

This is an Open Access document downloaded from ORCA, Cardiff University's institutional repository: <https://orca.cardiff.ac.uk/id/eprint/176167/>

This is the author's version of a work that was submitted to / accepted for publication.

Citation for final published version:

Thompson, Erin S., Holwell, David A., McDonald, Iain , Blenkinsop, Thomas G. , Reichow, Marc, Hughes, Hannah S.R., Canham, Kate R., Loader, Matthew A., Du Preez, Lara, Acheampong, Kofi and Lloyd, Andy 2025. Magmatic stratigraphy and platinum group element mineralization at Tweefontein, Northern Bushveld Complex: Evidence of a complex intrusion history of lower, critical, and main zone magmas. *Economic Geology* 120 (1) , pp. 1-27. 10.5382/econgeo.5123

Publishers page: <https://doi.org/10.5382/econgeo.5123>

Please note:

Changes made as a result of publishing processes such as copy-editing, formatting and page numbers may not be reflected in this version. For the definitive version of this publication, please refer to the published source. You are advised to consult the publisher's version if you wish to cite this paper.

This version is being made available in accordance with publisher policies. See <http://orca.cf.ac.uk/policies.html> for usage policies. Copyright and moral rights for publications made available in ORCA are retained by the copyright holders.



Magmatic stratigraphy and PGE mineralisation at Tweefontein, northern Bushveld Complex: evidence of a complex intrusion history of Lower, Critical and Main Zone magmas

Erin S. Thompson^{1*}, David A. Holwell¹, Iain McDonald², Thomas Blenkinsop², Marc Reichow¹, Hannah S.R. Hughes³, Kate R. Canham¹, Matthew A. Loader⁴, Lara Du Preez⁵, Kofi Acheampong⁵ and Andy Lloyd⁵

¹Centre for Sustainable Resource Extraction, University of Leicester, Leicester, UK

²School of Earth and Environmental Sciences, Cardiff University, Cardiff, UK

³Camborne School of Mines, Department of Earth and Environmental Sciences, University of Exeter, Penryn, UK

⁴Anglo American UK, 17 Charterhouse Street, London, UK

⁵Anglo American South Africa, 144 Oxford Road, Rosebank, Johannesburg, South Africa

*Email: erin.thompson805@gmail.com <https://orcid.org/0000-0001-8062-7126>

Statements and Declarations: The authors declare no competing interests.

Author Contributions:

Conceptualization and methodology: DAH, IM, HH, AL, EST; investigation (including field work): EST; logistical planning of field work and sample collection: EST, DAH, LDP, KA, AL, KRC; supplying Anglo American secondary data: LDP, KA, AL; writing: EST; supervision, review and editing, DAH, MR, TB, IM, HH, KRC, MAL, LDP, KA, AL.

For the purposes of open access, the author has applied a creative commons attribution (CC BY) licence to any Author

Accepted Manuscript version arising from this submission.

20 The Platreef, northern limb of the Bushveld Complex, South Africa, forms one of the world's largest resources of platinum-
21 group elements (PGEs), with additional Ni-Cu-Co mineralisation. It is widely considered that the Platreef formed via the
22 emplacement of a series of discrete magmatic units, however the relationship between this magmatic stratigraphy and the
23 distribution of Ni-Cu-Co-PGE mineralisation remains poorly constrained. This study constitutes the first in-depth
24 examination of the Platreef magmatic stratigraphy at Tweefontein 238 KR, located directly north of the Flatreef extension
25 at Turfspruit. Petrology, whole-rock and mineral chemistry define three magmatic units: the Upper Platreef, Main Zone
26 Finger and Lower Zone Transition, each displaying distinct pyroxene Mg# contents (79.6, 71.2 and 88.6 respectively),
27 mineral assemblages and bulk geochemistries. Up dip the sequence thins considerably from >600 m to <350 m, and
28 contamination signatures of elevated CaO and FeO increase. However, local contamination is seldom evident in the PGE-
29 bearing Upper Platreef. The intrusion of the overlying Main Zone is proposed to have eroded the Upper Platreef
30 considerably in some locations, locally reducing the economic viability of this mineralised horizon. The presented
31 stratigraphy indicates that at Tweefontein (1) the Lower and Critical Zone magmas are not necessarily separate, and evolve
32 from Lower to Critical over a distinct transitional zone; (2) there is only one main Critical Zone unit that is host to the PGE
33 mineralisation, and (3) the Main Zone not only forms a magmatic uniformity at the top of the Critical Zone, but also
34 intrudes the Critical Zone.

Introduction

The Rustenburg Layered Suite (RLS) of the Bushveld Complex, South Africa (Fig. 1A) hosts the largest platinum-group element (PGE) deposits in the world; the UG2 chromitite and the Merensky Reef in the eastern and western limbs of the RLS, and the Platreef in the northern limb, plus a number of other deposits within its stratigraphy in the northern limb (Kinnaid and McDonald, 2005; McDonald and Holwell, 2011; Kinnaid et al., 2017). As such, the Platreef is placed as one of the most important sources of PGE, as well as Ni, Cu and Co for years to come, and whilst modern mining of the deposits started in 1993 is ongoing, there are still many questions about the genesis of the deposit which impact upon exploration and mining approaches.

The RLS was emplaced within the northern part of the Kaapvaal Craton, between the regional unconformity of the Rooiberg Group volcanics and the Transvaal Supergroup (Clarke et al., 2009). The RLS consists of a 7-8 km thick sequence of intrusive rocks, varying in composition from dunite to diorite (Kinnaid and McDonald, 2005), with an age of the emplacement well constrained at 2.06 Ga (Walraven et al., 1990). As well as being divided spatially into the northern, eastern, southern, western and far western limbs (Fig. 1A), traditionally, the stratigraphy of the RLS is divided into Upper (UZ), Main (MZ), Critical (CZ), Lower (LZ) and Marginal Zones based on changes in modal mineralogy (Cawthorn, 1999). Typically, the UZ consists of anorthosites and gabbros, and is also characterised by up to 25 magnetite layers, the MZ of gabbro-norites, the CZ of chromitite-pyroxenite-norite cyclic units, the LZ of pyroxenites, harzburgites and dunites, and the Marginal Zone of norites, although it is often not present (McDonald and Holwell, 2011). It is at the base of the chromitite-pyroxenite-norite cyclic units of the CZ, that the PGE-enriched horizons, such as the UG2 chromitite and Merensky Reef appear in the eastern and western limbs (Eales and Cawthorn, 1996).

The Platreef is a complex package of CZ rocks in the northern limb of the Bushveld Complex which differ from the CZ of the wider Bushveld in that high grade PGE mineralization is spread over much greater thicknesses, commonly 3-4 g/t 4E (Pt + Pd + Rh + Au), but locally up to 15 g/t, over > 10 m (compared to 3-4 g/t 4E over < 1 m in the Merensky Reef of the eastern and western limbs (Yudovskaya et al., 2011)). Additionally, the Platreef also contains significantly higher base metal contents, with economic occurrences of Ni and Cu, and a higher Pd/Pt ratio (>1) than the reefs in the eastern and western limbs, which typically have Pd/Pt ratios <1 (McDonald et al., 2005). The exact definition of the Platreef can vary in the scientific literature, as well as between academic and industrial fields, however in this study the Platreef is defined as “the mafic units enriched in Ni-Cu-PGE that occur between the Archean granite-gneiss basement or the Transvaal Supergroup, and the gabbros and gabbro-norites of the Main Zone” as proposed by Kinnaid and McDonald (2005). Although the term Platreef is sometimes used to refer to only the mineralised horizons, it is becoming more common that the term is applied

to the entire sequence of magmatic rocks between the overlying MZ, and underlying Transvaal and Archean lithologies (Manyeruke et al., 2005; McDonald and Holwell, 2011; Yudovskaya et al., 2011).

As the Platreef lies north of the Thabazimbi-Murchison lineament, and therefore rests directly on the metasedimentary Transvaal Supergroup, Archean basement, and their accompanying footwall structures, these structures are likely to have had a significant impact on the emplacement and magmatic pathways of the northern limb magmas, and thus their resultant stratigraphy (Clarke et al., 2005; Nex, 2005; Kinnaird et al., 2005; Clarke et al., 2009). Furthermore, local contamination by differing footwall lithologies along strike is known to have created important variations in Platreef mineralogy and geochemistry (Cawthorn et al., 1985; Barton et al., 1986; White, 1994; Harris and Chaumba, 2001; Pronost et al., 2008; Ihlenfeld and Keays, 2011). Better understanding of the role of the magmatic pathways and contamination events in the northern limb is key to developing robust genetic and exploration models in the area.

The Platreef itself is thought to have formed via the emplacement of a series of discrete magmatic units or sills, each with their own variable metal budgets, geochemical characters, and thicknesses (e.g. Kinnaird, 2005; McDonald and Holwell, 2011). Previous studies have divided the Platreef into three or four discrete magmatic units, often separated by metasedimentary interlayers, at various locations along the northern limb. At Turfspruit, this has been achieved by examining changing mineralogy, Pt/Pd and Ni/Cu ratios (Kinnaird, 2005; Grobler et al., 2019); at Townlands, via trace element and S isotope analysis (Manyeruke et al., 2005); at Tweefontein 238 KR via bulk rock major and trace element geochemistry (Nyama et al., 2005); and north of Sandsloot using variations in platinum-group mineral (PGM) assemblages (Yudovskaya et al., 2011). However, there remains little understanding of the control that this primary magmatic stratigraphy plays in controlling the distribution of PGE-Ni-Cu-Co mineralisation.

In this study, the petrology, bulk geochemistry and mineral chemistry of the Platreef at Tweefontein 238 KR (hereafter referred to as simply Tweefontein) are examined, with the aim of establishing the primary magmatic stratigraphy at this location, and how this stratigraphy varies both down dip and along strike. We aim to investigate if the distribution of these units exhibits a direct control on the location of PGE mineralisation, and therefore which magma sources and/or contamination pathways may lend themselves to higher grade horizons. Given that Tweefontein is located directly to the north of the farm Turfspruit, it allows us to make the first detailed comparison between the deep sections of PGE-mineralised stratigraphy in this sector of the Platreef with that of the Flatreef (Grobler et al., 2019). We show that the Tweefontein sequence is made up of a Lower-Critical Zone transition, a Critical Zone (Platreef) and an intrusive Main Zone unit.

The Platreef at Tweefontein

The farm Tweefontein contains the southernmost portion of the central sector of the Platreef, bordering the farms Turfspruit to the south and Sandsloot to the north (Fig. 1B-D). The footwall lithologies of the Transvaal Supergroup vary along strike at Tweefontein, leading to this region commonly being divided into the Tweefontein North and Tweefontein Hill sub-sectors. At Tweefontein Hill, directly north of Turfspruit, the Platreef lies on the argillaceous shales of the Duitschland Formation. Tweefontein Hill itself is composed of Transvaal sediments, with the crest of the hill correlating with the approximate northern edge of the Penge Formation outcrop. A microgranite sheet, up to 100 m in thickness, has also been mapped on the northern and eastern sides of the hill (Nex, 2005). In some locations, the ironstones are noted to be partially metamorphosed into magnetite-bearing hornfels (McDonald and Holwell, 2011). On the Farm Vaalkop 819 LR, the footwall transitions from the Penge Formation into the Malmani Dolomite Subgroup, as the Platreef transgresses downward in the Transvaal stratigraphy. Xenoliths of Duitschland shales and banded ironstone (BIF) of the Penge Formation, which underlies the Duitschland, and forms the footwall to the Platreef at Tweefontein North, are commonly observed in the Platreef (Nyama et al., 2005).

The structure of the footwall contact at Tweefontein Hill has been examined in a structural mapping study by Nex (2005), who identified several phases of pre-Bushveld deformation. Two phases of ductile formation (NE-SW compression, forming NW-SE trending folds followed by NNW-SSE compression, forming ENE-trending folds) are believed to have formed a pre-Bushveld fold structure within the Transvaal country rocks. This second deformation event, forming a large ENE-trending syncline, is inferred by Nex (2005) to exhibit a direct control on the location of massive and net-textured sulfide mineralisation at Tweefontein Hill, allowing the sulfide liquid to pool via gravitational settling within the down warp structure. The relatively inert nature of the ironstone footwall at this location is likely to have aided the preservation of this deposit (Nex, 2005).

At Tweefontein Hill, the Platreef forms a 100 – 220 m thick package, dominated by pyroxenites with minor norites (White, 1994). Nyama et al. (2005) used Mg# and Fe/Ti ratios to divide the Platreef into at least three different magmatic packages at this location. At Tweefontein North, the Platreef is generally thinner (approximately 150 m), with the occurrence of chromitite stringers towards the top of the Platreef noted by White (1994). Closer to the ironstone footwall, the Platreef has been locally contaminated, producing a distinctive Fe-enrichment towards footwall contact (Buchanan et al., 1981; Ihlenfeld and Keays, 2011), however this has also been noted towards the top of the Platreef at Tweefontein (Nyama et al., 2005).

120

Methods

121 The drillholes chosen to investigate the variations in the Platreef magmatic stratigraphy in this study are (from south west
122 to north east): RTN021, RTN020, TN304, TN303 and TN287 (Fig. 1C). The transect, from SW to NE, allows for the
123 identification and correlation of distinct magmatic units from the down dip area in the SW, to shallower up dip area in the
124 NE. Additionally, RTN020 allows for the identification of along strike variations within the deeper Platreef. The magmatic
125 units proposed are based primarily on their major element composition, largely reflecting bulk mineralogy. This
126 stratigraphy is then tested further via examining each unit's trace element and mineral chemistry composition.

127 Downhole geochemical data and lithological core logging results for the selected drillholes were provided by Anglo
128 American. Bulk rock geochemistry for metre-intervals of half core for the entire intersection of the Platreef in each drillhole
129 was collected via ICP-OES for major elements, and ICP-MS for trace elements by Bureau Veritas Minerals on behalf of Anglo
130 American. Prior to analysis, samples were crushed and milled until 85% of the sample passes through a 75-micron sieve.
131 Additionally, Pt, Pd and Au grades were collected via lead collection fire assay fusion followed by ICP-MS also by Bureau
132 Veritas Minerals

133 Data supplied by Anglo American was supplemented by further analysis of 10 samples via XRF and ICP-MS for major and
134 trace elements respectively at the University of Leicester (see Appendices and Fig. A1). Each sample was crushed with a
135 hardened steel press, and milled in an agate planetary ball mill. After each run, the apparatus was decontaminated and
136 sterilised using water and industrial methylated spirit. XRF analysis was conducted on a PANalytical Axios Advanced XRF
137 spectrometer, operating with PANalytical SuperQ software. Loss on ignition (LOI) was calculated by weighing each dried
138 sample in ceramic crucibles before and after ignition in a 950°C furnace for 3 hours. Major elements were determined via
139 analysis on fusion beads prepared using a lithium tetraborate flux, followed by XRF. Powdered samples for trace element
140 analysis were digested in HF, HCl and HNO₃ acid to a 1000 x dilution, and spiked with a 100 mL of Rh/Ir before analysis.
141 Analysis was conducted using a Thermo Scientific iCAP-Qc quadrupole ICP mass spectrometer. The USGS mafic rock
142 reference standards BCR-1 and BHVO-2 were used as standards. These repeat results were in good agreement with the
143 previous analyses conducted by Anglo American (see Appendix 5).

144 The petrological study was conducted using 36 polished thin sections prepared at the University of Leicester, aided by high
145 resolution photography and hyperspectral mineralogy of the drillcores provided by Coreshed and Intellicore. TN287 was
146 unavailable for direct sampling. Full petrological descriptions of the magmatic domains are presented below, and those of
147 the metasedimentary xenolith domains are found in the Appendices (Fig. A4).

148 Quantitative pyroxene mineral chemistry data was collected on a ZEISS Sigma 300 SEM fitted with two EDS detectors at the
149 University of Leicester. For all analyses a working distance of 8.5 mm, detection time of 30 s, 30 µm aperture and an

accelerating voltage of 15 kV was applied. Quantification of the EDS spectra was derived from the different peak intensities using the Bruker Esprit 2.3.1 software and their standardless Phi-Rho-Z quantification method. Oxygen was calculated by stoichiometry for the oxide compositions.

Remote mapping of the Tweefontein area was completed to assess the local Transvaal footwall structures and their potential influence on the emplacement of the Platreef magmas. The mapping was completed using a set of aerial, satellite and hyperspectral images of area from Tweefontein Hill to the SE edge of the Sandsloot open pit (approx. 6 km of Platreef strike) (Fig. 2). Mapping of units and structures onto the map was aided via historic and contemporary geological maps (Nex, 2005; Yudovskaya et al., 2013; Grobler et al., 2019) and current geological mapping undertaken by Anglo American. The airborne hyperspectral survey was flown by the advanced hyperspectral and geospatial solution company SpecTIR, using a ProSpecTIR-VS sensor, measuring 360 bands with a spectral range from 390nm to 2450nm at 5nm spectral resolution, from the 25-26th July 2019. The data was then corrected to reflectance by SpecTIR, and a ternary RGB image of 3 product ratios was produced. This image was used in conjunction with the Anglo American hyperspectral mineralogy map, and aeromagnetic map (Fig. 2B) of the northern limb to validate the mapping.

Remote Mapping Results

The results of the remote mapping are presented in Figure 2. The hyperspectral imagery (Fig. 2C) shows layering within the Malmani Subgroup, and a change in strike of the Malmani Subgroup is observed around Tweefontein Hill. Layering within the Malmani Subgroup transitions locally from a roughly NW-SE strike to an E-W direction around Tweefontein Hill, returning to a NW-SE to the SE of Tweefontein Hill. The Platreef also appears to follow this change in strike. This remote mapping supports the observations made by Nex (2005) that there is a synform structure present within the footwall at Tweefontein Hill.

To the NW of Tweefontein Hill, a structure is seen intruding into the Transvaal succession, cross-cutting the Malmani layering (outlined in dark red in Fig. 2C). This post-Transvaal feature shows the inter-fingering of Platreef magmas into the Transvaal footwall, and is clearly visible within both satellite and hyperspectral imagery (Fig. 2). Although this structure is not visible within the aeromagnetic data (Fig. 2B), it is highly likely that the strong responses from the magnetite-rich Penge Fm has obscured the weaker responses from both the Platreef and other Transvaal footwall units. Therefore, the aeromagnetic survey does not provide as detailed a view as the high resolution airborne hyperspectral imagery. Observations from satellite and hyperspectral imagery have since been verified during fieldwork, assessing the remote mapping area with views from Tweefontein Hill. The compositions of this structure and surrounding area have also been verified via the mineral composition map produced from the hyperspectral imaging by Anglo American. These results show that the area in the middle of the intruding feature is composed of dolomite, whereas the intruding lithology itself is composed of iron-rich minerals with a gossan cap, corresponding to an outcrop of mafic-ultramafic Platreef magmas. As a result, the geological map of the Tweefontein Hill area has been updated, shown in Fig. 2D, with the structure interpreted as intruding Platreef magmas into the Malmani Dolomite, forming a large dolomite raft.

Petrology

The majority of the units studied at Tweefontein contain similar mineral assemblages of varying proportions of orthopyroxene, plagioclase, clinopyroxene and olivine. It should be noted that in several samples the modal abundance of plagioclase in the pyroxenitic units totals over 10%, and therefore these rocks should be classified as a norite under the IUGS classification (Le Bas and Streckeisen, 1991). However, in keeping with traditional Bushveld terminology, whereby lithologies are named after their cumulus phases, and to avoid confusion with the MZ norites and gabbronorites, which contain cumulus plagioclase, these lithologies are termed 'feldspathic pyroxenites'. The main accessory minerals identified are phlogopite and base metal sulfides (BMS). The main alteration products of the mafic minerals are serpentinite, saponite, chlorite, talc, tremolite, actinolite and other minor amphiboles. Plagioclase is commonly observed to have undergone alteration to sericite and less commonly, albite. Zoning in plagioclase is uncommon.

A large variety of igneous and hybrid textures are observed within the magmatic units and metasedimentary interlayers which separate them. The main textures observed are pegmatoidal, poikilitic, equigranular and inequigranular, with several units also displaying recrystallization textures. Grain sizes vary from very fine (< 1 mm) to pegmatoidal (> 10 mm). The most common oikocrysts are plagioclase and clinopyroxene, with minor orthopyroxene. The chadacrysts are predominately orthopyroxene and olivine when present. The Hybrid Zone in TN287 (Fig. 3) was not available for sampling and is therefore has not been included in this section.

Drillcore Observations

Using observations from drillcore and downhole major element geochemistry presented below, the Platreef sequence at Tweefontein has been divided into discrete units which are correlatable across all drillholes. The magmatic units have been termed the Upper Platreef (UP) composed of largely pyroxenites, a gabbro-norite Main Zone Finger (MZF), and a Lower Zone Transition (LZT) made up of dunites grading up into pyroxenites. The xenolith raft domains, termed X_1 , X_2 and X_3 , are made up of hornfels, calcsilicates and proximal hybrid lithologies (Fig. 4), which are historically termed 'parapyroxenites'. The term parapyroxenite is typically used to refer to highly metasomatized and contaminated serpentinitised (clino-) pyroxenites and calcsilicate hybrid lithologies in close proximity to carbonate xenoliths in the Platreef (Kinnaird et al., 2005; Nex et al., 2008). The lithological characteristics, as well as their geochemical properties of the magmatic units identified in this study (UP, MZF and LZT) are summarised in Table 1.

The UP is the uppermost magmatic package at Tweefontein and is characterised petrologically by coarse grained (feldspathic-) pyroxenites, with disseminated to blebby textured sulfides (Fig. 4A). It exhibits the highest PGE grades of the identified units (Fig. 3 and Table 1), with the highest grades found in RTN021. The thickness of the UP varies up dip from 289 m in RTN021, to 26 m in TN304, to 130 m in TN303. Along strike the thickness is more consistent, at 222 m in RTN020.

The MZF sits beneath a zone of metasedimentary interlayers, in the middle of the studied sequence, and is recognised by the increased abundance of plagioclase, including cumulus plagioclase (Fig. 4B). It is barren of PGE grade in all drillholes (Fig. 3 and Table 1). The thickness of the MZF decreases up dip from > 200 m to < 70 m, and the unit pinches out between TN304 and TN303. Along strike, in RTN020, the unit is interrupted by, or was emplaced around, a large xenolith raft (Fig. A2B).

The LZT forms the base of the studied succession at Tweefontein, excluding RTN021, where the base of the magmatic sequence is sits on calcsilicates (X_3). This package is so called as it transitions downhole from pyroxenites, into harzburgites and finally dunites at the base of the observed sequence (Fig. 4D). The medium-coarse grained textures, dominated by olivine and pyroxene, including the high degrees of serpentinitisation particularly in the dunitic portions of the unit, are

223 typical of LZ textures (Kinnaird et al., 2005; McDonald and Holwell, 2011; Yudovskaya et al., 2013). Additionally, this
224 package is barren of economic PGE grades (Fig. 3 and Table 1).

225 The xenolith raft domains have been termed 'units' for ease of phrasing, but it is recognised that these zones are unlikely
226 to be continuous in nature, and are more likely to be lenses of xenoliths/remnant footwall rafts and their surrounding
227 highly altered pyroxenites (parapyroxenites), that are present intermittently throughout the Platreef; though the mapping
228 shown in Figure 2 illustrates how these can be on a large (100s metre) scale. They could also still be connected to the
229 Transvaal footwall in up dip areas, but further drilling would be required to verify this. They are characterised by
230 alternating zones of metasediments, calcsilicates and hornfels, with remnant Transvaal sedimentary layering often
231 preserved (Fig. 4E). They have been termed X_{1-3} , referring to the order in which they appear downhole in the studied
232 stratigraphy (Fig. 3). Sporadic spikes in PGE grades are present within several of these xenolith-dominated domains where
233 they contain the PGE mineralised UP, and the BIF footwall in TN287 (Fig. 3).

Upper Platreef

The UP is characterised by coarse-grained to pegmatoidal pyroxenites and feldspathic pyroxenites (Fig. 5A-D), as reflected in the bulk rock geochemistry (Fig. 5E-F). Chadacrysts of orthopyroxene and clinopyroxene are up to 15 mm in size, and are surrounded by oikocrysts of plagioclase, with minor interstitial quartz (Fig. 5A-B). The orthopyroxenes display a rounded morphology, suggesting re-equilibration of the cumulate phases as the surrounding magma cooled. Undulose extinction is common within both plagioclase and quartz. Kinked and cross-cutting twinning forming conjugate sets is also present within some plagioclase grains, showing evidence of post-emplacement deformation. Evidence of orthopyroxene exsolution from clinopyroxene, and vice versa is common, as well as anhedral inclusions of clinopyroxene in orthopyroxene (Fig. 5B). Inclusions of clinopyroxene are also common in interstitial plagioclase.

Alteration is more prevalent adjacent to the xenolithic sections, such as in RTN020, shown via elevated CaO contents (Fig. 5F). Sericite is present in varying amounts, up to 30% modal abundance in the most altered samples (Fig. 5C). Here the abundance of clinopyroxene also increases to above that of orthopyroxene (50% compared to 10%) whereas the opposite is true for unaltered and uncontaminated samples (Fig. 5C, E-F).

Main Zone Finger

The MZF is characterised by an increased abundance of plagioclase. It is dominated by a mixture of feldspathic pyroxenites and gabbro-norites. Plagioclase is often the dominant mineral and can be present as cumulus, euhedral laths, as well as interstitially (Fig. 6A-D). The increased abundance of plagioclase in this unit is reflected via increased Al_2O_3 and CaO in the bulk rock geochemistry (Fig. 6G-H). The laths are fine- to medium-grained and are orientated randomly throughout the section (Fig. 6A-B). Some albitization of the plagioclase is observed, as well as minor sericitization. Cumulus orthopyroxene is also present but at a lower modal abundance than plagioclase (50% and 30% respectively), and is present either as laths or with a rounded morphology (Fig. 6B, E). It is occasionally altered to tremolite and actinolite (Fig. 6F), with some samples extensively serpentinised. Clinopyroxene is present as an intercumulus phase as well as minor quantities of phlogopite. As with the UP, inclusions of clinopyroxene are common within orthopyroxene. The margins of the cumulus orthopyroxene are often embayed with later growths of interstitial plagioclase or clinopyroxene. Although this unit is generally barren of PGE grade, disseminated BMS are sometimes present (2%), mostly pyrrhotite and minor pentlandite. Phlogopite is commonly associated with the BMS.

Lower Zone Transition

The LZT is distinct in mineralogy from the UP and LZT, shown in both the petrography and bulk rock geochemistry (Fig. 7). It displays a systematic downward trend of pyroxenites into olivine-bearing pyroxenites, into harzburgites, followed by dunites, resulting in a smooth downward increase in MgO to > 40 wt% (Fig. 7E-F). The pyroxenites are characterised by

medium-coarse grained, rounded, cumulus orthopyroxene, variable modal abundances of olivine (0 – 25%), and minor (< 5%) interstitial plagioclase (Fig. 7A). Where plagioclase is present it commonly displays undulose extinction. Orthopyroxene commonly forms adcumulate textures, with slight variations in the abundance of interstitial plagioclase (Fig. 7A). Serpentine veins which crosscut all minerals, and thin zones (< 20 cm) of massive serpentinite are also present, particularly within TN304. Minor phlogopite and clinopyroxene are sometimes present as part of the pyroxenite assemblage. Exsolution of clinopyroxene in orthopyroxene is common (Fig. 7B).

The (feldspathic-) harzburgites contain up to 15% interstitial plagioclase (including sericite), 35% olivine and 45% orthopyroxene. Two phases of sulfide formation are present in the form of disseminated pentlandite/pyrrhotite, and veins of BMS, which can cross cut grain boundaries.

The dunites are coarse grained with adcumulate (with interstitial orthopyroxene) textures (Fig. 7C-D). The cumulus olivine most commonly displays a rounded morphology, are typically fractured, often with small, anhedral inclusions of orthopyroxene. Often, poikilitic textures are present, with olivine forming the chadacrysts, and orthopyroxene the oikocrysts (Fig. 7C). Occasionally, minor interstitial plagioclase is also observed in some portions of the section (approximately 7%), and alteration rims are visible around several of the olivine rims.

Despite being the basal unit in most drillholes, the LZT shows little evidence of local contamination in the bulk rock major element data, never deviating outside of the mineral field (Fig. 7E-F).

Bulk Rock Geochemistry

Major Elements

In addition to the binary major element plots included in Figures 5 -7, downhole bulk rock major element results for the Platreef from a representative drillhole (TN304) are presented in Fig. 8A (see Fig. A2 for additional drillholes). In these plots, intervals dominated by late-stage quartzo-feldspathic veins are omitted. Geochemical parameters were selected to identify key differences between the pyroxenite packages and determine whether these geochemical differences correlate with elevated PGE grade within these units. The contrasting primitive nature of the pyroxenite and norite units are illustrated using Mg#, and CaO/Al₂O₃ ratio is used as a proxy for crustal contamination (Kinnaird, 2005) (Table 1). Pure plagioclase has a CaO/Al₂O₃ ratio of 0.6 while pure orthopyroxene contains negligible quantities of both elements. Therefore, mixtures of the two minerals, forming norites, feldspathic pyroxenites and pyroxenites, which form the majority of the Platreef stratigraphy, should display a similar ratio. Deviations above 0.6, likely due to the presence of clinopyroxene, indicate carbonate (Ca-rich) contamination, whereas values below 0.6 are suggestive of shale (Al-rich) contamination. The downhole major element data shows clearly the juxtaposition between the xenolith-dominated domains and the pyroxenite units, with the xenolith-dominated domains showing increased variation in all major elements,

particularly in CaO, TiO₂ and Mg#, compared to mostly uniform downhole trends for the pyroxenite units. The pyroxenite packages also display contrasting geochemistries between them, most notably in Cr₂O₃, Mg# and Al₂O₃ which will be outlined further below. Key characteristics in the xenolithic domains (X₁₋₃) include highly variable downhole geochemistry (Fig. 8A), elevated CaO/Al₂O₃, TiO₂ and elevated light rare earth elements (LREEs) contents compared to the igneous units (Table 1).

The UP is characterised by relatively uniform downhole geochemistry (Table 1). The bulk geochemistry of the MZF reflects the increased abundance of plagioclase in the norites and gabbro-norites within this unit, showing elevated Al₂O₃ and Na₂O, but depleted Cr₂O₃ compared to the UP and LZT (Fig. 8A). The CaO/Al₂O₃ ratio averages at 0.83, slightly elevated compared to 0.7 in the UP, likely also reflecting the increased plagioclase abundance (Fig. 8A).

The LZT displays a more primitive geochemical signature exemplified by a higher Mg# contents (65 – 80, Table 1), reflecting the increased abundance of olivine. Higher Ni/Cu ratios are also characteristic (Fig. 3). The CaO/Al₂O₃ ratio varies between an average of 0.73, 0.74 and 0.66 in RTN020, TN304 and TN303 respectively, but increases to 1.14 in RTN021 reflecting increased contamination at the contact with calcsilicate xenoliths in X₃ (Fig. A2). It is worth noting that the FeO contents of the LZT is approximately 5 wt% lower than the typical expected concentration for orthopyroxene and olivine dominated sequences elsewhere in the Bushveld (Fig. 9C).

In TN287, located closest to the Transvaal footwall contact, the Platereef has thinned considerably (Table 1) and an additional unit, termed the Hybrid Zone, is identified at the base of the sequence (Table 1, Fig. A2D). This zone is PGE-poor, and heavily contaminated (Table 1). This is influenced by a granite xenolith from 354 – 363 m (producing a large spike in Na₂O, SiO₂ and Al₂O₃), and the underlying BIF footwall. As a result, this zone displays significant Fe enrichment (Fig. 9A), resulting in Mg# steadily decreases from 29 to 19 with increasing proximity to the footwall. High CaO/Al₂O₃ contents (> 8) also alludes to significant carbonate contamination (Table 1, Fig. A2D). Local Fe enrichment due to the Penge footwall is only present in the shallowest portions of the transect (TN287 and TN303) (Fig. 9).

Chromium/MgO ratios have been shown to be useful as proxy for distinguishing between units of CZ (Cr/MgO > 80) or MZ (Cr/MgO 40 – 60) affinity in the Bushveld (Seabrook et al., 2005). At Tweefontein, the UP and LZT typically show Cr/MgO of > 80, and therefore plot within the CZ field as defined by Seabrook et al. (2005) (Fig. 8B). The highest Cr/MgO values (> 400) within these units are likely associated with zones of disseminated chromite. The MZF contains lower Cr/MgO values (40 to 80), displaying a geochemical signature more consistent with the MZ, and reflecting an increased abundance of plagioclase, including cumulus plagioclase, observed in this unit (Fig. 8B).

Where Mg# is higher (> 60) but Cr/MgO plots below the CZ field, and sometimes the MZ field, reflects areas where the MgO content of the magma has been enriched through contamination with dolomitic material. This is shown mostly within the xenolith-dominated units (X_1 - X_3). The Hybrid Zone in TN287 also plots significantly below the MZ field (Fig. 8B), reflecting the depletion in MgO due to the enrichment of CaO, and particularly FeO (Fig. 9) within this unit. Therefore Cr/MgO < 60 may also be used a proxy for xenoliths and footwall contamination at this location.

Trace Elements

Chondrite-normalised (Lodders, 2003) REE profiles for the Platreef at Tweefontein are presented in Fig. 10A-F. The majority of units identified, including the xenolith-domains, can be characterised by an enrichment in LREEs (La-Sm), a negative Eu anomaly, and minor fractionation of heavy rare earth elements (HREEs) (Gd-Lu). These patterns have previously been identified elsewhere in the Platreef (Manyeruke et al., 2005; Holwell and McDonald, 2006; Stephenson, 2018), the GNPA member in the southern sector of the northern limb (Smith, 2014) and the UCZ elsewhere in the Bushveld (Maier and Barnes, 1998).

The xenolith dominated domains (Fig. 10F) have the most fractionated profiles (La/Yb_N 5.0-9.7) and are much more enriched in REEs overall compared to the pyroxenite units. Therefore, local increases in overall REE contents in the pyroxenite units may be interpreted as contamination via these xenolith packages, or the footwall of the same composition. All xenolith domains have a large negative Eu anomaly (Eu/Eu^* 0.645 – 0.831), excluding Unit X_2 in TN304, which has a strong positive anomaly (Eu/Eu^* 1.49), as well as notable HREE enrichment.

The MZF is notably more enriched in REEs in compared to the uncontaminated UP, and is significantly less fractionated (La/Yb_N 2.3-4.8). A positive Eu anomaly (Eu/Eu^* 0.98 – 1.35) and decreased fractionation of HREEs is also characteristic of the MZF, indicating an increased plagioclase content (Table 1).

At the base of the sequence, in the LZT, the most depleted REE compositions are observed, elevated within RTN021 only due to local contamination (Figs. 10A). This is the opposite to the trend observed at Townlands, in the southern sector, where the lower Platreef was found to be more enriched in REEs compared to the upper Platreef (Manyeruke et al., 2005). The LZT contains an Eu negative anomaly (Fig. 10 and Table 1), increasing in size up dip from RTN020 to TN303 (Eu/Eu^* 0.986 – 0.706), suggesting increased contamination of the basal unit with increasing proximity to the footwall contact. Excluding RTN021, it is the most fractionated magmatic unit observed at Tweefontein (La/Yb_N 6.8-9.3, Table 1).

The Hybrid Zone is notably more enriched in REEs than the UP, and contains a stronger Eu negative anomaly (Eu/Eu^* 0.821, compared to 0.933 in the UP in TN287), due interactions with the underlying footwall. Above the Hybrid Zone, the UP is more fractionated, and lacks a strong Eu anomaly suggesting less contamination from the Transvaal sediments. Both units show an enrichment in HREEs from Tm to Lu.

Primitive mantle normalised spidergrams (Taylor and McLennan, 1985) show consistent profiles across the magmatic units, characterised by strong depletions in high field-strength elements (HFSEs) such as Nb and Hf. The MZF is enriched in some LILEs, including Ba and Sr, as well as containing a strong Nb negative anomaly (Fig. 10G). The Hybrid Zone shows a more distinct trend, notably a lack of variation in Ba-U concentrations, and with the largest Nb and Sr negative anomalies. Additionally, all magmatic units at Tweefontein are dominated by $(\text{Nb}/\text{Th})_{\text{PM}} < 1$ and $(\text{Th}/\text{Yb})_{\text{PM}} > 1$, indicative of crustal contamination in mantle derived magmas (Lightfoot and Hawkesworth, 1988; Lightfoot et al., 1990; Ihlenfeld and Keays, 2011). The UP and LZT tend to show the highest variation in $(\text{Th}/\text{Yb})_{\text{PM}}$, often > 30 , in excess of those displayed in many of the MZ and Merensky Reef samples. The MZF and Hybrid Zone are constrained to $(\text{Th}/\text{Yb})_{\text{PM}} < 20$ (Fig. A3).

Mineral Chemistry

The pyroxene compositions of the studied sequence at Tweefontein vary between all three of the magmatic units (Fig. 11). There is a large range of Mg# values from 91.74 in the LZT, to 61.94 in the MZF (Fig. 11B). Pyroxene compositions in the UP sit between those of the MZF and LZT, with an average Mg# of 79.55. Pyroxene mineralogy is dominated by enstatite with minor diopside, with three distinct populations reflecting the different magmatic units in both clino- and orthopyroxene compositions (increasing MgO contents from the UP to LZT). There is a small degree of overlap between the UP and MZF compositions, with both clino- and orthopyroxene from one location in the UP (TN303 595) showing elevated FeO contents. The range in pyroxene compositions is most variable in the MZF, with augite also present as a common clinopyroxene (Fig. 11A). This compositional variability in clinopyroxene, compared to the more restricted orthopyroxene compositions likely reflects more varied textural settings and mineral associations compared to orthopyroxene (Fig. 6). When compared to results from sequences elsewhere in the northern limb, the MZF shows a significant overlap with MZ compositions, whereas the LZT overlaps with LZ compositions. The UP shows a more restricted Mg# contents, but does fall within the range of values for the Platreef at both Overysel and Sandsloot (Fig. 11B).

Discussion

Three geochemically distinct magmatic units have been identified within the Platreef at Tweefontein (Fig. 12). These are listed below:

- *Upper Platreef (UP)*: Homogeneous PGE-rich (feldspathic-) pyroxenite. Little evidence of consistent local contamination or alteration (only present in RTN020, Figs. 5 and A2B) and also contains negative Eu anomalies ($\text{Eu}/\text{Eu}^* 0.92$, Table 1).

- *Main Zone Finger (MZF)*: Barren gabbro-norite, with the increased abundance of plagioclase (Fig. 6) producing lower Cr/MgO values (Fig. 4), positive Eu anomalies and less fractionated REE profiles (Fig. 10).
- *Lower Zone Transition (LZT)*: Barren sequence of pyroxenites, olivine-bearing pyroxenites and increasing occurrences of harzburgites and dunites downhole. Geochemically, it is characterised by elevated Cr contents, increasing Mg# up to > 75 and little evidence of local contamination (Fig. 8A).

The Hybrid Zone, at the contact with the Penge Fm, is a barren “pyroxenite” at the base of TN287. Both significant BIF and carbonate contamination, evident via elevated Fe₂O₃ contents (> 20 wt%) and CaO/Al₂O₃ (> 8) (Table 1, Fig. 9) mean this unit cannot be interpreted as primary magmatic unit and is interpreted to be a hybrid unit, reflecting the intense mixing between the intruding magmas and the Transvaal footwall at the base of the Platreef sequence. Such hybrid lithologies are often observed along the northern limb (Toens, 1954; McDonald et al., 2005; Kinnaird et al., 2005; Pronost et al., 2008) and are often termed parapyroxenites, some of which are also observed in RTN020 (Fig. 12). Bau and Dulski (1996) showed that the Penge Fm contains a strong enrichment in both Y and the HREEs, which may explain the less fractionated REE contents of this zone (Fig. 10), as well as the positive Y anomaly observed (Fig. 6H). However, the low Cr₂O₃ contents of this unit (<0.01, Table 1) compared to the UP suggests this magma pulse may have originally been of MZ affinity; which is also consistent with a significantly lower Mg#, lack of PGE mineralisation and unfractionated REE profile, (Table 1, Fig. 10). As such, the Hybrid Zone in TN287 could be considered to be a highly BIF-contaminated MZF.

Although all of the magmatic units display some similar characteristics, key differences in their mineralogy, bulk rock and pyroxene geochemistry, and most significantly, PGE contents, are observed. As these units do not systematically decrease in Mg#, or increase in incompatible trace elements upward, they cannot be defined as a single differentiating magma column, and so similarly to previous studies in the northern limb (Kinnaird, 2005; Manyeruke et al., 2005; Nyama et al., 2005; Yudovskaya et al., 2011), are interpreted as discrete units emplaced as a series of magma injections. Additionally, this study demonstrates the presence of both a post-Platreef MZ intrusion, and a LZ succession located at the base of the Platreef, rather than as part of a satellite body, for the first time at Tweefontein.

It is generally assumed that the Platreef is a package of pyroxenitic units of CZ affinity, with overlying MZ rocks, and in places, underlying cumulates of the LZ (Yudovskaya et al., 2013). Therefore, it is pertinent to assess the four units at Tweefontein first in this framework. The results show Cr/MgO ratios remain a useful tool for establishing broad trends of CZ and MZ affinity in the Bushveld magmas, but are heavily affected by local contamination processes in the northern limb, due to increased MgO from dolomite contamination. Therefore, other factors including incompatible trace element geochemistry and mineral chemistry must be taken into account.

Elsewhere in the eastern and western limbs of the Bushveld, the UCZ has been characterised by a strong positive Eu anomaly due to the increased abundance of cumulus plagioclase, and LREE enrichment, compared to the LCZ. Typically the MZ can be characterised by a lesser positive Eu anomaly ($\text{Eu}/\text{Eu}^* 2.11$), and an increased enrichment in REEs compared to the CZ (Maier and Barnes, 1998), although the MZ in the northern limb contains a positive Eu anomaly at several locations (Holwell and McDonald, 2006). The Platreef at Sandsloot, Overysel and Townlands contains minor Eu negative anomalies (for example $\text{Eu}/\text{Eu}^* 0.72\text{--}0.93$ at Sandsloot) (McDonald et al., 2005). At Sandsloot this has been attributed to local contamination from the Malmani Dolomite, which has a pronounced Eu negative anomaly, with the Duitschland Fm to the south showing a more moderate negative anomaly (Stephenson, 2018). This is reflective of the trace element compositions observed in the xenolith domains (X_{1-3}) observed at Tweefontein (Fig. 10F). This pattern is repeated in the magmatic units, with the UP containing a negative Eu anomaly (Fig. 10) consistent with varying degrees of contamination. The pyroxene compositions of the UP also overlap strongly with compositions from the Platreef elsewhere in the northern limb (Fig. 11). However, one difference to note at Tweefontein compared with other locations along strike is that there is no evidence of multiple CZ intrusions (e.g., at Townlands; Kinnaird et al. 2005, and Turfspruit; Manyeruke et al., 2005), with only a single, PGE-mineralised pyroxenite unit being identified as the UP.

The MZF has been so called as many of the geochemical and petrological features we describe within this unit overlap with signatures and observations more consistent with the MZ, rather than the Platreef; and as such, implies that this extensive and consistent, yet PGE-barren unit is actually a lateral intrusion of MZ magma. The increased presence of plagioclase and lower Cr/MgO values (40 – 60) are typical MZ signatures seen throughout the wider Bushveld Complex (Seabrook et al., 2005). Previous examples of MZ-like packages in the CZ sequence have been identified in the Platreef at Zwartfontein (Holwell and Jordaan, 2006), and in the GNPA member at Rooipoort (Smith, 2014; Smith et al., 2016), and have been proposed as intrusions of MZ emplaced into at least partly, if not totally crystallised Platreef. Bulk rock data from these examples has been compared to the MZF unit in Figure 6G-H, and whilst showing more elevated Al_2O_3 , there is good correlation between the three in CaO and MgO contents, and all are distinct from the more typical CZ signature in the UP (Fig. 5E-F). The higher bulk Al_2O_3 contents in the MZ and GNPA member compared to the MZF is likely linked to increased accumulation of cumulus plagioclase in these zones. Pyroxene Mg# results from the MZF also overlap significantly with MZ data from elsewhere in the northern limb (Fig. 11), as does the shape of their REE profiles, Eu anomalies and Cr/MgO ratios (Fig. 13). The fact that these units are always barren of PGE is also indicative of a lower MZ affinity. The total REE enrichment in the LGN compared to the MZF is the only significant difference. This enrichment may be due to contamination from the underlying quartzite footwall at Grasvally, as has previously been inferred (Smith, 2014).

With the identification of CZ and MZ packages in the sequence at Tweefontein, the presence of olivine-rich cumulates at the base of the sequence raises the possibility that this represents a unit of LZ rocks, although olivine-bearing lithologies

such as (feldspathic-) harzburgites are common in the Flatreef (Grobler et al. 2019) and some parts of the Platreef at Sandsloot (Holwell et al 2006). A consistent Mg# of > 80 is typically used as a criteria for identifying the LZ in the Bushveld Complex (McDonald et al., 2005). As the LZT has a Mg# consistently increasing to > 75 downhole, it is interpreted to represent a transition from Platreef (CZ) to LZ at Tweefontein, and is named accordingly (Fig. 12). This implies there is no sharp break between the LZ and the Platreef, and instead there appears to be a consistent fractionation up from the base the LZT (Fig. 8A). This is further supported by the presence of dunites and harzburgites at the base of the sequence, which gradually become less olivine-rich as they transition upwards into pyroxenites, and the overlapping pyroxene compositions with the LZ at Overysel and Zwartfontein (Fig. 11).

The LZ was thought to be present in the northern limb as a series of satellite bodies, separate from the main RLS succession, however Yudovskaya et al. (2013) and Maier et al. (2022) have recently identified more consistent LZ sequences elsewhere in the northern limb; however, many of these bodies are present as sills within the footwall, and are not in direct contact with the Platreef intrusions and thus the relative timing between the LZ and the CZ has remained unclear. As with our data from Tweefontein (Fig. 10), Yudovskaya et al. (2013) identified that the underlying LZ was significantly depleted in HREEs, compared to the overlying Platreef at both Sandsloot and Turfspruit. The full transition from Platreef to LZ has not been observed as an uninterrupted sequence in the northern limb, but our clearly transitional data indicate that Tweefontein may preserve an evolving package from LZ into CZ without the discordant intrusive relationships that are more commonly preserved. A similar trend has also been observed at the start of the LZ at Zwartfontein (Kate R. Canham, *pers comm*).

In summary, whilst complicated by the xenolithic rafts, the UP appears to be the only magmatic unit of true CZ affinity within the Platreef stratigraphy at Tweefontein. As such, there appears to be only one package of PGE-fertile magma at Tweefontein. In addition, the base of the sequence sees a transition into LZ rocks through the LZT, and a late intrusion of MZ magma has formed the extensive MZF unit. Thick zones of contaminated/hybrid magmas and calc-silicate/serpentine/hornfels rafts separate the three main magmatic units.

Contamination

The effects of local contamination are all too evident on a metre scale at Tweefontein, particularly around xenoliths and in close proximity to the floor. This local contamination is well documented in the Platreef through bulk rock geochemistry (Barton et al., 1986; Harris and Chaumba, 2001; Ihlenfeld and Keays, 2011) and S and O isotope studies (Sharman-Harris et al., 2005; Holwell and McDonald, 2006; Smith et al., 2016; Keir-Sage et al., 2021). Elsewhere in the northern limb, in both the Platreef and Flatreef, local assimilation with the Transvaal footwall and xenoliths has been linked to sulfide saturation and resultant PGE mineralisation (Buchanan et al., 1981; Gain and Mostert, 1982; White, 1994; Grobler et al., 2019). As a

result, the highest PGE grades have often been found at the base of the Platreef, particularly in up dip areas (Kinnaird et al., 2005), and linked to local contamination events. However, this is not always the case for all locations along strike and due to the often stark variability in the grade and stratigraphic position of mineralisation, debate remains surrounding the trigger for sulfide saturation in the northern limb (Maier et al., 2008; Maier et al., 2021). Some authors argue that either in-situ or pre-emplacement contamination from the Transvaal footwall is required to trigger sulfur saturation (Gain and Mostert, 1982; White, 1994; Lee, 1996; McDonald et al., 2005). However, other processes such as fractional crystallisation and devolatilization of the floor rocks may have played a more important role (Houghton et al., 1974; De Waal, 1977; Maier et al., 2008). More recent studies have also shown that the Platreef contains both crustal and magmatic S isotope signatures (Holwell et al., 2007; Sharman et al., 2013; Sharman et al., 2013), and that the addition of external sulfur from the Transvaal footwall upon emplacement may have acted to dilute PGE grades in some locations (Hutchinson and McDonald, 2008; Ihlenfeld and Keays, 2011; Sharman et al., 2013).

In this study, major element data indicate that local assimilation of the footwall at Tweefontein is not a key control on mineralisation. Economic PGE mineralisation is constrained to the relatively uncontaminated UP at the top of the Platreef sequence, directly underlying the MZ. Occasional spikes in PGE are found in the xenolith-dominated packages directly beneath, likely due to local addition of S and/or volatiles, and resultant scavenging of PGE from the fertile UP magma pulse. Trace element data does indicate a homogenised pre-emplacement contamination event, evident via Nb negative anomalies, LILE enrichment, HFSE depletion and $(\text{Nb}/\text{Th})_{\text{PM}} < 1$ and $(\text{Th}/\text{Yb})_{\text{PM}} > 1$ values. However, this is observed in all identified units regardless of PGE grade at Tweefontein, and indeed throughout the wider Bushveld Complex (Harris and Chaumba, 2001; Wilson and Chunnett, 2006; Ihlenfeld and Keays, 2011), and therefore cannot be linked definitively to the inherent PGE fertility of certain units. Proximity to the Duitschland and Penge footwall contact at Tweefontein also does not appear to exhibit a control on the location of PGE mineralisation, with economic grades consistently held in uppermost Platreef from RTN021, through to TN287, despite results indicating increased local contamination in the MZF, the appearance of the highly contaminated hybrid zone, towards the footwall contact.

Comparisons to the Flatreef and southern Platreef

To the south of Tweefontein, the down-dip extension of the Platreef on the farms Turfspruit and Macalacaskop (Fig. 1B) is referred to as the Flatreef (Grobler et al., 2019; Keir-Sage et al., 2021; Maier et al., 2023; Maier et al., 2021). It is typically characterised as the less disturbed and less contaminated equivalent of the up-dip, near surface and outcropping Platreef, and has been correlated with the UCZ of the western limb of the Bushveld Complex, including equivalents of the UG2, Bastard and Merensky Reefs (Grobler et al., 2019; Keir-Sage et al., 2021; Maier et al., 2021a; Mayer et al., 2021; Keet et al., 2021; Maier et al., 2023). The stratigraphy of the Flatreef was first characterised by Grobler et al. (2019) who described a basal sequence of heavily contaminated, but poor mineralised pyroxenites and norites, followed by the mineralised

interval of pyroxenites, containing the proposed UG2, Merensky and Bastard Reef equivalents. Xenoliths and hornfels of dolomite, shale and quartzite are common in the basal sections. Given that Tweefontein is the adjacent property/farm to Turfspruit (Fig. 1), it allows us to make the first detailed comparison between the deep sections of PGE-mineralised stratigraphy in this sector of the Platreef.

When compared to the Tweefontein section, the Flatreef shows significantly less evidence for carbonate contamination, with CaO and Al₂O₃ contents in the typical CZ field between orthopyroxene and plagioclase (Fig. 14A), overlapping with portions of both the UP and LZT. In terms of trace elements, the lower degrees of contamination result in lower Σ REE contents in the Flatreef, compared to the contaminated Platreef at Tweefontein (Fig. 14B).. These units also differ in terms of their Eu/Eu* contents (Fig. 14B), which could be attributed to a lesser degree of carbonate contamination in the Flatreef, which has instead been shown to be affected by significant amounts of shale contamination at Turfspruit (Sharman-Harris et al., 2005) There is little overlap with the MZF or LZT.

The Platreef at Townlands, located south of Macalacaskop (Fig. 1), has been sub-divided into three domains termed the Upper, Middle and Lower Platreef based on bulk rock geochemistry and S-isotope data (Manyeruke et al., 2005). The sequence displays a reversed differentiation trend, and shows a typical contamination signature of elevated Σ REE and elevated CaO due to increased clinopyroxene contents (Fig. 14A-B). Manyeruke et al. (2005) showed that the Σ REE contents increased downward, from the Upper to Lower Platreef at Townlands, suggesting enhanced contamination of the basal magma fluxes. However, this trend, as well as the reversed differentiation, is not observed at Tweefontein, where the basal LZT is the least enriched in REEs (Fig. 10) and the most primitive in composition. Variations of the Transvaal footwall along the northern limb may explain this in part, with the quartzites of the Timeball Hill Fm more likely to enrich the initial magma influxes in REEs at Townlands, compared to the Penge Fm BIF at Tweefontein.

Overall, the studied sequence at Tweefontein is shown to be influenced more strongly by interactions with the Transvaal footwall than the down-dip Flatreef in the southern sector, but that there is no clear correlation with the defined stratigraphy (including chromitites) of the Flatreef. Additionally, with only one true CZ magma pulse at Tweefontein, the true Platreef magmatic stratigraphy is simpler than the sequence observed at Townlands.

Continuity of the magmatic units

The units identified at Tweefontein vary in thickness considerably between drillholes, particularly the UP. These variations are inferred to be the result of changing footwall topography, with unit thickness generally increasing down-dip where the footwall contact also deepens, as well as the truncation of units where footwall rafts have been entrained into the magmatic sequence, for example below the LZT in RTN021.

The UP displays the most drastic variation in thickness at Tweefontein. Between RTN021 and TN304, a distance of approximately 400 m, its thickness decreases by over 250 m, before increasing in thickness by over 100 m in TN303. As these drillholes dip to the NW these variations can be considered changes in true thickness. This variation is particularly significant as the UP is the only PGE-hosting unit within the Platreef at Tweefontein. Several hypotheses are put forward to account for this lateral variation in thickness.

The first hypothesis relates to the role of the footwall topography. Kinnaird et al. (2005) propose that the Platreef thins above footwall dome structures, and therefore the presence of a domal structure beneath TN304 may account for the thinning of UP. However, a significant change in thickness is not observed in the any other units present in TN304.

Lateral variations in sill thickness during emplacement may also explain the differences observed in all units identified in this study. Mafic sill complexes are thought to propagate as 'magma fingers' (Schofield et al., 2012; Magee et al., 2016), which inherently show variations in thickness and lateral extent, and may or may not coalesce depending on magma supply. The extent of each finger protrusion may also depend on the nature of both the footwall and hanging-wall during emplacement, as well as pressures within the magma body itself (Menand, 2011). The 'magma fingers' model explains the lateral variations observed within most of the Platreef units, with different finger propagations 'pinching out' at different times, accounting for the truncation of the MZF between TN304 and TN303. The presence of xenolith rafts, may also cause finger intrusions to split around more resistant portions for the Transvaal footwall, as with the MZF in RTN020 (Fig. 12), and re-join at a later point. This model accounts for the lesser changes in thickness and local variation, however if the UP magma finger began to pinch out in TN304, we would not expect it to thicken again significantly up dip at TN303, as it is observed to do, unless the variations in thickness are due to a secondary processes, such as magmatic erosion.

A final hypothesis is that the decreased thickness in UP is due to magmatic erosion during the emplacement of the MZ at this location. The nature of the MZ and Platreef contact is generally characterised as a sharp, planar and undulating contact (Kinnaird et al., 2005), and is known to be erosive in nature (Holwell, 2006; Holwell et al., 2005; Holwell and Jordaan, 2006). Cross-cutting of Platreef features, as well as xenoliths of Platreef identified within its hanging-wall, suggest that the contact can be characterised as a magmatic unconformity, with a significant hiatus between Platreef, and later MZ emplacement (Holwell et al., 2005). The degree of Platreef erosion at the contact remains difficult to quantify. However, the MZ can reach up to > 3000 m thickness within the northern limb (McDonald and Holwell, 2011), and therefore the large initial magmatic pulses which formed the lower MZ would likely have the potential to significantly erode the unit below. No PGE assays have been completed on the MZ above TN304 to determine if PGEs were scavenged from the Platreef into the intruding MZ magma, as previously shown at Sandsloot (Holwell et al., 2005). Although, it should be noted that PGEs do not appear to have been scavenged from the UP into the MZF. At Tweefontein, and several other locations

along the northern limb (Yudovskaya et al., 2011; Stephenson, 2018), the most significant Ni-Cu-PGE grades are found in the upper Platreef. Therefore, this model of Platreef erosion during MZ emplacement has important implications for the Ni-Cu-PGE exploration in the northern limb, further outlining the potential for the MZ to have scavenged significant PGE grades from the underlying Platreef during its emplacement.

The xenolith raft domains are a volumetrically significant part of the sequence at Tweefontein, and other locations along the strike of the Platreef. Calcsilicate xenoliths up to 100 m in thickness, and 500 m in length are common in the Platreef and MZ in the northern limb (Kinnaird et al., 2005). Therefore, it is not implausible that several of the metasedimentary interlayers observed may be correlatable between drillholes on such a scale. This may be the case chiefly for unit X₁ in RTN021 and TN304 (Fig. 8A, A2). Here, a general increase in Mg# downhole is observed, followed by a plateau at Mg# 80, corresponding to a basal calcsilicate layer. The thickness of Unit X₁ does vary between RTN021 and TN304, outlining the lateral variations in these rafts zones as well as the magmatic units themselves. It may also be possible, given their thickness, that either at depth or in the up-dip portions of the Platreef, these xenolith domains are connected to the Transvaal footwall itself, however further drilling would be required to verify this.

A 'snap shot' of the process of xenolith raft formation is highlighted in the remote mapping of the area to the NW of Tweefontein Hill (Fig. 2). The geometry of the structure can be explained by an injection of Platreef magma intruding into weakened horizons in the footwall, although the drillholes included in this study do not intersect this area. This injection splits around a more resistant portion of the footwall, and then coalesces, resulting in a portion of the Transvaal being lifted from the footwall, forming a large xenolith raft (Fig. 15E). It is possible that the magma injection exploited a fault as a previous plane of weakness for magma propagation, as shown in the remote mapping (Fig. 2). This process appears to be in the process of repeating itself on the SE corner of the intrusion, with the magma injections being halted and cooling before they could merge. Further ground truthing is required to verify the presence of this structure, as hyperspectral imagery is often only appropriate for surface features and may not always reflect bedrock, as it can be influenced by the presence of weathering products such as calcrete and ferricrete which can be present on the Transvaal ground surface. However, should the presence of large footwall rafts being lifted from the Transvaal footwall during Platreef emplacement be verified, it has important implications for exploration within the region. Typically drilling is halted when Transvaal lithologies have been reached, assuming the footwall has been reached, and no more Platreef magmatic units lie below. These results indicate that packages of inter-fingered Platreef magmas may sit several tens or hundreds of metres below these rafts, and if these magmas are PGE-enriched, high-grade horizons may be missed by halting drilling at shallower depths.

Emplacement model

The magmatic unconformity between the Platreef and the MZ in the northern limb (Holwell et al., 2005) places a time constraint on when interactions between magmas of CZ and MZ affinity must have taken place. Previous studies have argued that mixing between these magma types took place in a staging chamber beneath the emplacement level of the Platreef, likely the plumbing system formed during the emplacement of the LZ (McDonald and Holwell, 2007). As the magmatic units which form the Platreef at Tweefontein are geochemically distinct, a multi-phase emplacement model is proposed. A model for the emplacement as a result of this study is proposed below (Fig. 15) whereby the LTZ is emplaced first in the down dip region at Tweefontein. As the LZT magma pulse represents the emplacement of unmixed LZ magma, it is therefore thought to have been emplaced the earliest, as is assumed for the wider Bushveld Complex (Yudovskaya et al., 2013). The basal contact is unknown from present data but is inferred to be the Penge Fm as it extends down-dip. The UP is then emplaced as a later pulse of PGE-enriched CZ magma, followed by the MZ post-Platreef consolidation forming a magmatic unconformity with the Platreef (Holwell et al. 2005), eroding the upper portions of the UP in some areas, including where drillhole TN304 intersects. The MZF is intruded into the Platreef stratigraphy syn-MZ emplacement, and forms a dyke/sill which crosscuts both the Platreef and Transvaal stratigraphy. Where this injection truncates in unknown at present.

During the emplacement of the Platreef magmas, to the NW of Tweefontein Hill, injections of magma exploited weaknesses in the Transvaal footwall structures to infiltrate and coalesce, forming a large raft (Fig. 15E). This 'snap-shot' is likely the same process which formed many of the larger xenolith (X₁₋₃) observed in the described sequence at Tweefontein and elsewhere in the northern limb.

Stratigraphic comparisons to the wider Platreef and UCZ of the eastern and western limbs

A simplified version of the Platreef stratigraphy at Tweefontein, as presented in this study, has been compared to the accepted general stratigraphy for the wider Platreef in the northern limb, and the UCZ of the eastern and western Bushveld Complex, in Figure 16. As highlighted in the sections above, the two key differences between the stratigraphy at Tweefontein, and the typical Platreef, is the presence of a post-Platreef MZ magma injection, and a sequence of increasingly LZ affinity magmas at the base of the succession, and in contact up CZ-affinity magmas (Figs. 12 and 16). These results demonstrate the complex nature of the Platreef stratigraphy, which can vary significantly even on a scale of < 1 km along strike, and highlights the need for caution when extrapolating known stratigraphies over larger distances in the northern limb.

When comparing the stratigraphy at Tweefontein to the UCZ of the western and eastern limbs, besides the clear differences in the styles and locations of mineralisation shown by previous studies (Armitage et al., 2002; McDonald et al.,

2005; Kinnaird et al., 2005; Yudovskaya et al., 2011), the proximity of the Platreef to the metasedimentary Transvaal footwall also creates significantly more complex contamination signatures compared to the UCZ. This has also been outlined in several past studies on the Platreef along the northern limb (Barton et al., 1986; Harris and Chaumba, 2001; Pronost et al., 2008; Ihlenfeld and Keays, 2011). These contamination signatures, alongside the presence of thick metasedimentary interlayers, not typically found in the UCZ, can make correlating magmatic stratigraphy more difficult in the northern limb. Additionally, the MZ-UCZ contact is not thought to be a magmatic unconformity in the eastern and western limbs (Wagner, 1929; White, 1994; Seabrook et al., 2005; McDonald and Holwell, 2011). Therefore, features such as the MZF identified in this study are unlikely to be found in the eastern and western limb.

Conclusions

This study confirms and provides more detailed evidence that the Platreef at Tweefontein is formed of three magmatic units, often separated and/or split by thick zones of metasedimentary interlayers, and their proximal altered and highly contaminated hybrid lithologies. Each of these units display their own variations in thickness, geochemical signatures, mineralogy and PGE grade. The LZT comprises the start of the Platreef to LZ transition at Tweefontein, the UP the only true CZ magma injection, and the MZF a later MZ intrusion. The presence of these discrete units is further evidence for the episodic, multi-phase emplacement of the Platreef.

Large xenoliths are common within the sequence at Tweefontein, and remote mapping of the area NW of Tweefontein Hill has revealed evidence for the inter-fingering of Platreef magmas into the Transvaal footwall, and uplifting of large xenoliths during magma propagation. This may have implications for drilling campaigns in the region, as if the intruding magma is PGE-bearing this may create economic Platreef horizons beneath these xenolith rafts, which could be easily classed as true footwall given their size.

Local contamination from both the carbonate and BIF footwall is evident, increasing from SW to NE as the Platreef shallows. However, PGE mineralisation is constrained to the uppermost Platreef, and locally in xenolith rafts below this mineralised horizon. This enrichment in PGE is not linked to localised contamination from the underlying Transvaal footwall, as has been suggested for much of the Platreef along the northern limb, and it remains difficult to ascribe a particular parental magma and/or contamination event unique to this unit and its increased PGE fertility. Post-Platreef emplacement processes are evident at Tweefontein, which may have altered the geometry of the mineralised horizon. These include the significant magmatic erosion of the UP during MZ emplacement, along with the intrusion of a MZ sill within the Platreef stratigraphy. Such events are important for exploration models for the area.

646

Acknowledgements:

647 The study was funded by Anglo American as part of the NL4D (Northern Limb in 4D) research consortium, awarded to the
648 University of Leicester, Cardiff University and Camborne School of Mines at Exeter University. The authors wish to thank
649 Anglo American for access to their data from the study location, and samples which were analysed as part of the study.
650 Thin sections were made at the University of Leicester by Dr Annika Burns, and thanks is also given to Dr Leon Hicks, Adam
651 Cox and Lin Marvin for their help during SEM, ICP-MS and XRF analysis at the University of Leicester.

- 654 Armitage, P.E.B., McDonald, Iain., Edwards, S.J., and Manby, G.M., 2002, Platinum-group element mineralization in the
655 Platreef and calc-silicate footwall at Sandsloot, Potgietersrus District, South Africa: Transactions of the
656 Institutions of Mining and Metallurgy, Section B: Applied Earth Science, v. 111.
- 657 Barton, J.M., Cawthorn, R.G., and White, J., 1986, The Role of Contamination in the Evolution of the Platreef of the
658 Bushveld Complex: Economic Geology, v. 81, p. 1096–1104.
- 659 Bau, M., and Dulski, P., 1996, Distribution of yttrium and rare-earth elements in the Penge and Kuruman iron-formations,
660 Transvaal Supergroup, South Africa: Precambrian Research, v. 79, nos. 1–2, p. 37–55.
- 661 Buchanan, D.L., Nolan, J., Suddaby, P., Rouse, J.E., Viljoen, M.J., and Davenport, J.W.J., 1981a, The genesis of sulfide
662 mineralization in a portion of the Potgietersrus limb of the Bushveld complex: Economic Geology, v. 76, no. 3, p.
663 568–579.
- 664 Cawthorn, R. g., 1999, The platinum and palladium resources of the Bushveld Complex: South African Journal of Science, v.
665 95, no. 11/12, p. 481–489.
- 666 Cawthorn, R.G., Barton, J.M., and Viljoen, M.J., 1985, Interaction of floor rocks with the Platreef on Overysel, Potgietersrus,
667 northern Transvaal.: Economic Geology, v. 80, no. 4, p. 988–1006.
- 668 Clarke, B., Uken, R., and Reinhardt, J., 2009, Structural and compositional constraints on the emplacement of the Bushveld
669 Complex, South Africa: Lithos, v. 111, nos. 1–2, p. 21–36.
- 670 Clarke, B.M., Watkeys, M.K., and Reinhardt, J., 2005, Folding of the Rustenburg layered suite adjacent to the Steelpoort
671 pericline: implications for syn-Bushveld tectonism in the eastern Bushveld Complex: South African Journal of
672 Geology, v. 108, p. 397–412.
- 673 Eales, H.V., and Cawthorn, R.G., 1996, The Bushveld Complex: Developments in Petrology, v. 15, no. C, p. 181–229.
- 674 Gain, S.B., and Mostert, A.B., 1982, The geological setting of the platinoid and base metal sulfide mineralization in the
675 Platreef of the Bushveld Complex in Drenthe, North of Potgietersrus: Economic Geology, v. 77, no. 6, p. 1395–
676 1404.
- 677 Grobler, D.F., Brits, J.A.N., Maier, W.D., and Crossingham, A., 2019, Litho- and chemostratigraphy of the Flatreef PGE
678 deposit, northern Bushveld Complex: Mineralium Deposita, v. 54, no. 1, p. 3–28.
- 679 Harris, C., and Chaumba, J.B., 2001, Crustal contamination and fluid-rock interaction during the formation of the Platreef,
680 northern limb of the Bushveld complex, South Africa: Journal of Petrology, v. 42, no. 7, p. 1321–1347.
- 681 Holwell, D.A., 2006, The roles of magmatism, contamination and hydrothermal processes in the development of the
682 Platreef mineralization, Bushveld Complex, South Africa: Cardiff University.
- 683 Holwell, D.A., and Jordaan, A., 2006, Three-dimensional mapping of the Platreef at the Zwartfontein South mine:
684 Implications for the timing of magmatic events in the northern limb of the Bushveld Complex, South Africa:
685 Transactions of the Institutions of Mining and Metallurgy, Section B: Applied Earth Science, v. 115, no. 2, p. 41–
686 48.
- 687 Holwell, D.A., and McDonald, I., 2006, Petrology, geochemistry and the mechanisms determining the distribution of
688 platinum-group element and base metal sulphide mineralisation in the Platreef at Overysel, northern Bushveld
689 Complex, South Africa: Mineralium Deposita, v. 41, no. 6, p. 575–598.
- 690 Holwell, D.A., Armitage, P.E.B., and McDonald, I., 2005, Observations on the relationship between the Platreef and its
691 hangingwall: Transactions of the Institutions of Mining and Metallurgy, Section B: Applied Earth Science, v. 114,
692 no. 4.
- 693 Holwell, D.A., Boyce, A.J., and McDonald, I., 2007, Sulfur isotope variations within the Platreef Ni-Cu-PGE deposit: Genetic
694 implications for the origin of sulfide mineralization: Economic Geology, v. 102, p. 1091–1110.

695 Hutchinson, D., and McDonald, I., 2008, Laser ablation ICP-MS study of platinum-group elements in sulphides from the
696 Platreef at Turfspruit, northern limb of the Bushveld Complex, South Africa: *Mineralium Deposita*, v. 43, no. 6, p.
697 695–711.

698 Ihlenfeld, C., and Keays, R.R., 2011a, Crustal contamination and PGE mineralization in the Platreef, Bushveld Complex,
699 South Africa: Evidence for multiple contamination events and transport of magmatic sulfides: *Mineralium*
700 *Deposita*, v. 46, no. 7, p. 813–832.

701 Ihlenfeld, C., and Keays, R.R., 2011b, Crustal contamination and PGE mineralization in the Platreef, Bushveld Complex,
702 South Africa: Evidence for multiple contamination events and transport of magmatic sulfides: *Mineralium*
703 *Deposita*, v. 46, no. 7, p. 813–832.

704 Keet, J.J., Roelofse, F., Gauert, C.D.K., Grobler, D., and Butler, M., 2021, A comparative study of sulfur isotope variations
705 within the Flatreef and Merensky Reef of the Bushveld Complex: *Canadian Mineralogist*, v. 59, no. 6, p. 1363–
706 1380.

707 Keir-Sage, E., Leybourne, M.I., Jugo, P.J., Grobler, D.F., and Mayer, C.C., 2021, Assessing the extent of local crust
708 assimilation within the Flatreef, northern limb of the Bushveld Igneous Complex, using sulfur isotopes and trace
709 element geochemistry: *Mineralium Deposita*, v. 56, no. 1, p. 91–102.

710 Kinnaird, J.A., 2005, Geochemical evidence for multiphase emplacement in the southern Platreef: *Transactions of the*
711 *Institutions of Mining and Metallurgy, Section B: Applied Earth Science*, v. 114, no. 4.

712 Kinnaird, J.A., and McDonald, I., 2005, An introduction to mineralisation in the northern limb of the Bushveld Complex:
713 *Transactions of the Institutions of Mining and Metallurgy, Section B: Applied Earth Science*, v. 114, no. 4.

714 Kinnaird, J.A., Hutchinson, D., Schurmann, L., Nex, P.A.M., and de Lange, R., 2005, Petrology and mineralisation of the
715 southern Platreef: Northern limb of the Bushveld Complex, South Africa: *Mineralium Deposita*, v. 40, no. 5, p.
716 576–597.

717 Kinnaird, J.A., Yudovskaya, M., McCreesh, M., Huthmann, F., and Botha, T.J., 2017, The Waterberg Platinum Group Element
718 Deposit: Atypical Mineralization in Mafic-Ultramafic Rocks of the Bushveld Complex, South Africa: *Economic*
719 *Geology*, v. 112, no. 6, p. 1367–1394.

720 Le Bas, M.J., and Streckeisen, A.L., 1991, The IUGS systematics of igneous rocks: *Journal of the Geological Society*, v. 148,
721 p. 825–833.

722 Lee, C.A., 1996, A Review of Mineralization in the Bushveld Complex and some other Layered Intrusions, in Cawthorn, R.G.
723 ed., *Developments in Petrology*: Elsevier, p. 103–145.

724 Lightfoot, P., and Hawkesworth, C.J., 1988, Origin of Deccan Trap lavas: evidence from combined trace element and Sr, Nd
725 and Pb-isotope studies: *Earth and Planetary Science Letters*, v. 91, p. 89–104.

726 Lightfoot, P.C., Hawkesworth, C.J., Devey, C.W., Rogers, N.W., and Van Calsteren, P.W.C., 1990, Source and Differentiation
727 of Deccan Trap Lavas: Implications of Geochemical and Mineral Chemical Variations: *Journal of Petrology*, v. 31,
728 no. 5, p. 1165–1200.

729 Lodders, K., 2003, Solar system abundances and condensation temperatures of the elements: *The Astrophysical Journal*, v.
730 591, p. 1220–1247.

731 Magee, C., Muirhead, J.D., Karvelas, A., Holford, S.P., Jackson, C.A.L., Bastow, I.D., Schofield, N., Stevenson, C.T.E., McLean,
732 C., McCarthy, W., and Shtukert, O., 2016, Lateral magma flow in mafic sill complexes: *Geosphere*, v. 12, no. 3, p.
733 809–841.

734 Maier, W.D., and Barnes, S., 1998, Concentrations of rare earth elements in silicate rocks of the Lower, Critical and Main
735 Zones of the Bushveld Complex: *Chemical Geology*, v. 150, p. 85–103.

736 Maier, W.D., de Klerk, L., Blaine, J., Manyeruke, T., Barnes, S.J., Stevens, M.V.A., and Mavrogenes, J.A., 2008, Petrogenesis
737 of contact-style PGE mineralization in the northern lobe of the Bushveld Complex: Comparison of data from the
738 farms Rooipoort, Townlands, Drenthe and Nonnenwerth: *Mineralium Deposita*, v. 43, no. 3, p. 255–280.

739 Maier, W.D., Abernethy, K.E.L., Grobler, D.F., and Moorhead, G., 2021a, Formation of the Flatreef deposit, northern
740 Bushveld, by hydrodynamic and hydromagmatic processes: *Mineralium Deposita*, v. 56, no. 1, p. 11–30.

741 Maier, W.D., Yudovskaya, M., and Jugo, P., 2021b, Introduction to the special issue on the Flatreef PGE-Ni-Cu deposit,
742 northern limb of the Bushveld Igneous Complex: *Mineralium Deposita*, v. 56, no. 1, p. 1–10.

743 Maier, W.D., Barnes, S.J., Godel, B.M., Grobler, D., and Smith, W.D., 2023, Petrogenesis of thick, high-grade PGE
744 mineralisation in the Flatreef, northern Bushveld Complex: *Mineralium Deposita*.

745 Manyeruke, T.D., Maier, W.D., and Barnes, S.J., 2005, Major and trace element geochemistry of the Platreef on the farm
746 Townlands, northern Bushveld complex: *South African Journal of Geology*, v. 108, no. 3, p. 381–396.

747 Mayer, C.C., Jugo, P.J., Leybourne, M.I., Grobler, D.F., and Voinot, A., 2021, Strontium isotope stratigraphy through the
748 Flatreef PGE-Ni-Cu mineralization at Turfspruit, northern limb of the Bushveld Igneous Complex: evidence of
749 correlation with the Merensky Unit of the eastern and western limbs: *Mineralium Deposita*, v. 56, no. 1, p. 59–
750 72.

751 McDonald, I., and Holwell, D.A., 2007, Did lower zone magma conduits store PGE-rich sulphides that were later supplied to
752 the Platreef? *South African Journal of Geology*, v. 110, no. 4, p. 611–616.

753 McDonald, I., and Holwell, D.A., 2011, Geology of the Northern Bushveld Complex and the Setting and Genesis of the
754 Platreef Ni-Cu-PGE Deposit, in *Reviews in Economic Geology: Society of Economic Geologists*, v. 19, p. 297–327.

755 McDonald, I., Holwell, D.A., and Armitage, P.E.B., 2005, Geochemistry and mineralogy of the Platreef and “Critical Zone” of
756 the northern lobe of the Bushveld Complex, South Africa: Implications for Bushveld stratigraphy and the
757 development of PGE mineralisation: *Mineralium Deposita*, v. 40, no. 5, p. 526–549.

758 Menand, T., 2011, Physical controls and depth of emplacement of igneous bodies: A review: *Tectonophysics*, v. 500, nos.
759 1–4, p. 11–19.

760 Nex, P., Kinnaird, J., Jones, B., and Colloty, A., 2008, Platreef rock type definitions and descriptions.:

761 Nex, P.A.M., 2005, The structural setting of mineralisation on Tweefontein Hill, Northern Limb of the Bushveld Complex,
762 South Africa: *Transactions of the Institutions of Mining and Metallurgy, Section B: Applied Earth Science*, v. 114,
763 no. 4, p. 243–251.

764 Nyama, N., Nex, P., and Yao, Y., 2005, Preliminary Petrological Studies of the Platreef on Tweefontein Hill, Bushveld
765 Igneous Complex, South Africa, in *2nd Platreef Workshop, Mokopane 28–30 October 2005*.

766 Pronost, J., Harris, C., and Pin, C., 2008, Relationship between footwall composition, crustal contamination, and fluid–rock
767 interaction in the Platreef, Bushveld Complex, South Africa: *Mineralium Deposita*, v. 43, no. 8, p. 825–848.

768 Schofield, N.J., Brown, D.J., Magee, C., and Stevenson, C.T., 2012, Sill morphology and comparison of brittle and non-brittle
769 emplacement mechanisms: *Journal of the Geological Society*, v. 169, no. 2, p. 127–141.

770 Seabrook, C.L., Cawthorn, R.G., and Kruger, F.J., 2005, The Merensky reef, Bushveld Complex: Mixing of minerals not
771 mixing of magmas: *Economic Geology*, v. 100, no. 6, p. 1191–1206.

772 .

773 Sharman, E.R., Penniston-Dorland, S.C., Kinnaird, J.A., Nex, P.A.M., Brown, M., and Wing, B.A., 2013, Primary origin of
774 marginal Ni-Cu-(PGE) mineralization in layered intrusions: $\delta^{33}\text{S}$ evidence from the Platreef, Bushveld, South
775 Africa: *Economic Geology*, v. 108, no. 2, p. 365–377.

776 Sharman-Harris, E.R., Kinnaird, J.A., Harris, C., and Horstmann, U.E., 2005, A new look at sulphide mineralisation of the
777 northern limb, Bushveld Complex: a stable isotope study: *Applied Earth Science*, v. 114, no. 4, p. 252–263.

778 Smith, J.W., 2014, The nature and origin of PGE mineralization in the Rooipoort area, northern Bushveld Complex, South
779 Africa. PhD Thesis, University of Leicester 1–291 p.

780 Smith, J.W., Holwell, D.A., McDonald, I., and Boyce, A.J., 2016, The application of S isotopes and S/Se ratios in determining
781 ore-forming processes of magmatic Ni-Cu-PGE sulfide deposits: A cautionary case study from the northern
782 Bushveld Complex: *Ore Geology Reviews*, v. 73, p. 148–174.

783 Stephenson, H., 2018, The Platreef magma event at the world-class Turfspruit Ni-Cu-PGE deposit: implications for
784 mineralisation processes and the Bushveld Complex stratigraphy. PhD Thesis, Cardiff University.

785 Taylor, S.R., and McLennan, S.M., 1985, *The Continental Crust: Its Composition and Evolution*: Blackwell Scientific
786 Publications (Oxford), 312 p.

787 Toens, P.D., 1954, Hybrid rocks in the floor of the Bushveld Complex: *Transactions of the Geological Society of South Africa*,
788 v. 57, p. 39-60.

789 Wagner, P.A., 1929, *The platinum deposits and mines of South Africa*. 1973 edition.: Struik (Pty), Ltd, 338 p.

790 Walraven, F., Armstrong, R.A., and Kruger, F.J., 1990, A chronostratigraphic framework for the north-central Kaapvaal
791 craton, the Bushveld Complex and the Vredefort structure: *Tectonophysics*, v. 171, nos. 1–4, p. 23–48.

792 White, J.A., 1994, The Potgietersrus prospect—geology and exploration history, in *South African Institute of Mining and
793 Metallurgy Symposium Series – Proceedings of the 15th Congress of the Council of Metallurgical and Mining
794 Institutions*, Volume 3, p. 173–181.

795 Wilson, A., and Chunnett, G., 2006, Trace element and platinum group element distributions and the genesis of the
796 Merensky Reef, Western Bushveld Complex, South Africa: *Journal of Petrology*, v. 47, no. 12, p. 2369–2403.

797 Yudovskaya, M., Kinnaird, J., Naldrett, A.J., Mokhov, A.V., McDonald, I., and Reinke, C., 2011, Facies variation in PGE
798 mineralization in the Central Platreef of the Bushveld Complex, South Africa: *Canadian Mineralogist*, v. 49, no. 6,
799 p. 1349–1384.

800 Yudovskaya, M.A., Kinnaird, J.A., Sobolev, A.V., Kuzmin, D.V., McDonald, I., and Wilson, A.H., 2013, Petrogenesis of the
801 Lower Zone olivine-rich cumulates beneath the Platreef and their correlation with recognized occurrences in the
802 Bushveld Complex: *Economic Geology*, v. 108, no. 8, p. 1923–1952.

Figure Captions

Fig. 1. A) Map showing the location of the Bushveld Complex in South Africa. The northern limb is highlighted in red. B) Geological map of the northern limb, adapted from Ihlenfeld and Keays (2011). Location of study area is shown in the black box. Black dashed lines represent farm boundaries. C) Simplified geological map of the Tweefontein area after Nex (2005). Collars of drillholes included in study are shown. Legend is the same as B. Layering within the Malmani Dolomite is shown via the blue lines. D) Photograph looking to the SW towards Mokopane from the top of Tweefontein Hill. Approximate location of drillhole collars and Tweefontein-Turfspruit boundary are marked in red.

Fig. 2. Results from the remote mapping at Tweefontein Hill. A) Satellite image of the mapping area; B) Aeromagnetic results from the mapping area. The strongest signals (highlighted in pink) are associated with the magnetite-rich banded iron formations of the Penge Fm; C) RGB image produced from the hyperspectral scanning, with mapping of lithological contacts and structures annotated; D) Updated geological map of the Tweefontein Hill area following the results of the remote mapping (key is the same as Fig. 1).

Fig 3. Downhole Pt and Pd grades, Pt/Pd and Ni/Cu ratios for all drillholes and identified Platreef units. Pd grade (red) not always present for xenolith-raft domains (X_{1-3}). X axis not shown for Pt and Pd grades. UP = Upper Platreef, MZF = Main Zone Finger, LZT = Lower Zone Transition, Hybrid = Hybrid Zone at base of TN287 at contact with the Penge Fm. X_{1-3} represent the metasedimentary interlayers.

Fig. 4. Drill core photographs of the units identified within the Platreef stratigraphy at Tweefontein. Photos provided by Coreshed on behalf of Anglo American. For scale the core width = 7cm; A) Pyroxenite from the Upper Platreef (UP) in RTN021. Blebby sulfide present; B) Gabbronorite from the Main Zone Finger (MZF) from RTN020. This unit is barren of sulfides; C) Barren pyroxenite from the Platreef-Lower Zone Transition (LZT) in TN304. Note the change in grain size from the UP; D) Barren dunite from the base of TN304, forming the bottom of the observed LZT sequence; E) An example (X_2 from RTN020) of the metasediments and calcsilicates which form the metasedimentary interlayers between the magmatic units at Tweefontein. Drillcore images of TN287 were not available.

Fig. 5. Thin section photomicrographs of silicate and sulfide textures, and bulk rock major element data from the Upper Platreef (UP). Images A-D in XPL A) Unaltered feldspathic pyroxenite (RTN021 441.1) with rounded, fractured opx oikocrysts within a plagioclase chadacryst; B) Feldspathic pyroxenite (RTN021 631) with minor sericitization and cpx inclusions within the opx; C) Altered pyroxenite (RTN020 597) displaying alteration of opx to tremolite and undulose extinction in interstitial plagioclase. Extensive sericitization and disseminated BMS throughout. The grain boundaries of the remaining primary orthopyroxenes are embayed and the exsolution of clinopyroxene is evident on their margins.; D)

Unaltered feldspathic pyroxenite (TN303 614) with opx oikocrysts within plagioclase chadacrysts. Minor phlogopite also present; E) Al_2O_3 vs MgO for the UP and Hybrid Zone in TN287; F) CaO vs MgO for the UP and Hybrid Zone in TN287. All data shown has < 5 wt% LOI. Typical CZ compositions (plag-opx) and contamination vectors are shown. Mineral endmember compositions from Stephenson (2018). Abbreviations: opx = orthopyroxene, plag = plagioclase, cpx = clinopyroxene, trm = tremolite, phl = phlogopite, ser = sericite, ol = olivine, BMS = base metal sulfides).

Fig. 6. Thin section photomicrographs of silicate textures in the Main Zone Finger (MZF). Images A-F in XPL. A-B) Unaltered gabbroite (RTN020 762.5) dominated by cumulate plagioclase (> 50%) over anhedral opx and cpx. The pyroxenes commonly show embayed margins due to growth around the plagioclase grains. Annealed textures between some plagioclase grains are visible in B (bottom right). C) Norite with extensive granoblastic texture (TN304 947). Primary opx and minor phlogopite also present; D) Pyroxene dominated by up to 50% interstitial plagioclase (TN304 1020). Exsolution of cpx within opx and anhedral interstitial cpx present, replacing opx in places (bottom right); E) Gabbro-norite (TN304 1020) with elongate plagioclase laths, often with embayed margins, and interstitial plagioclase and minor cpx; F) Heavily altered pyroxenite (TN303 815) dominated by sericite, tremolite, cpx and opx; G) Al_2O_3 vs MgO for the MZF, Main Zone from elsewhere in the northern limb, and Lower Gabbro-norite (LGN) at Grasvally; H) CaO vs MgO for the MZF, Main Zone and LGN. All data shown has < 5 wt% LOI. Typical CZ compositions (plag-opx) and contamination vectors are shown. Mineral endmember compositions from Stephenson (2018). Main Zone data from elsewhere in the northern limb from Holwell (2006), and LGN, from the GNPA member, Grasvally data from Smith (2014). For abbreviations see Fig. 7.

Fig. 7. Thin section photomicrographs of silicate textures and bulk rock major element data from the Lower Zone Transition (LZT). Images A-E in XPL. A) Pyroxenite with rounded cumulate opx and minor interstitial plagioclase (RTN020 1227). Sulfide inclusions present within most phases; B) Olivine-bearing pyroxenite (TN304 1098). Olivine appears to be interstitial to the coarser cumulate opx, and displays anomalous interference colors; C) Dunite composed of only olivine and opx (TN304 1151). Here the opx appears to be interstitial to the olivine and sulfide inclusions are common in both phases; D) Coarse grained dunite (TN304 1143). Sample displays an adcumulate texture dominated by > 90% olivine. Magnetite veins are present within the olivines as well as disseminated, interstitial BMS; E) Al_2O_3 vs MgO; F) CaO vs MgO. All data shown has < 5 wt% LOI. Mineral endmember compositions from Stephenson (2018). For abbreviations see Fig. 7.

Fig. 8. Downhole major element results for Tweefontein drillholes. A) Downhole lithology column and major element profiles for TN304. See Fig. A1 for profiles of the remaining drillholes included in study. Unit boundaries are marked in red, with names in black. All units in wt %. Key for lithology log at bottom; B) Downhole Cr/MgO (log scale) for RTN021, RTN020, TN304, TN303 and TN287 with unit boundaries marked out. Critical Zone and Main Zone ranges from Seabrook et al.

861 (2005). UP = Upper Platreef, MZF = Main Zone Finger; LZF = Lower Zone Transition and Hybrid = Hybrid Zone at base of
862 TN287 at the contact with the Penge Fm.

863 Fig. 9. Bulk rock FeO vs MgO for Upper Platreef, Main Zone Finger and Lower Zone Transition. Elevated FeO contents
864 highlights BIF contamination; A) Upper Platreef and Hybrid Zone from base of TN287; B) Main Zone Finger; C) Lower Zone
865 Transition. All data shown has < 5 wt% LOI to remove highly altered samples. Mineral endmember compositions from
866 Stephenson (2018) and Harris and Chaumba (2001).

867 Fig. 10. Trace element results for the Platreef at Tweefontein. A-F) Chondrite normalised rare earth element (REE)
868 spidergrams. Normalising factors from Lodders (2003). A) RTN020 B) RTN021 C) TN304 D) TN303 E) TN287 F) Xenolith raft
869 domains X₁-X₃; GG) Primitive mantle normalised trace element patterns for all Platreef units identified at Tweefontein.
870 Values shown are average compositions per unit (UP n=384, MZF n=126, LZF n=141, Hybrid n=39). Normalised factors from
871 Taylor and McLennan (1985). UP = Upper Platreef, MZF = Main Zone Finger; LZF = Lower Zone Transition and Hybrid =
872 Hybrid Zone in TN287 at the contact with the Penge Fm.

873 Fig. 11. Pyroxene mineral chemistry from the Platreef at Tweefontein, the Lower Zone, Main Zone and Platreef from
874 elsewhere in the northern limb. A) Ternary diagram for Wo, En and Fs compositions. Fields for Main Zone data shown in
875 light grey. B) Box plot showing Mg# for Tweefontein orthopyroxenes, compared to the Lower Zone, Main Zone and the
876 Platreef elsewhere in the northern limb. The straight line in the box shows the median, and the black circle shows the
877 mean value. Additional data from Holwell (2006), Yudovskaya et al. (2013) and Smith (2014).

878 Fig. 12. Lithology logs for all drillholes included in study. The identified magmatic units, and their correlations between
879 each drillhole, are outlined in red. Metasedimentary interlayers (X₁, X₂ and X₃) are combined and shown in grey.

880 Fig. 13. Comparison of the MZF to the LGN of the GNPA member and the MZ elsewhere in the northern limb. LGN data
881 from Smith (2014) and MZ data from Holwell (2006). A) Rare earth element spidergram. Normalised factors from Lodders
882 (2003); B) Eu/Eu* box plot. The straight line in the box shows the median, and the black circle shows the mean value.; C)
883 Cr/MgO box plot with CZ and MZ fields from Seabrooke et al. (2005) outlined. Cr/MgO values < 40 are due to local
884 contamination, reducing both Cr and MgO contents. This process is also evident in the hybrid zone in TN287 (Fig. 4B).
885 Legend is the same for A, B and C.

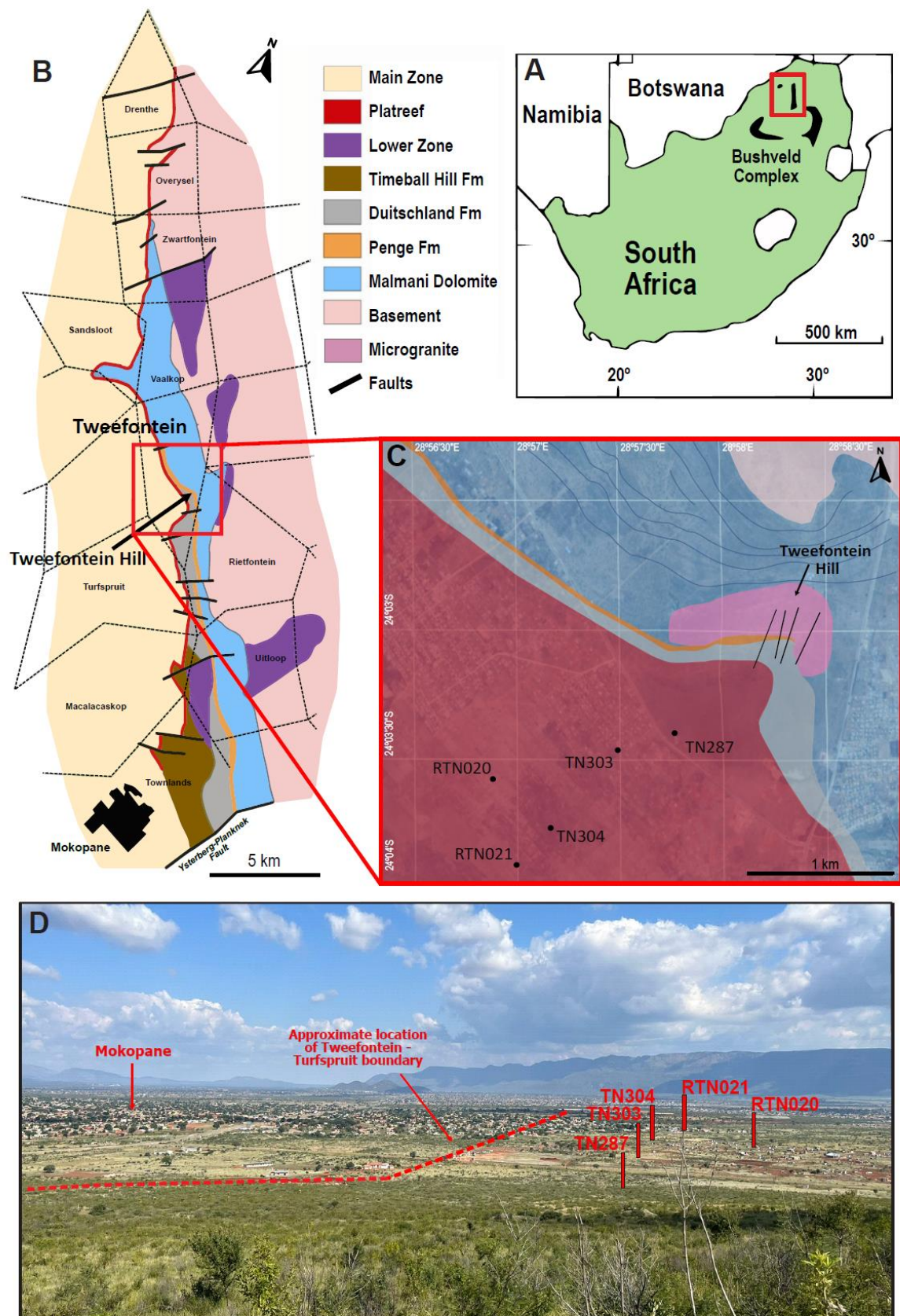
886 Fig. 14. Comparison of the Platreef at Tweefontein to the Flatreef, and Platreef at Townslands in the southern sector of the
887 northern limb. A) Al₂O₃ vs CaO. Vector for increasing CaO (via contamination from carbonates) shown; B) Chondrite
888 normalised rare earth element (REE) spidergrams. Data shown is the average composition. Normalising factors from

889 Lodders (2003); C) Primitive mantle normalised trace element patterns. Normalised factors from Taylor and McLennan
890 (1985). Townlands data from Manyeruke et al. 2005, and Flatreef data from Maier et al. 2021 and Keir-Sage et al. 2021. UP
891 = Upper Platreef, MZF = Main Zone Finger, LZT = Lower Zone Transition and Hybrid = Hybrid zone at base of TN287.

892 Fig. 15. A-D) Emplacement model for the Platreef at Tweefontein (not to scale). See text for full description. E) Model for
893 xenolith raft formation at Tweefontein Hill. Two injections of Platreef magma into the Transvaal footwall coalesce,
894 resulting in a portion of the Transvaal being lifted from the footwall, forming a large raft. Sulfide liquid may also sink below
895 the raft due to its higher density, potentially creating high-grade zones beneath these raft domains.

896 Fig. 16. The stratigraphy of the Rustenburg Layering Suite, including the northern limb at Tweefontein as identified in this
897 study, compared to the RLS of the wider northern limb and in the eastern and western limbs (not the scale, modified after
898 Stephenson (2018) and McDonald and Holwell (2011)). The Ni-Cu-PGE mineralisation horizons in all locations are
899 highlighted in red.

900



901

902 **Figure 1**

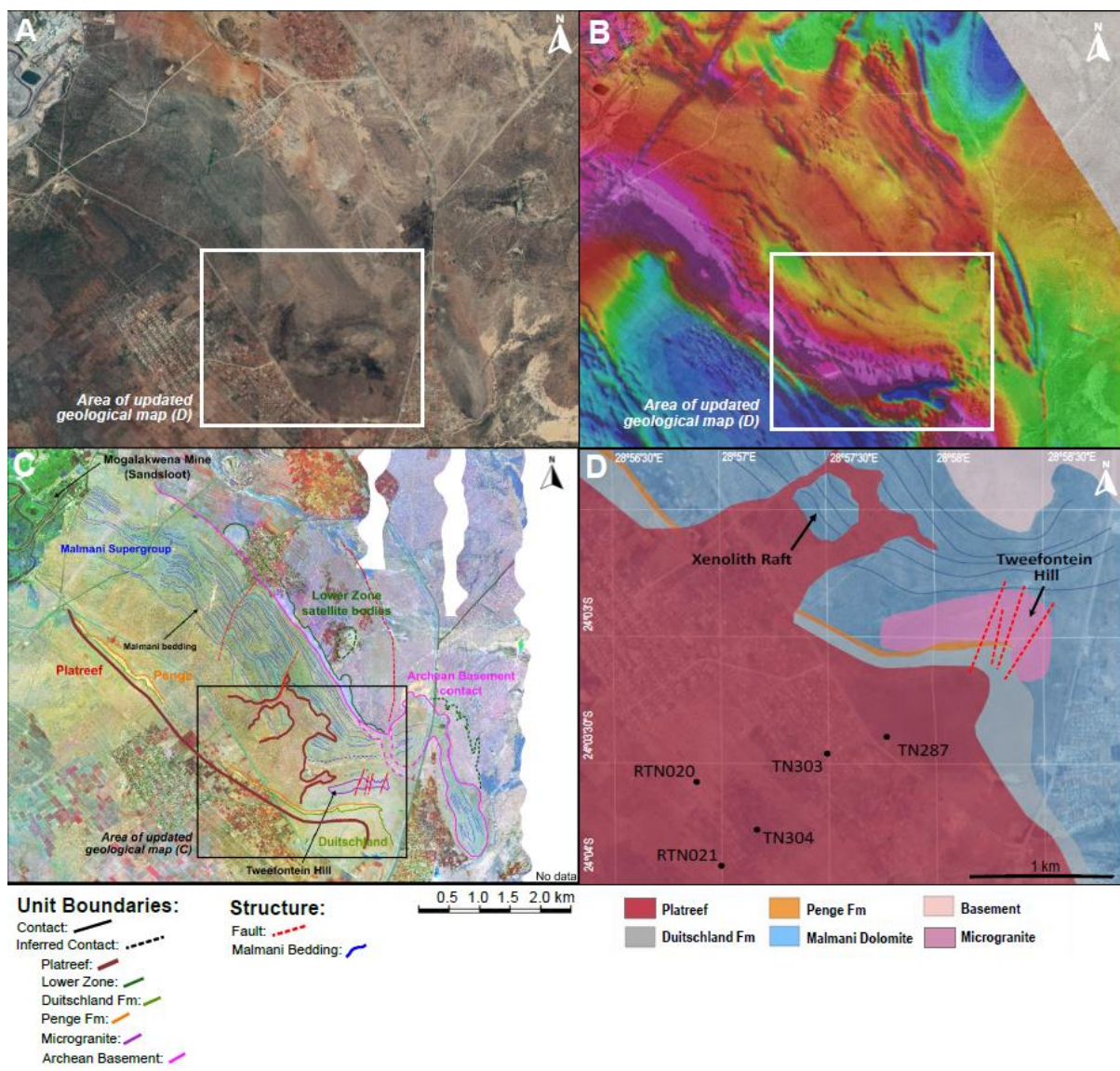


Figure 2

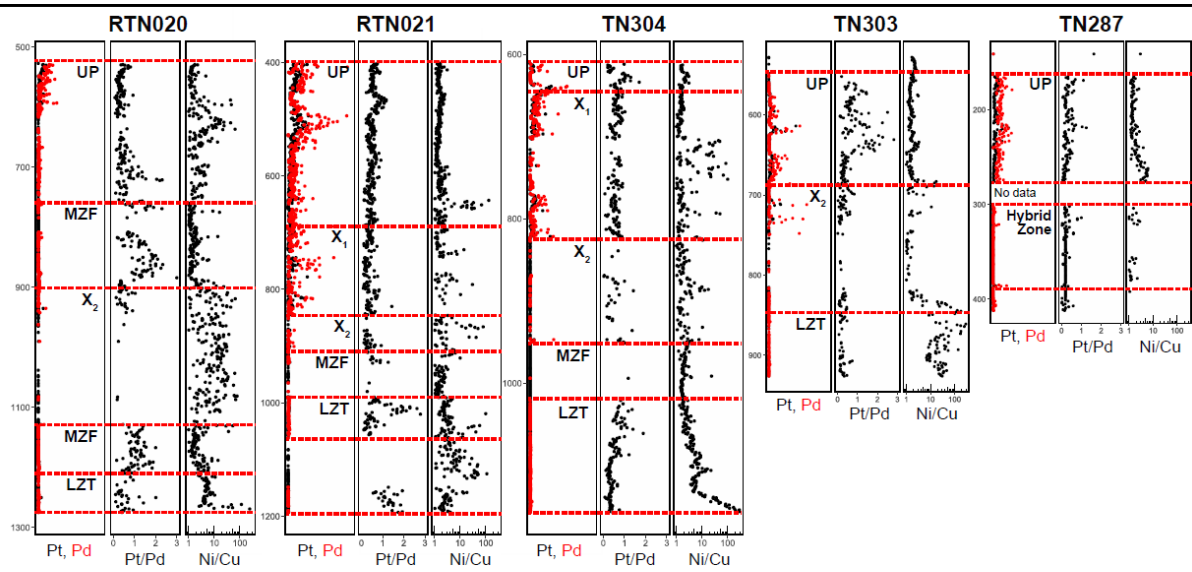
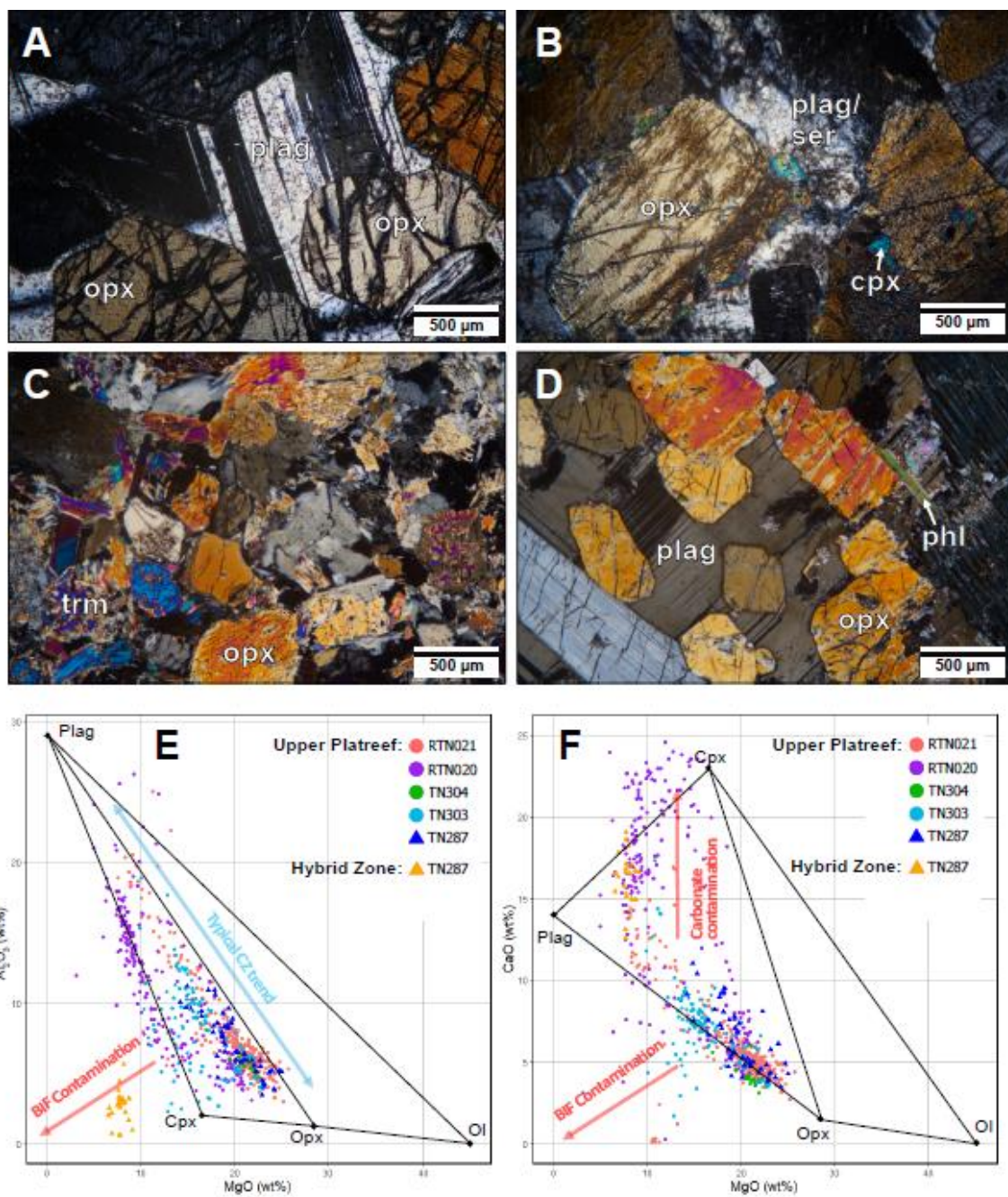


Figure 3



Figure 4



911

912 **Figure 5**

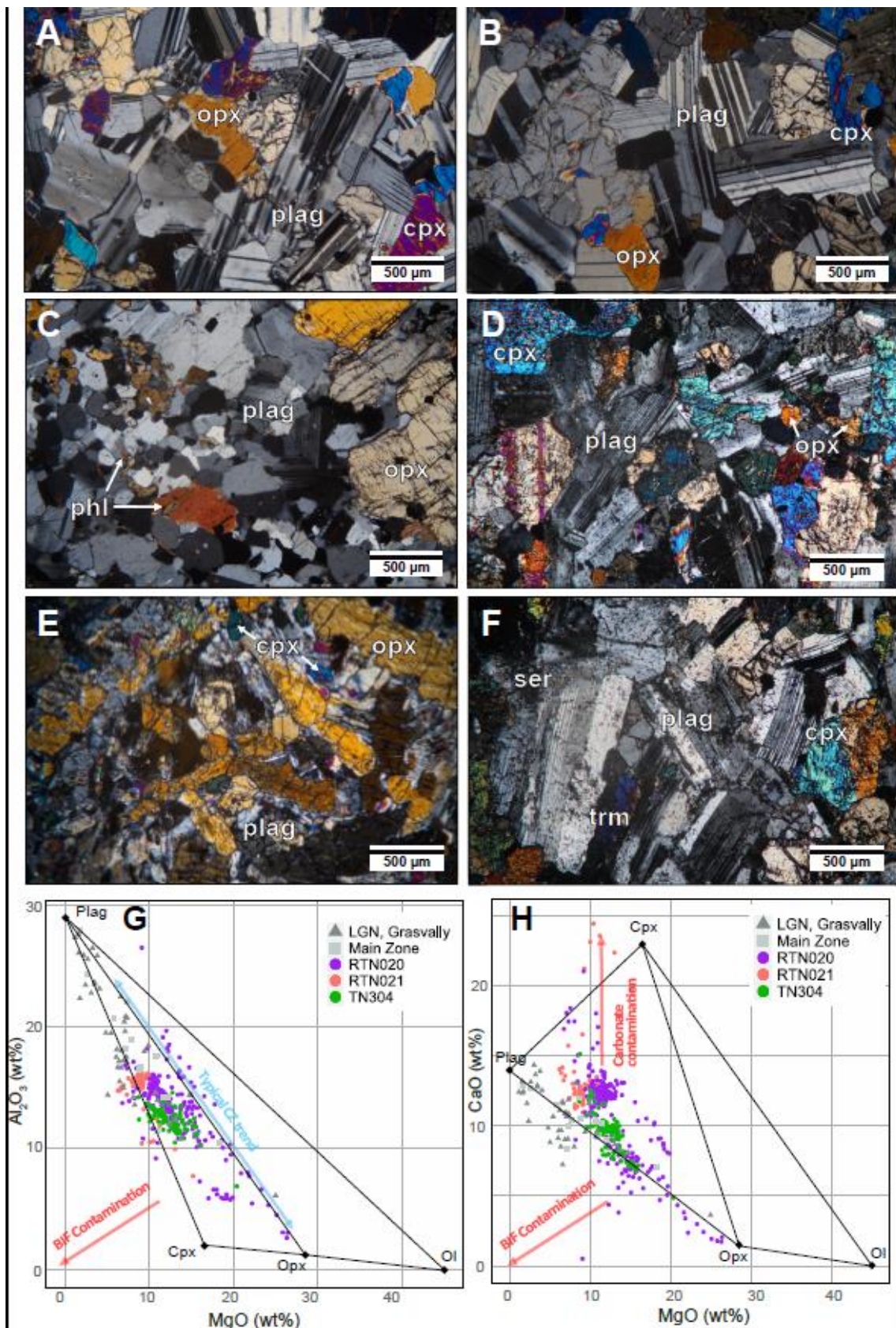


Figure 6

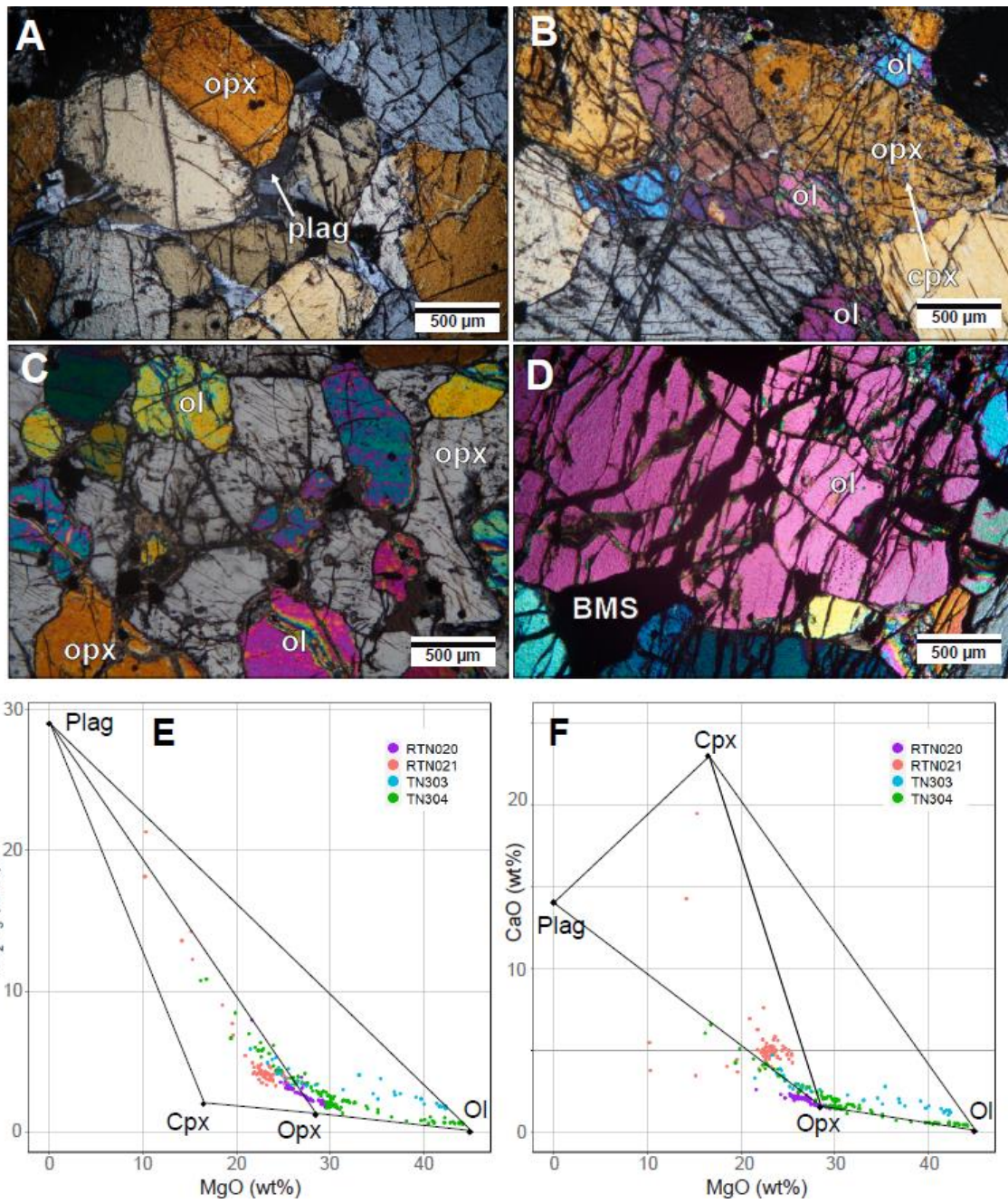


Figure 7

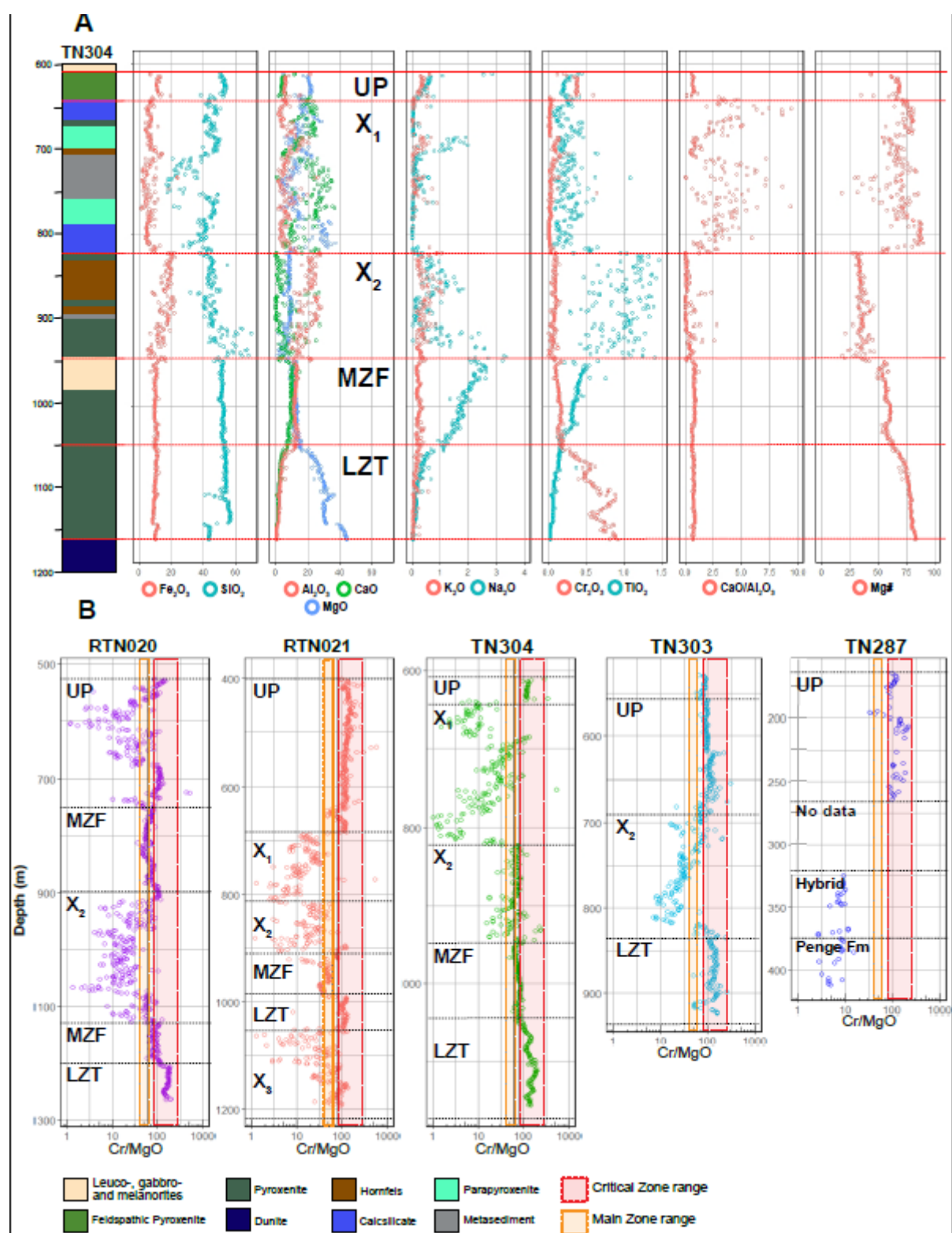


Figure 8

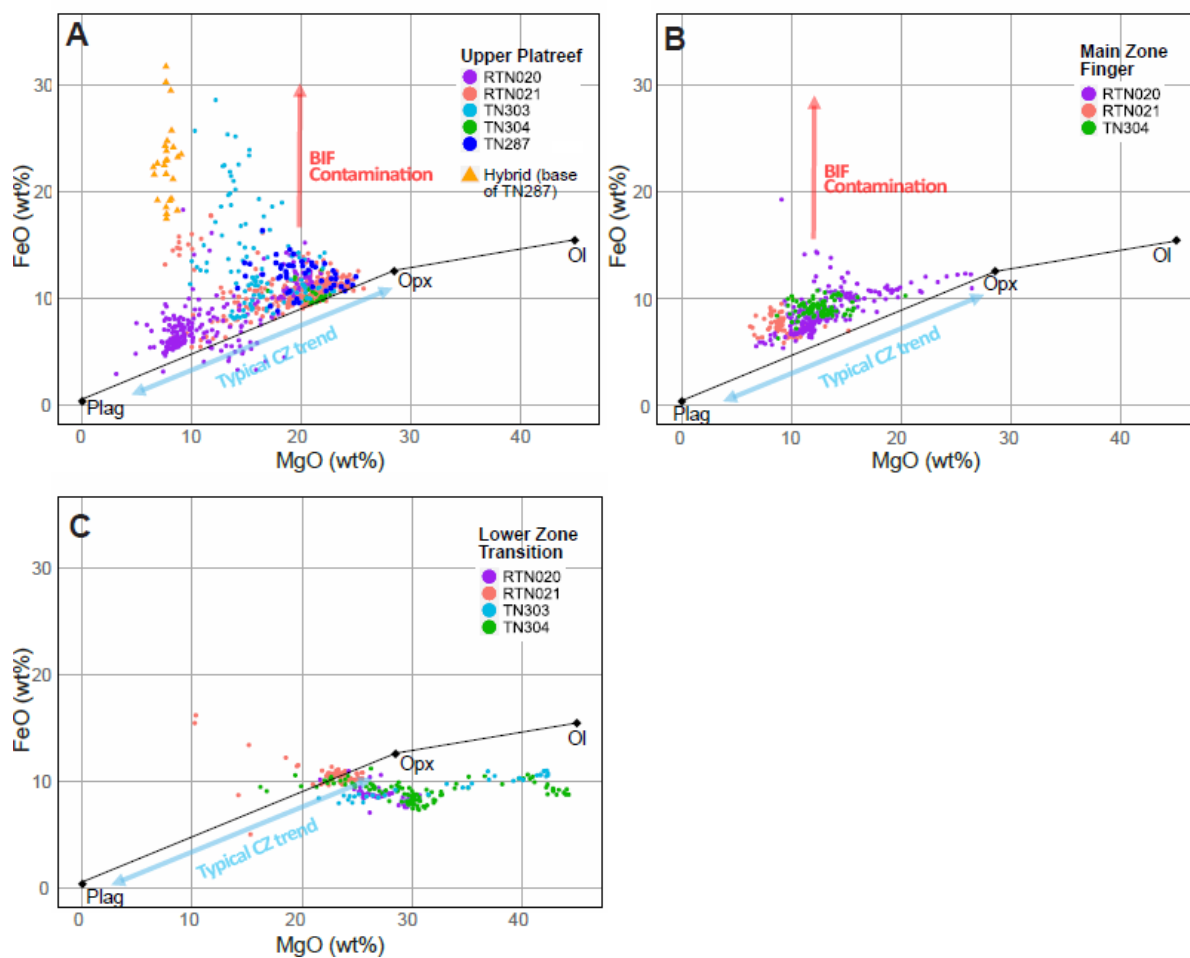


Figure 9

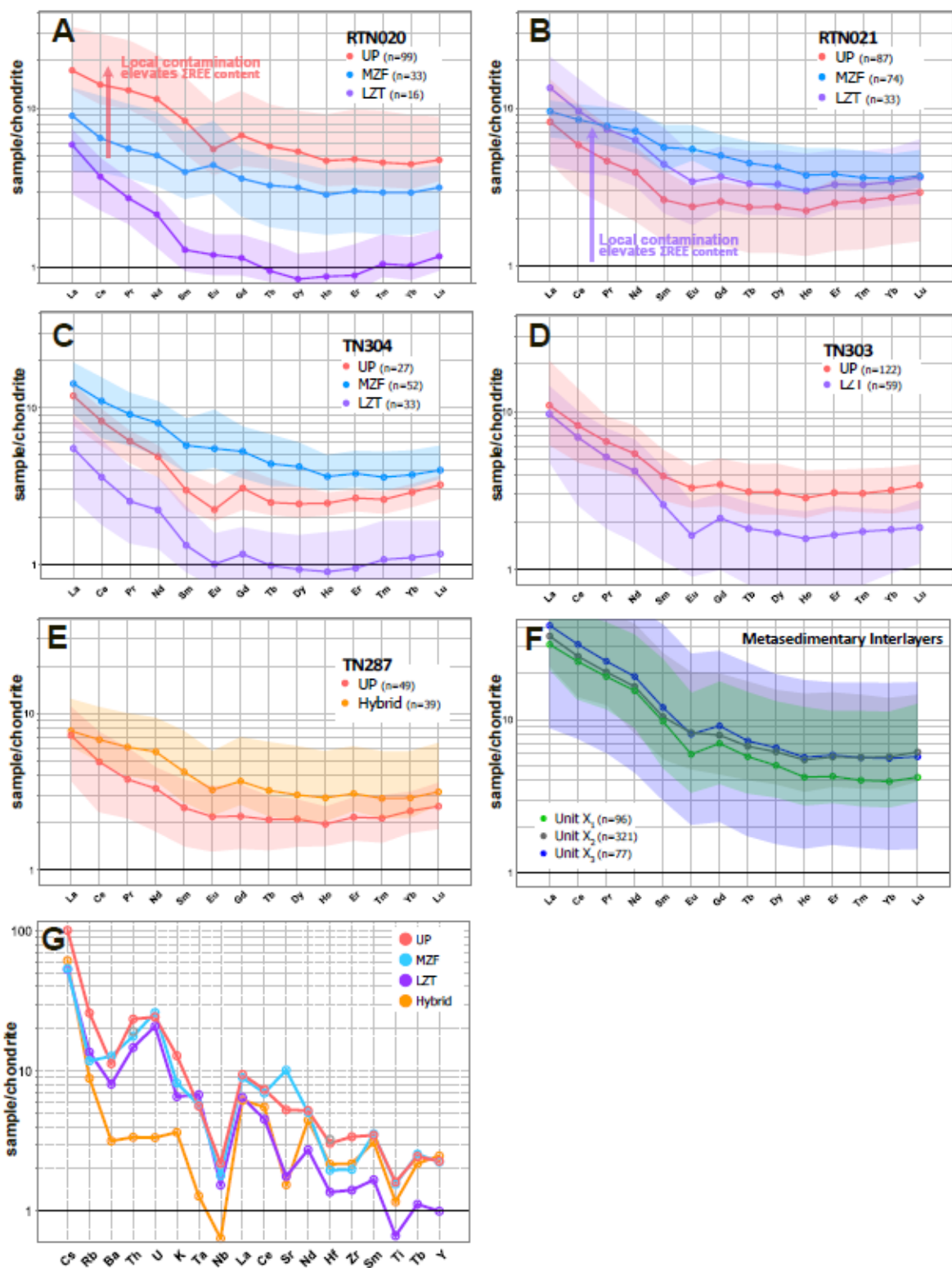


Figure 10

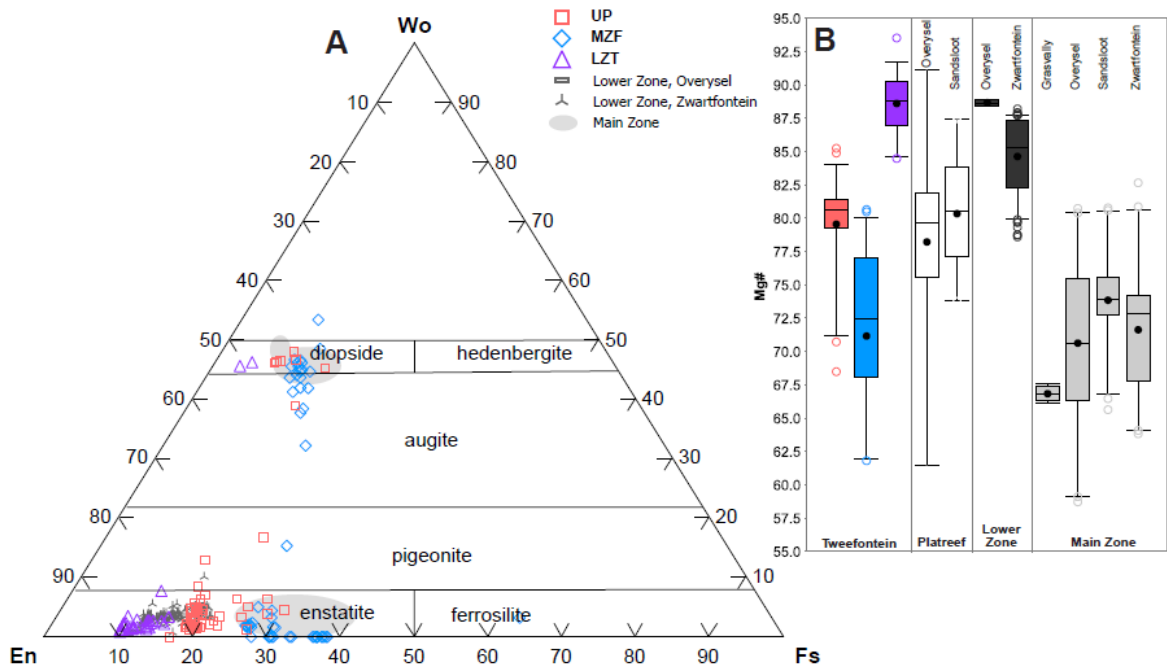


Figure 11

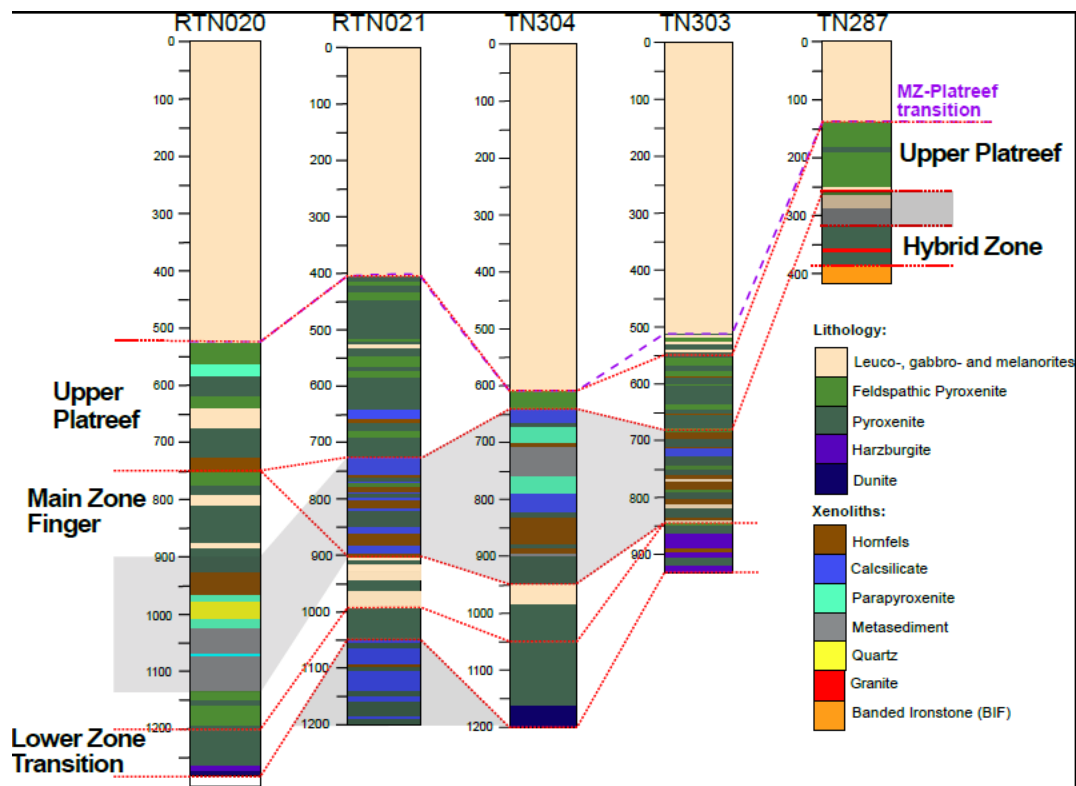


Figure 12

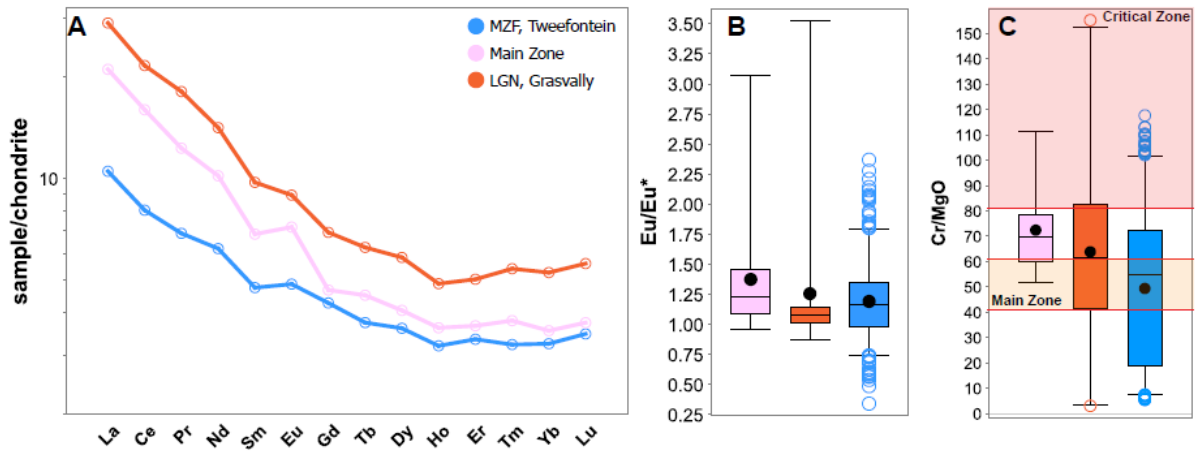


Figure 13

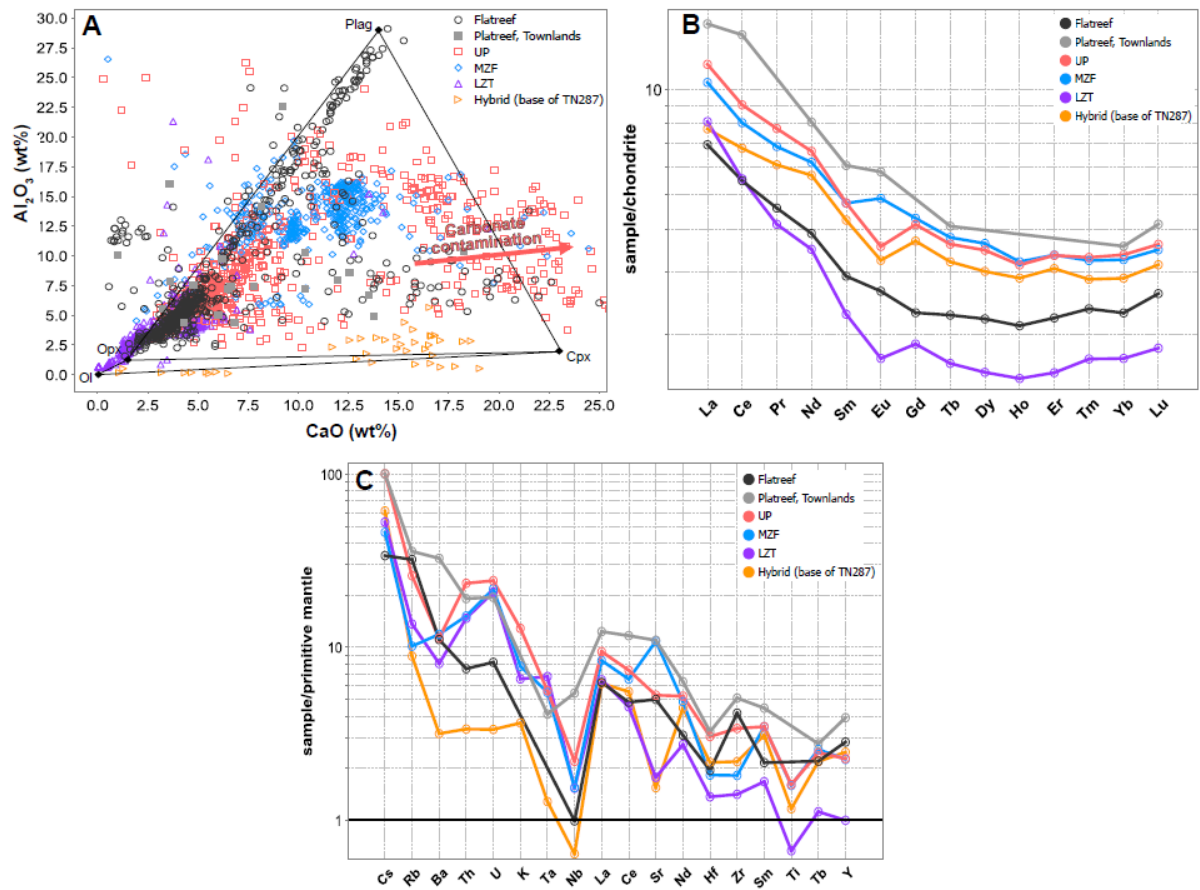


Figure 14

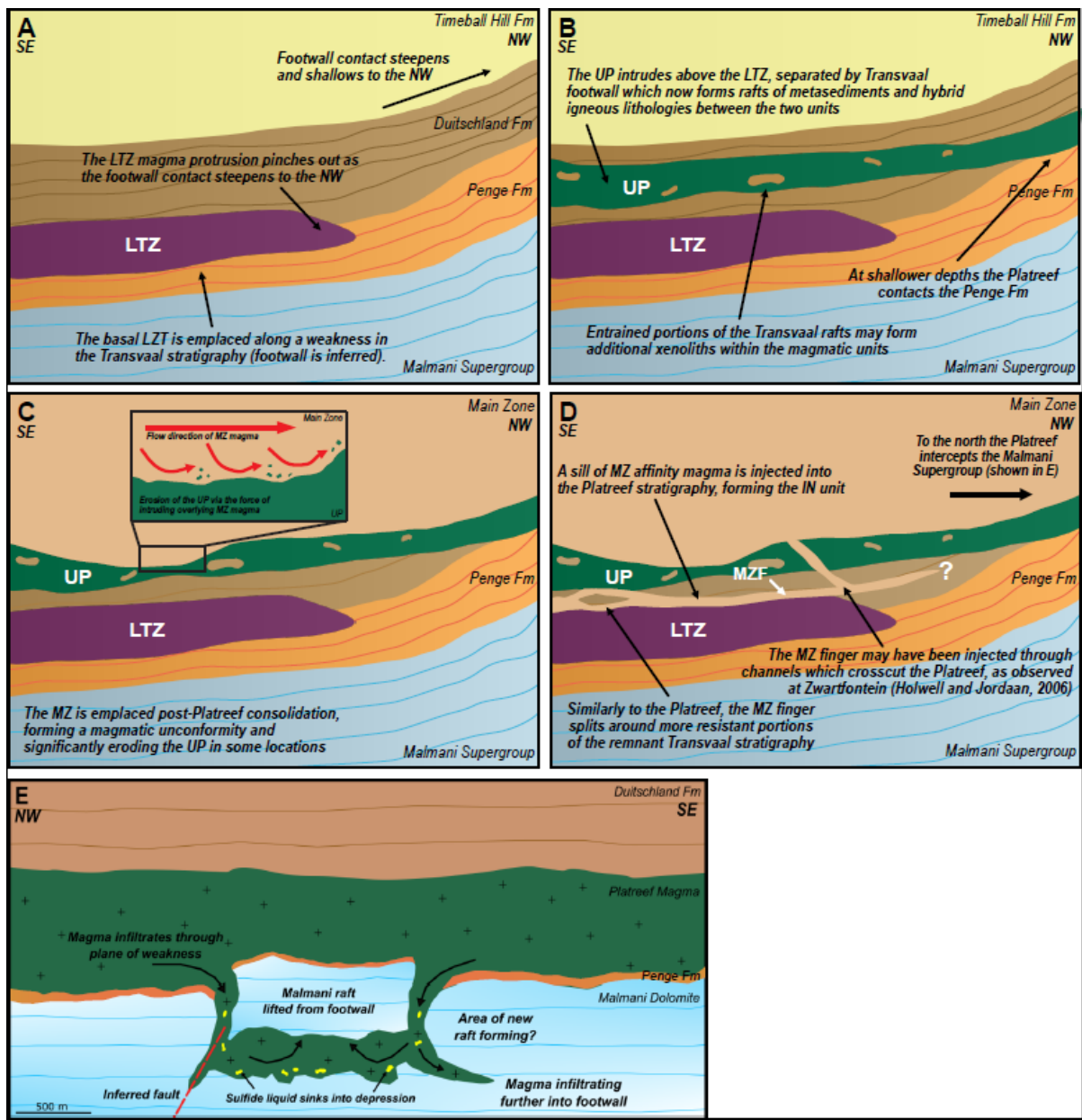


Figure 15

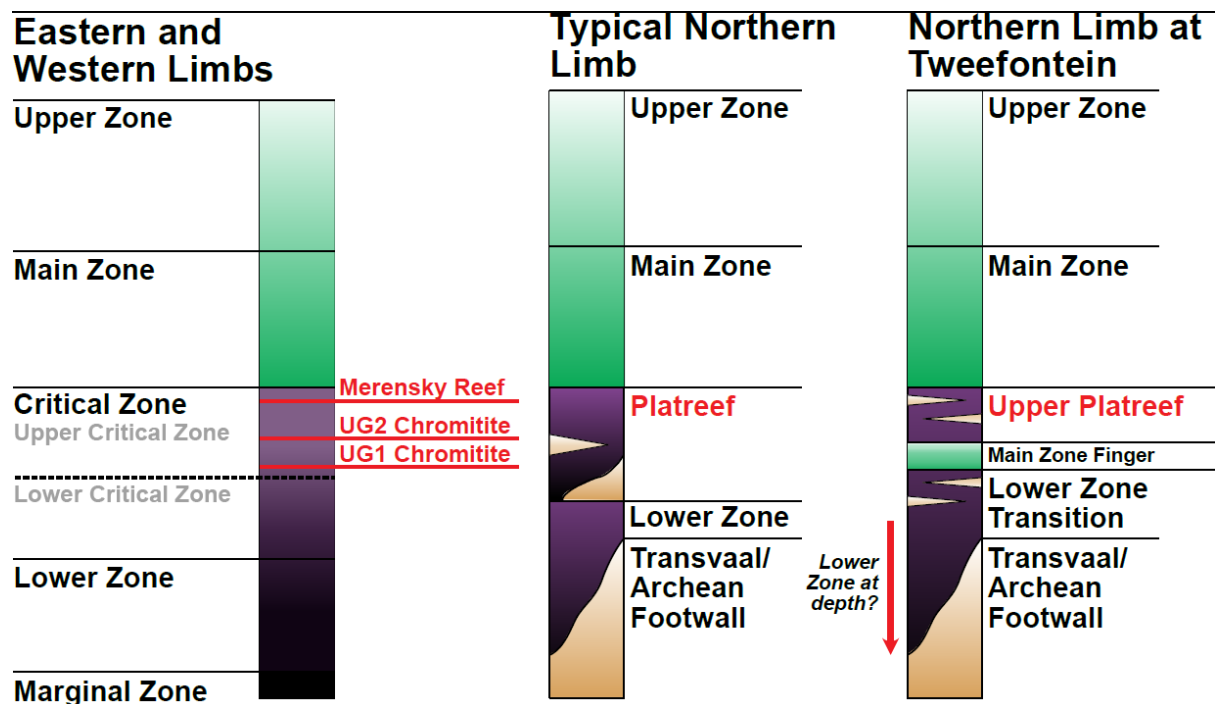


Figure 15

943

Tables

944

945

Table 1. Bulk rock geochemical characteristics, lithologies and associated PGE grades of each Platreef magmatic unit identified at Tweefontein. Based on data supplied by Anglo American. Xenolith raft domains (X₁₋₃) have been excluded as they are not the focus of this study.

Unit	Drillholes	Thickness m	Logged lithologies	Mg#	CaO/Al ₂ O ₃	Cr ₂ O ₃ wt%	Na ₂ O wt%	La/Sm	Gd/Yb	Eu/Eu*	PGE grade
Upper Platreef (UP)	RTN021, RTN020, TN304, TN303, TN287	26 - 289	Pyroxenites and feldspathic pyroxenites	65-70	0.7 ¹	0.25 - 0.5	<1	5.32	1.21	0.92	High
Main Zone Finger (MZF)	RTN021, RTN020, TN304	69 – 217 ²	Norites, gabbro-norites and feldspathic pyroxenites. Minor pyroxenites	40-65	0.83	<0.25	1-1.75	2.53	1.40	1.19	Barren
Lower Zone Transition (LZT)	RTN021, RTN020, TN304, TN303	74 – 106 ³	Pyroxenites, olivine- bearing pyroxenites, harzburgites and dunites	65 - 80	0.66	>0.4	<0.5	8.37	1.25	0.85	Barren
Hybrid Zone	TN287	78	Pyroxenites (highly contaminated)	23-29	8.9	<0.01	<0.1	3.83	1.35	0.82	Barren

946

947

948

¹Excluding RTN020 where CaO/Al₂O₃ increases to 1.14 due to the presence of a calcsilicate xenolith.

²The MZF is interrupted by xenolith raft X₂ in RTN020.

³The LZT is truncated by the end of the drillhole (EOH) every drillhole, apart from RTN021. Therefore, these thicknesses represent a minimum value.