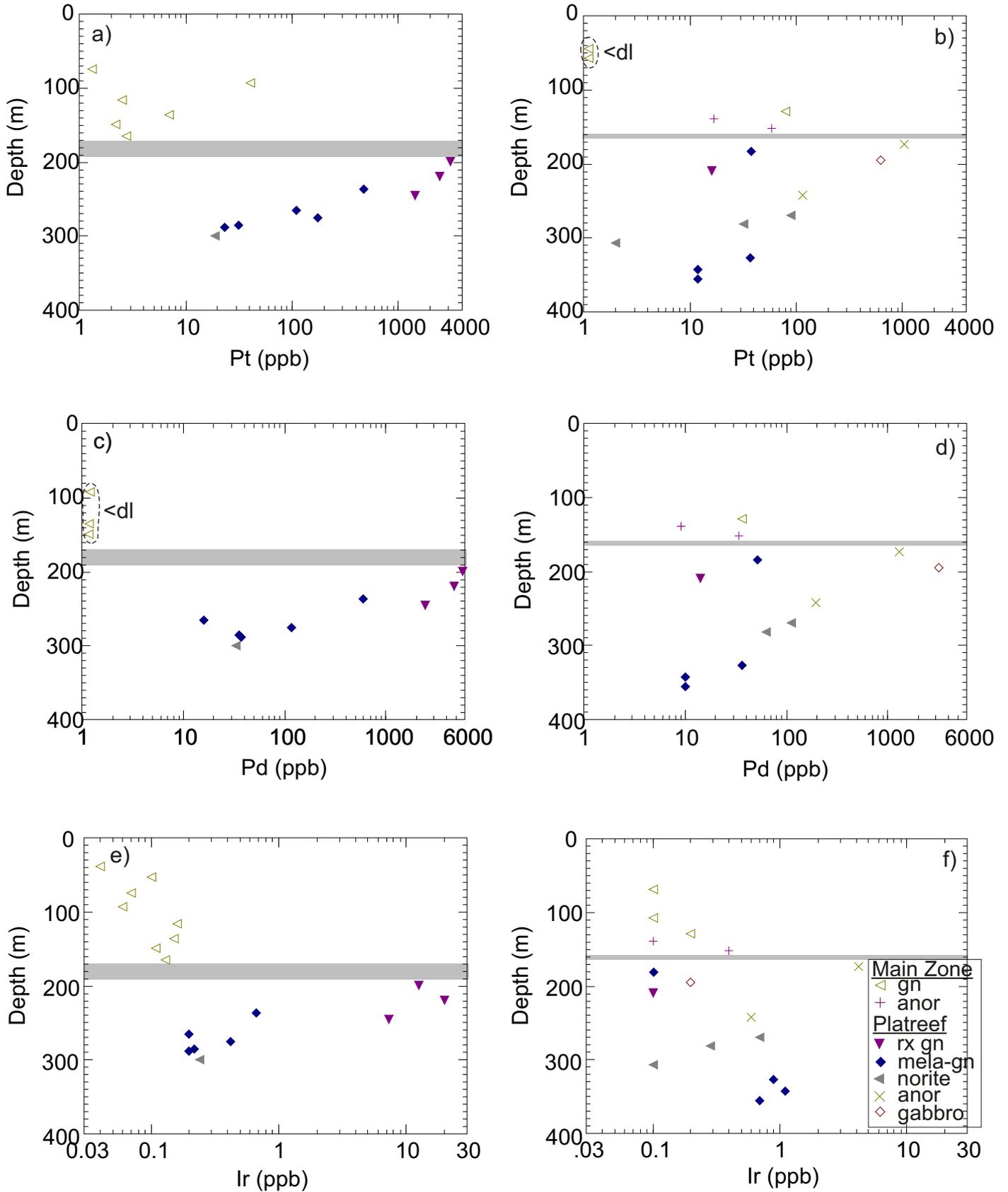


Fig. 6.11: Concentration of PGE and S in logarithmic scale plotted versus stratigraphic height (m). rx gn = recrystallized gabbronorite, gn = gabbronorite, mela-gn = mela-gabbronorite, anor = anorthosite, <dl = below detection limit. The shaded bar represents the boundary between Platreef and Main Zone.

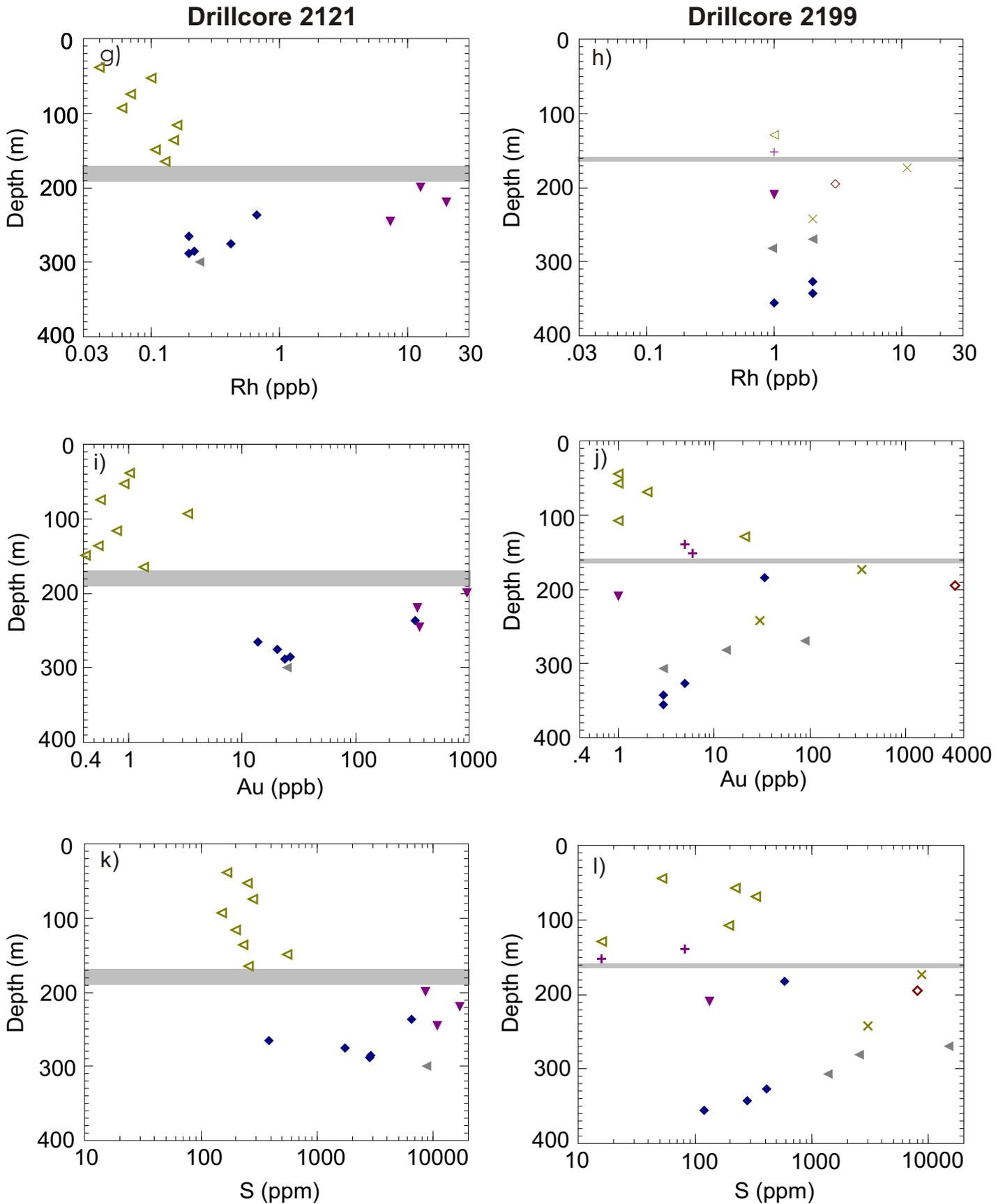


Fig. 6.11: (contd) Concentration of PGE and S in logarithmic scale plotted versus stratigraphic height (m). rx gn = recrystallized gabbro-norite, gn = gabbro-norite, mela-gn = mela-gabbro-norite, anor = anorthosite. The shaded bar represents the boundary between Platreef and Main Zone.



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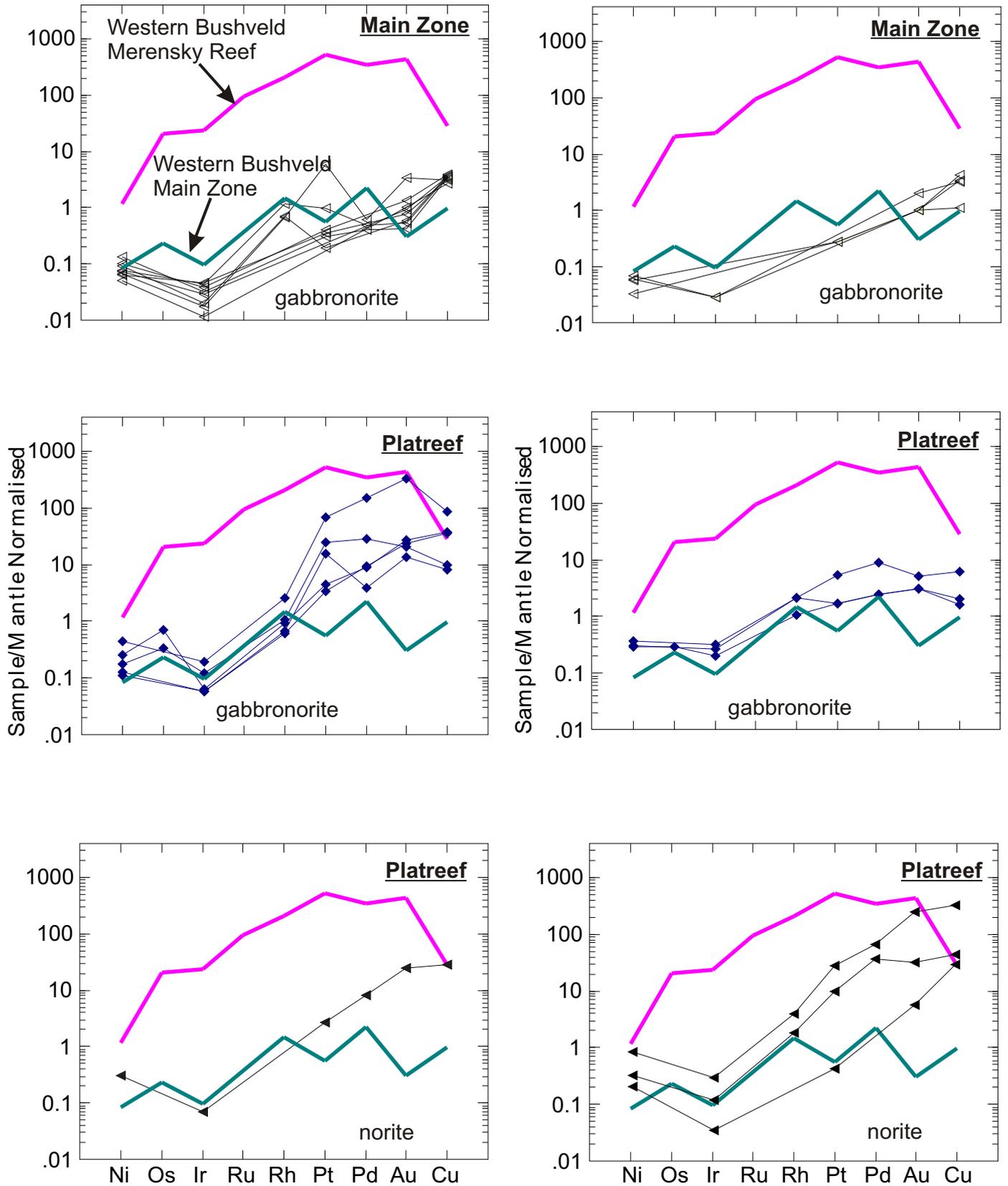


Fig. 6.12: Mantle-normalized PGE patterns for rocks from the Platreef and the Main Zone on the farm Nonnenwerth. Included are PGE concentrations for the Main Zone (Maier and Barnes, 1999 and the Merensky Reef (Barnes and Maier, 2002) in the western Bushveld Complex. (Normalization factors are from Barnes and Maier, 1999).

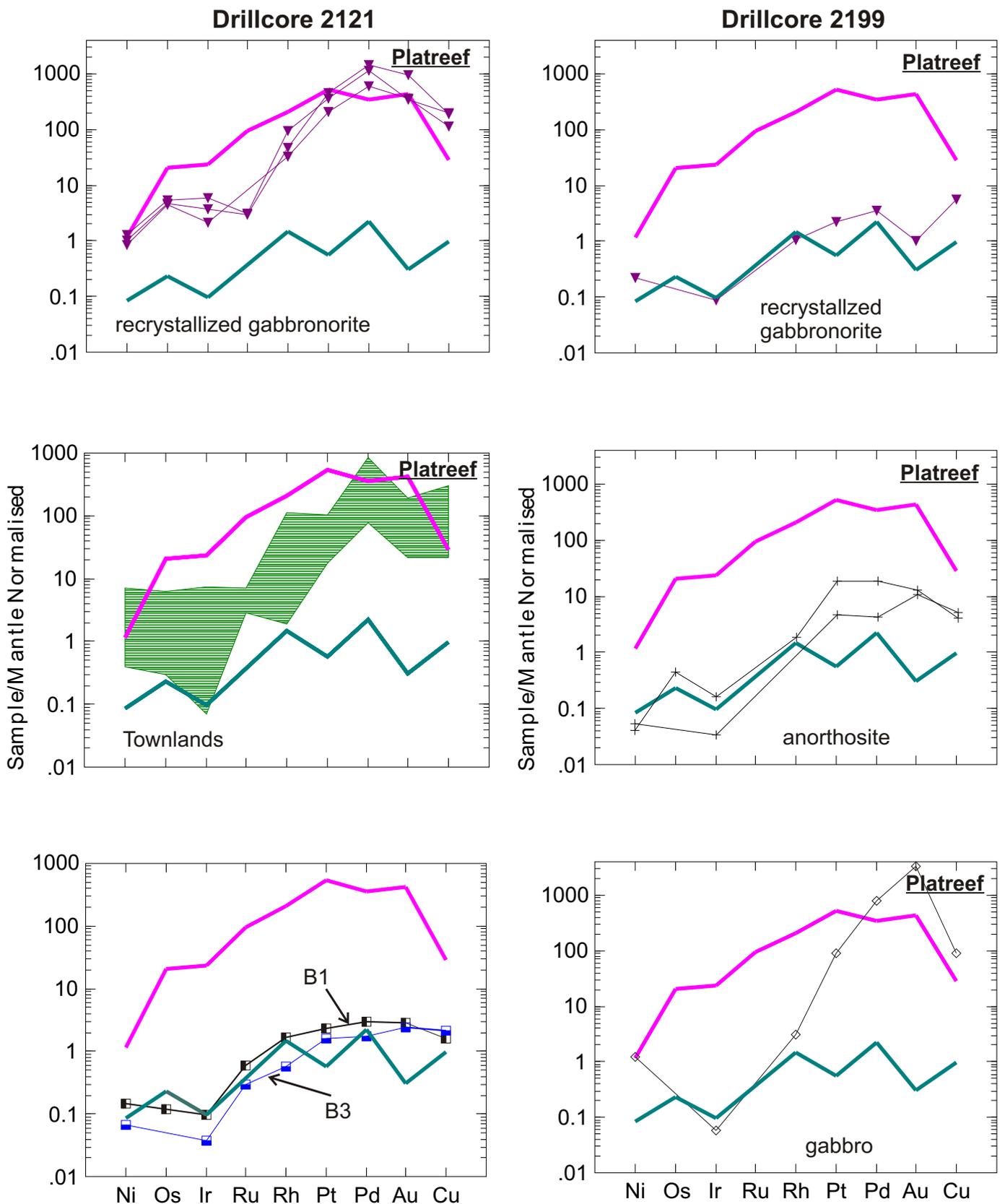


Fig. 6.12: (Contd) Mantle-normalized PGE patterns for rocks from the Platreef and the Main Zone on the farm Nonnenwerth, Townlands (Manyeruke and Maier, 2003) and B1 and B2 Bushveld parental magmas (Davies and Tredoux, 1985). Included are PGE concentrations for the Main Zone (Maier and Barnes, 1999 Merensky Reef (Barnes and Maier, 2002) in the western Bushveld Complex. (Normalization factors are from Barnes and Maier, 1999).



The diagrams highlight that Platreef rocks on Nonnenwerth have variable Pt and Pd contents, with some samples being as enriched as the Merensky Reef, but the shape of the metal patterns is different to that of the Merensky Reef due to a relative depletion in IPGE and, to a lesser degree, Rh. This results in more fractionated patterns with mostly steep slopes from Ir to Au ($\text{Pd/Ir} \gg 100$). Ni/Ir_N is mostly > 1 whereas Cu/Pd_N is mostly at unity or < 1 . This suggests that the sulphide melt segregated from a fertile magma in terms of PGE. The Main Zone gabbronorite has broadly similar metal patterns as the Main Zone elsewhere in the Bushveld Complex, with $\text{Cu/Pd}_N > 1$, suggesting that it crystallized from a magma that had experienced sulphide segregation prior to emplacement.

The patterns of most Platreef samples show a positive Pd anomaly, in contrast to the Merensky Reef which has a positive Pt anomaly. Pt/Pd ratios of samples with at least 0.1 wt. % S range from 0.2 to 1.5, averaging 0.7. For samples with less than 0.1 wt. % S, Pt/Pd ratios are mostly above unity and as high as 16.8. The variation of Pt/Pd ratio suggests that in the rocks with less than 0.1 wt. % S other phases besides sulphides exert some control on the PGE contents (e.g. silicates, oxides, PGM) or fractionation of the immiscible sulphide liquid during sulphide crystallization.

Metal patterns of Platreef samples at Townlands are also shown in Fig. 6.12. The patterns show broad similarities with the Platreef at Nonnenwerth, but Townlands has somewhat less fractionated patterns, resulting in lower Pd/Ir ratios (average 96).



6.4 Summary

Platreef samples from Nonnenwerth mostly plot near tielines joining plagioclase with orthopyroxene and clinopyroxene in most major element bivariate plots confirming that the chemistry of the rocks is controlled by the relative proportions of these phases and trapped melt. The data also show that plagioclase constitutes ca. 20 – 60 % of the rocks in agreement with the petrographic descriptions in chapter 5.

Trace element patterns at Nonnenwerth are unfractionated with Ce/Sm ratios between 5.7 and 10.6 (averaging 8) and show similarities to the Main Zone at Union Section. Major element data also overlap with central Main Zone. This suggests the Platreef has a B2/B3 magmatic lineage with little contamination or some dolomite contamination. At Townlands (Manyeruke *et al.*, 2005), the data indicate mixed B1-B2 signature i.e., higher and more fractionated REE contents (average Ce/Sm 12.6 at Townlands) more similar to Upper Critical Zone with relatively higher La/Yb_N. Moreover, the high concentration of the trace elements in some samples clearly indicates contamination with floor rock shale because the concentrations of the REE are too high to be explained by a trapped melt component of either B1 or B2 Bushveld lineage. It is possible that the entire crustal component is due to contamination with shale, and thus the importance of B1 is uncertain.

PGE at Nonnenwerth Platreef are more fractionated than elsewhere along the Platreef, with higher Pd/Ir ratios. This is in agreement with a more differentiated magma, suggested by the mineral and major elements chemistry and the absence of pyroxenite and chromitite. The present study has established a broad positive

correlation amongst the individual PGE and between individual PGE and S (for samples with > 0.1 % S), suggesting that magmatic sulphides were the primary PGE collector and that PGE are largely hosted by sulphides. However, there is also considerable scatter, notably in samples from borehole 2199, suggesting some secondary mobility of S, Cu, Pt and Pd. A similar pattern has been observed at Overysel (Holwell, *et al.*, 2005), Drenthe (Gain and Mostert, 1982) and at Townlands (Manyeruke, 2003; Manyeruke *et al.*, 2005).



CHAPTER SEVEN: COMPOSITION OF THE SILICATE MINERAL AT NONNENWERTH

The selected chemical compositions of the silicate minerals plagioclase, orthopyroxene and clinopyroxene are given in Tables 2a, b and c, respectively. Analytical details are given in Appendix 1c.

7.1 Plagioclase

The analysed plagioclase plots mostly in the labradorite field with only a few grains plotting in the bytownite and andesine fields (Fig. 7.1). There is no systematic compositional difference between plagioclase from the two drillcores. An (100 x cationic ratio of Ca / (Ca + Na + K)) contents in the Platreef tend to be similar to those in the Main Zone, but the spread in composition is much wider in the former i.e. An₃₇₋₇₅ versus An₆₀₋₇₆, respectively (Fig. 7.2). Furthermore, plagioclase becomes more calcic with height in the Platreef, but more sodic with height in the Main Zone. The increase in An of plagioclase with height in the Platreef is opposite to what might be expected in an intrusion crystallizing from the base upwards, from progressively differentiating magma. However, similar basal reversals in differentiation trend have been observed in many layered intrusions, including the Bushveld Complex (Hulbert, 1983). A further important observation is the distinct compositional break across the dolomite xenoliths in borehole 2121 to consistent lower An contents, but the break to consistent lower An contents in borehole 2199 occurs within the Main Zone rocks well above the dolomite xenolith. The high An contents close to the dolomite may be due to sub-solidus reaction between the dolomite and plagioclase with plagioclase gaining Ca from dolomite hence the high An contents towards the dolomite xenoliths.

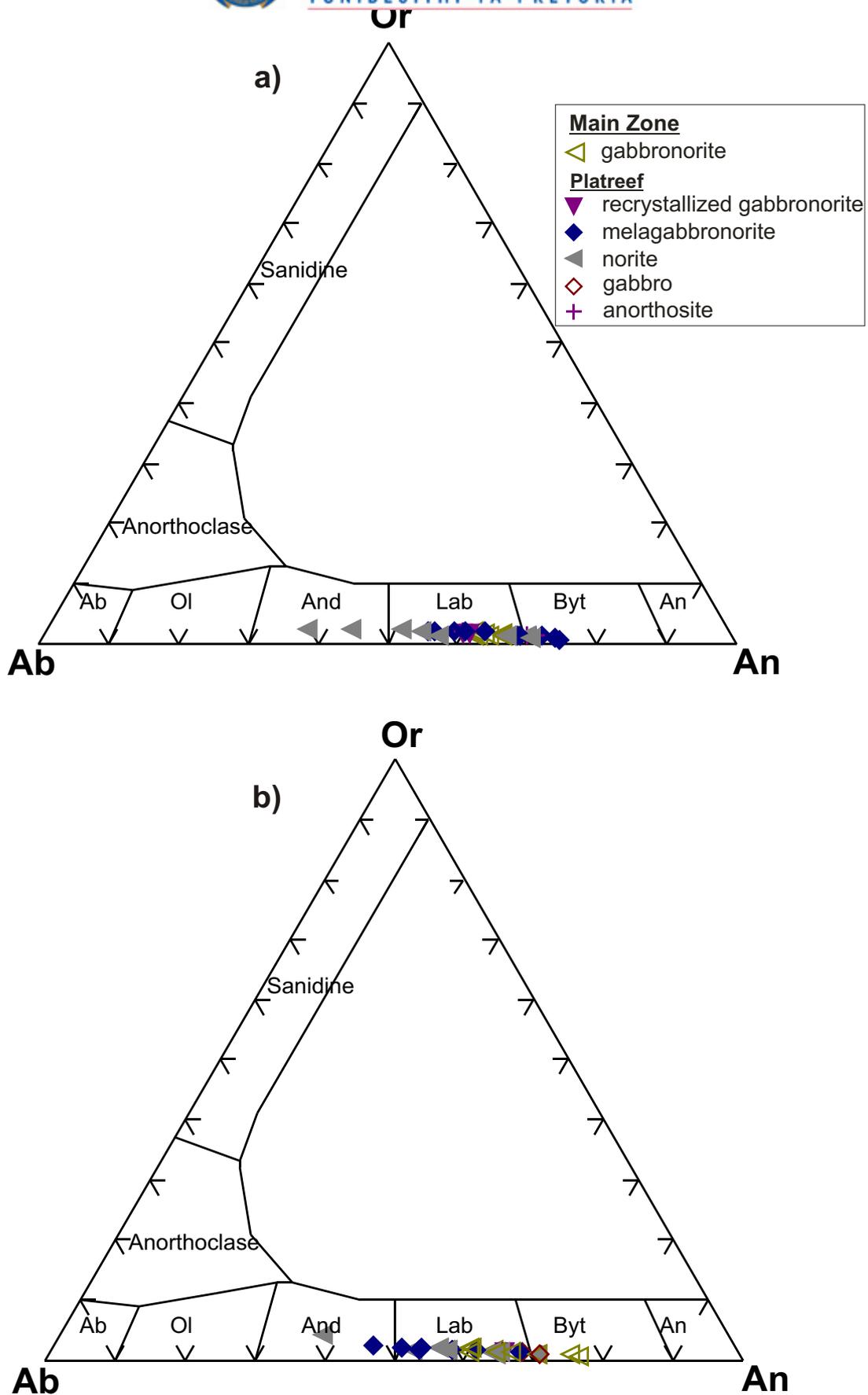


Fig. 7.1: Composition of plagioclase in Platreef and Main Zone rocks from Nonnenwerth
a) drillcore 2121, b) drillcore 2199

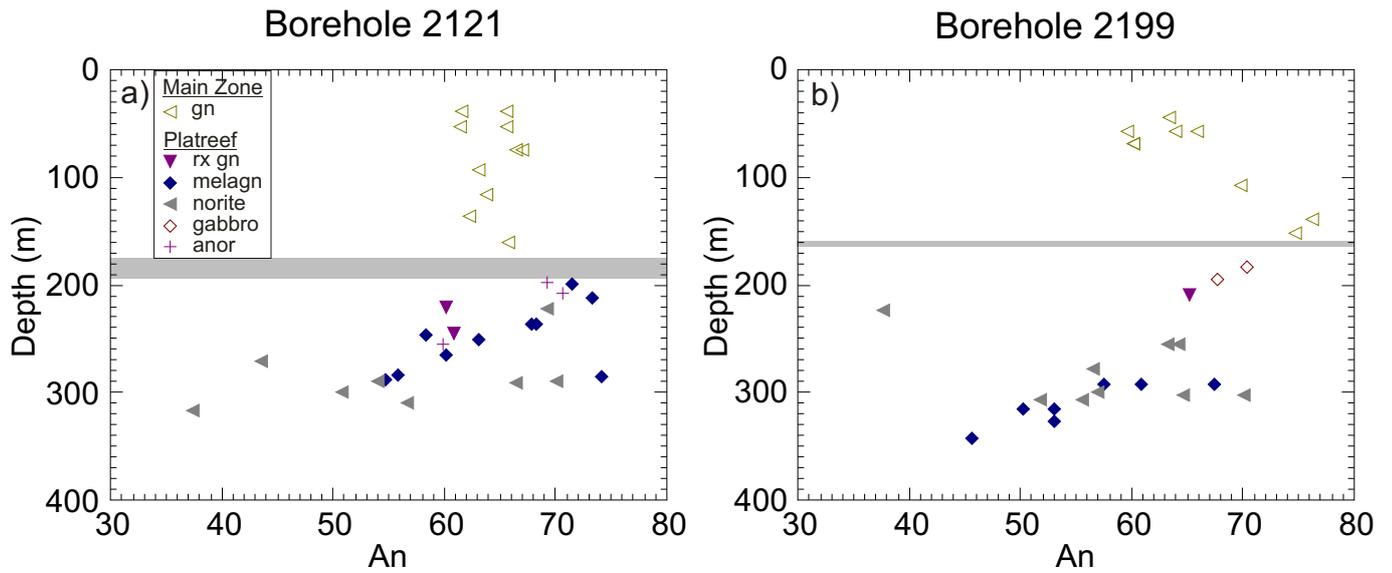


Fig. 7.2: (a and b) An content of plagioclase plotted versus depth. gn = gabbronorite, anor = anorthosite, melagn = melagabbronorite, rx = recrystallized gabbronorite. The shaded bar represents the dolomite layer defining the boundary between the Platreef and the Main Zone.



However, the plots of depth against An content shows different trends between the Main Zone and Platreef possibly suggesting that the rocks may have crystallized from distinct magma batches. It should also be noted that An values in the norites of both boreholes display an exceptionally wide range and the An contents of melagabbronorites are markedly different in the two boreholes. It is currently not known why this is so, but this may be attributed to localized effects and assimilation of xenoliths.

Plagioclase in the Platreef at Nonnenwerth is less An-rich than plagioclase on the farm Townlands (An₅₄₋₈₅; Manyeruke, 2003), where plagioclase is of broadly similar composition as plagioclase in the Upper Critical Zone (An₆₈₋₈₅; Cameron, 1982a; Naldrett *et al.*, 1986; Kruger and Marsh, 1985; Maier and Eales, 1997).

Inclusions of plagioclase within orthopyroxene in gabbronorite are more calcic than cumulus plagioclase (see Table 2a). Eales *et al.* (1994) noted a similar trend in the Upper Critical Zone at Union Section and attributed this to replenishment of the magma chamber with primitive magma leading to resorption of plagioclase phenocrysts suspended within the magma chamber.

7.2 Orthopyroxene

The orthopyroxenes at Nonnenwerth are mostly clinoenstatites with only three samples plotting in the pigeonite field (Fig. 7.3a and b). Enstatite contents vary between 70 and 56. Plots of Mg# ($100 \times \text{cationic ratio of } \text{Mg}^{2+} / (\text{Mg}^{2+} + \text{Fe}^{2+})$), NiO

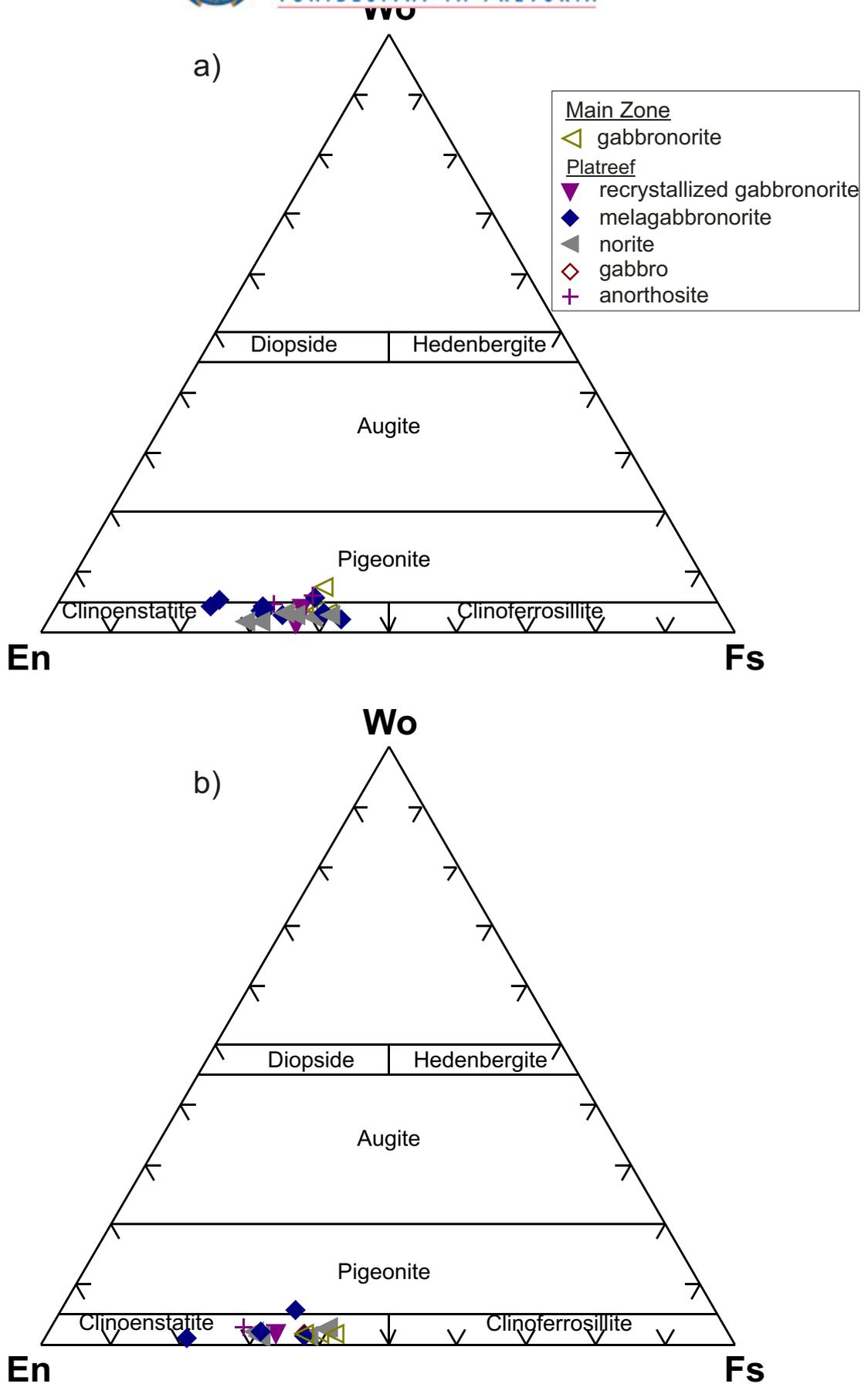


Fig. 7.3: Composition of orthopyroxene in Platreef and Main Zone rocks from Nonnenwerth a) drillcore 2121, b) drillcore 2199



and Cr_2O_3 against depth reveal an analogous compositional pattern as that observed in the case of plagioclase, i.e. a certain overlap in the composition of the Platreef and the Main Zone, but more compositional variation in the Platreef. Several Platreef samples have significantly higher Mg#, NiO and Cr_2O_3 contents than the Main Zone.

The plots of MnO and TiO_2 versus Mg# display an inverse linear relationship, except for TiO_2 versus Mg# in drillcore 2199 which does not show a clear trend (Fig. 7.5a and b). This indicates that Mn and Ti are incompatible in orthopyroxene and increase during differentiation. In contrast, Al_2O_3 increases with Mg# (Fig. 7.5c), indicating a simultaneous decrease in Mg and Al during differentiation. This pattern has also been described from the Upper Critical Zone of the Bushveld Complex (Eales *et al.*, 1993) and may be explained by co-precipitation of orthopyroxene and plagioclase.

The compositions of orthopyroxenes in the Main Zone at Nonnenwerth are similar to those of orthopyroxene in the central Main Zone elsewhere in the Bushveld Complex (Mitchell, 1986). This suggests that the lower Main Zone is not developed in the studied area, a conclusion that is in agreement with the published geological maps.

The orthopyroxenes from the Platreef at Nonnenwerth are more difficult to correlate with other sequences in the northern lobe or elsewhere, partly because of their compositional variations. The orthopyroxenes are markedly less magnesian ($\text{Mg}\#_{57-72}$) than orthopyroxenes in the Platreef on the farms Townlands ($\text{Mg}\#_{68-82}$; Manyeruke, 2003), Tweefontein ($\text{Mg}\#_{74-78}$; Buchanan *et al.*, 1981) and Sandsloot ($\text{Mg}\#_{76-80}$ for the primary reef, McDonald *et al.*, 2005). However, Platreef

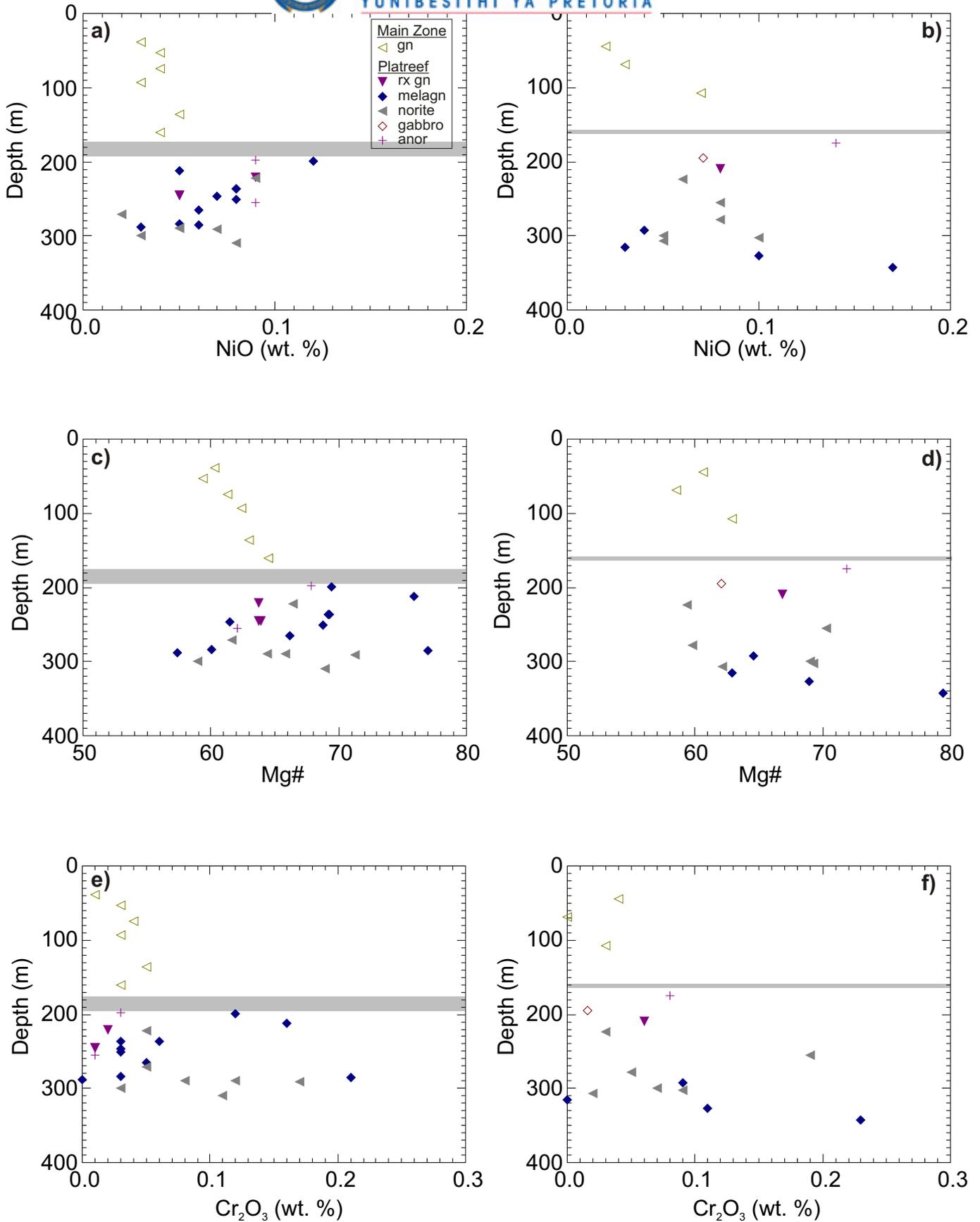


Fig. 7.4: Variation in orthopyroxene composition with depth at Nonnenwerth. (a and b): NiO. (c and d): Mg#. (e and f): Cr₂O₃. gn = gabbronorite, anor = anorthosite, melagn = melagabbronorite, rx gn = recrystallized gabbronorite. The shaded bar represents the boundary between the Platreef and the Main Zone.

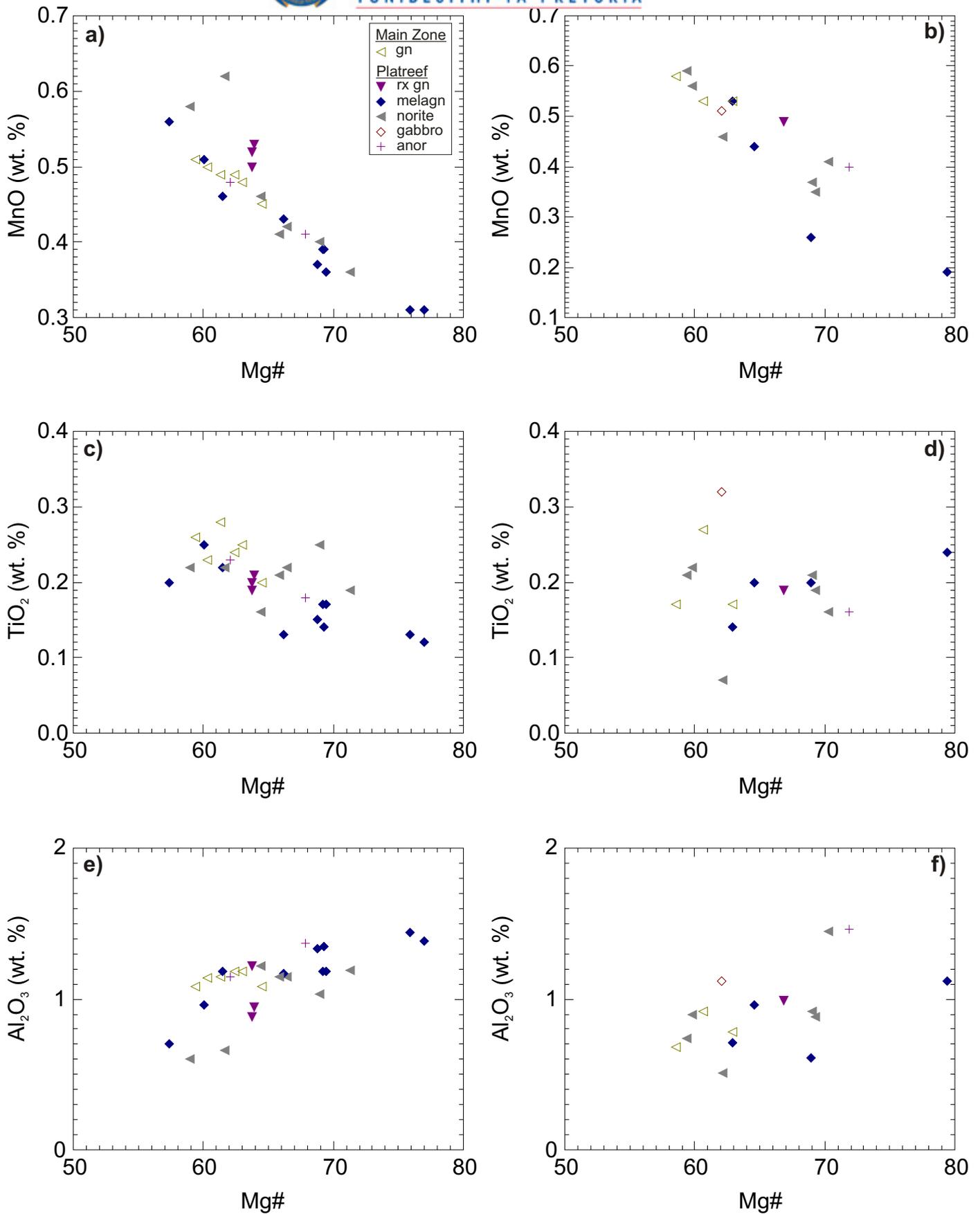


Fig. 7.5: Plots of (a and b) MnO versus Mg#, (c and d) TiO₂ versus Mg# and (e and f) Al₂O₃ versus Mg# in orthopyroxenes. gn = gabbronorite, anor = anorthosite, rx gn = recrystallized gabbronorite, melagn = mela-gabbronorite.



orthopyroxenes on Nonnenwerth have broadly similar maximum values of Mg# as orthopyroxenes on Drenthe and Overysel (Mg#₆₅₋₇₇; Gain and Mostert, 1982; Cawthorn *et al.*, 1985), where the reef is equally underlain by granite-gneiss and dolomite. Thus there is a trend of the Platreef orthopyroxene becoming less magnesian towards the north. In the southern sectors, the orthopyroxene have broadly similar composition as the Upper Critical Zone (Mg#_{78 - 84}; Cameron, 1982a; Naldrett *et al.*, 1986; Eales *et al.*, 1993; Maier and Eales, 1997; Cawthorn, 2002), whereas in the northern sectors, the composition of Platreef orthopyroxene overlaps with that of the lower to central Main Zone.

Cr₂O₃ contents in orthopyroxene of the Platreef on Nonnenwerth range from less than detection limit to 0.23 wt. % whereas those in the Main Zone are generally below 0.05 wt. % (Fig. 7.4e and f). The Cr₂O₃ contents in the Platreef orthopyroxenes are distinctively lower than those of typical Upper Critical Zone orthopyroxenes, which have Cr₂O₃ contents of 0.4 - 0.5 wt % (Eales and Cawthorn, 1996; Maier and Eales, 1997) and Townlands orthopyroxenes which have up to 0.41 wt. % Cr₂O₃ (Manyeruke, 2003; Manyeruke *et al.*, 2005). In contrast, the Cr₂O₃ contents of the Nonnenwerth orthopyroxene overlap with those of the lower to central Main Zone.

7.3 Clinopyroxene

Clinopyroxenes from the different lithologies mostly plot in the augite field of the pyroxene quadrilateral (Fig. 7.6), but several analyses plot in the diopside field. Mg# varies mostly between 64 – 80. The compositions are more ferric than those of

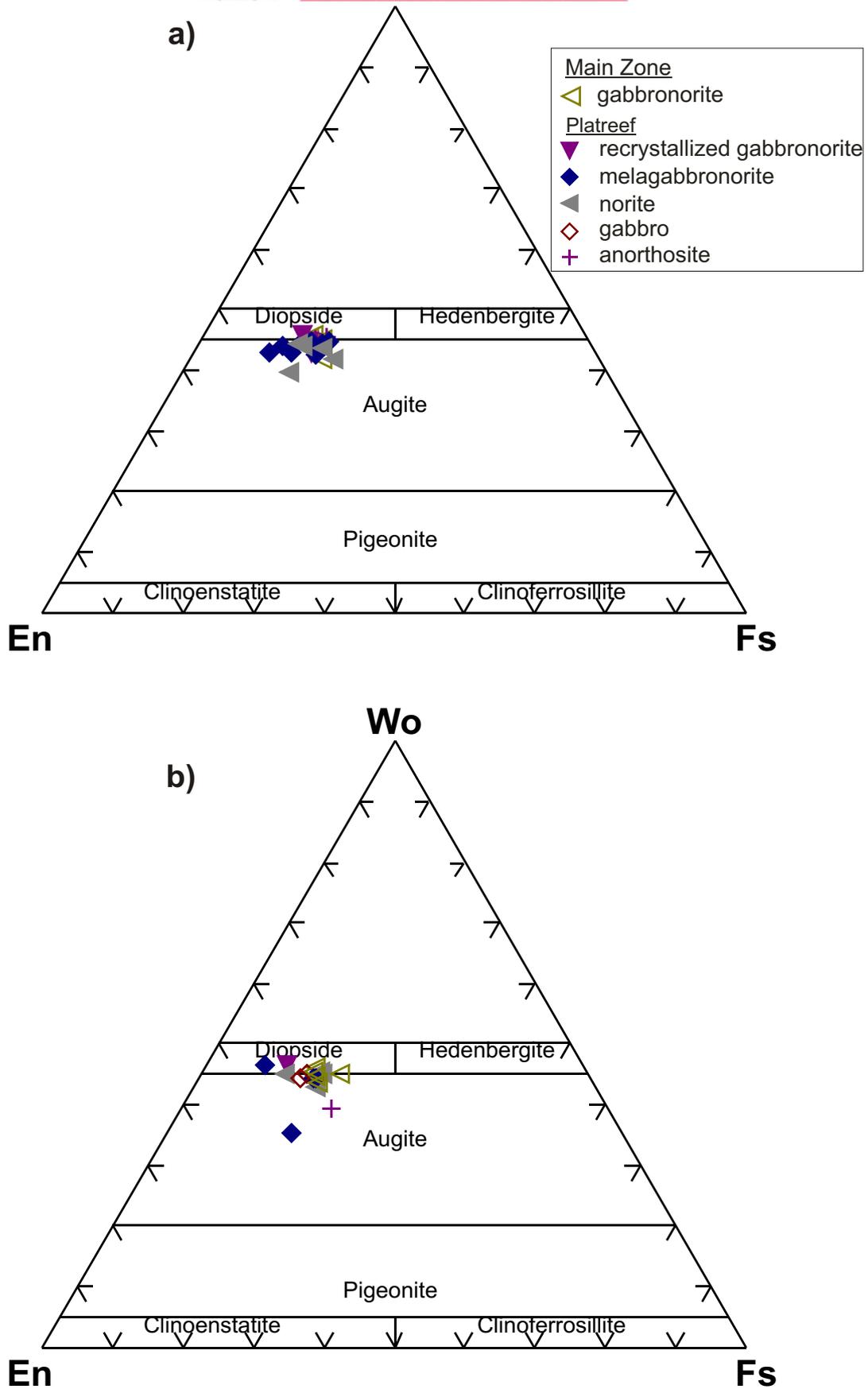


Fig. 7.6: Composition of clinopyroxene in Platreef and Main Zone rocks from Nonnenwerth.
a) Borehole 2121, b) borehole 2199



clinopyroxenes in the Platreef on Townlands (Mg#₇₆₋₉₁, Manyeruke, 2003; Manyeruke *et al.*, 2005) and Sandsloot (McDonald *et al.*, 2005), and clinopyroxenes from the Merensky Reef (Eales *et al.* 1993; Maier and Eales 1994; Cawthorn, 2002). However, clinopyroxene on Nonnenwerth shows similarities with that on Drenthe. Plots of NiO, TiO₂ and Mg# against depth reveal a broadly similar pattern as was observed in the plagioclase and orthopyroxene data, i.e. relatively more primitive compositions in some Platreef samples than in the Main Zone (Fig. 7.7a, c and e), a distinct break between the two intervals (Fig. 7.7a, c, d and e), a reverse differentiation trend with height in the Platreef (Fig. 7.7a) and normal differentiation with height in the Main Zone (Fig. 7.7c and e).

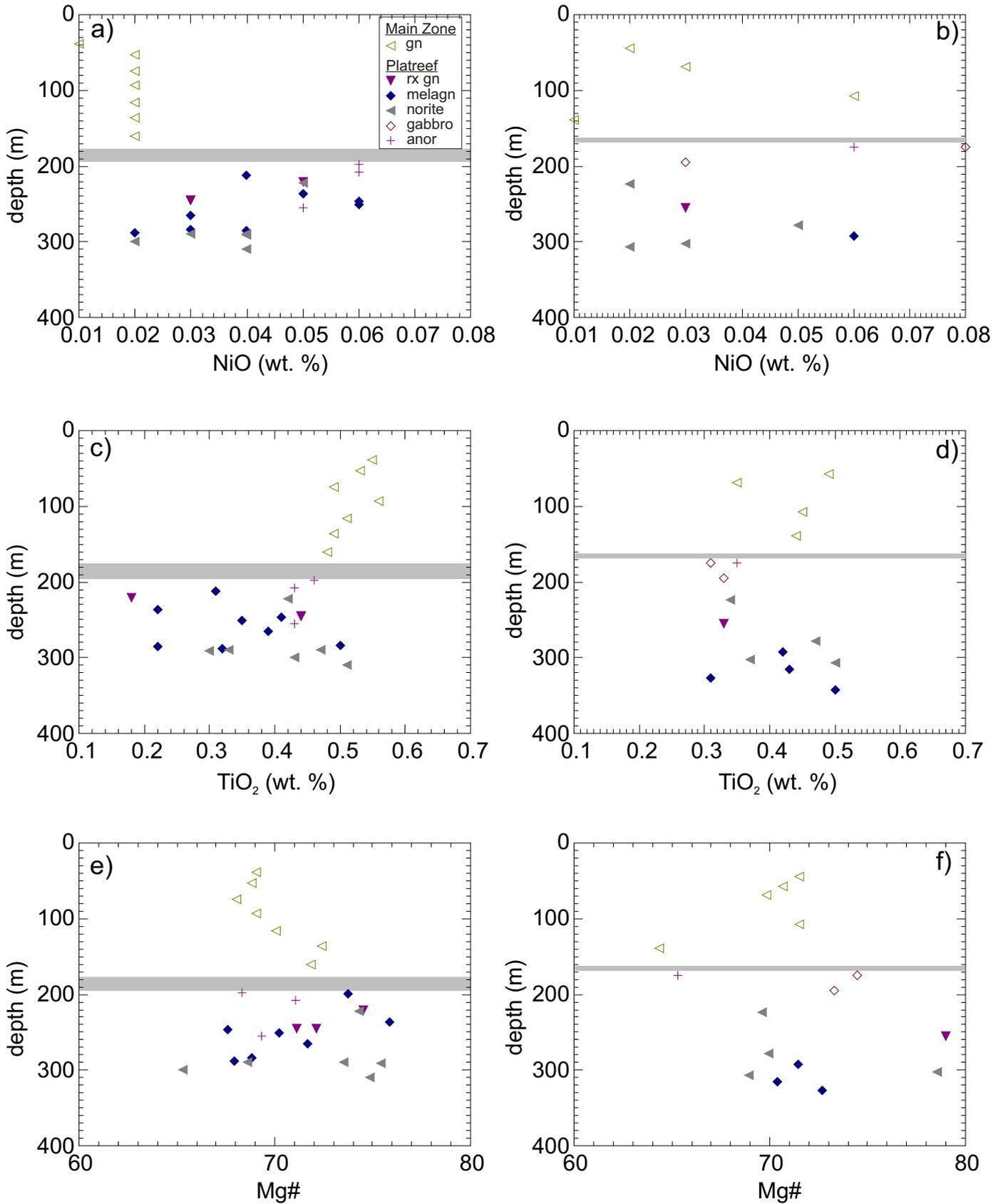


Fig. 7.7: Variation in clinopyroxene composition with depth at Nonnenwerth. NiO (a and b), TiO₂ (c and d) and Mg# (e and f). gn = gabbro, anor = anorthosite, rx gn = recrystallized gabbro, melagn = melagabbro. The shaded bar represents the boundary between Platreef and Main Zone.



7.4 Summary

Silicate minerals reveal a compositional break between the Platreef and Main Zone e.g. plagioclase becomes more calcic with height in the Platreef, but more sodic with height in the Main Zone. These compositional differences between the Platreef and the Main Zone suggest that the two units represent distinct influxes of magma. Although the composition of the two intervals overlap, the Platreef is more heterogeneous, with several samples having high Ni, Cr and Mg# in pyroxenes and An in plagioclase.

The orthopyroxenes at Nonnenwerth are markedly less magnesian ($Mg\#_{57-72}$) than orthopyroxenes in the Platreef on the farms Townlands ($Mg\#_{68-82}$; Manyeruke, 2003), Tweefontein ($Mg\#_{74-78}$; Buchanan *et al.*, 1981). Plagioclase in the Platreef at Townlands (An_{54-84} , average 71; Manyeruke *et al.*, 2005) is also more An-rich than plagioclase at Nonnenwerth (An_{47-75} , average 63). The former has a composition similar to plagioclase in the Upper Critical Zone (An_{68-85} ; Cameron, 1982a; Naldrett *et al.*, 1986; Kruger and Marsh, 1985; Maier and Eales, 1997).