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NORMAL REEF SUBFACIES OF THE MERENSKY REEF AT NORTHAM PLATINUM MINE, ZWARTKLIP FACIES, WESTERN BUSHVELD COMPLEX, SOUTH AFRICA

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ABSTRACT

The Normal Reef Subfacies of the Swartklip facies of the Merensky Reef along the western limb of the Rustenburg Layered Suite, exposed on Northam Platinum mine, displays lateral and vertical variations in its inter-chromitite lithologies, content in platinum-group elements and grade, and the mode of sulfide occurrence. Reef greater than 300 cm in thickness consists of a footwall of mottled anorthosite, overlain by a granular orthocumulate chromitite layer (the lower chromitite of the reef), followed by a pegmatitic feldspathic dunite, a 5- to 10-cm-thick massive, plagioclase-poor dunite, a heterogeneous pegmatitic harzburgite, succeeded by a coarse-grained pegmatitic pyroxenite, collectively comprising a pre-Merensky cyclic unit. The upper pegmatitic pyroxenite is in turn overlain by the granular (upper) chromitite of the reef, occurring at the base of the Merensky Cyclic Unit, which is overlain by a homogeneous poikilitic orthopyroxenite. Disseminated and clustered pentlandite, pyrrhotite and chalcopyrite occur throughout the inter-chromitite pegmatite, but are not observed in the massive, plagioclase-poor dunite, which typically occurs approximately 100 cm above the lower chromitite. Thermal recrystallization and downward migration of a reconstitution front and mechanical erosion of the medium-grained heterogeneous pegmatitic harzburgite accompanied progressive thinning of the reef from an inter-chromitite reef greater than 300 cm in thickness. Breaching of the massive, relatively impermeable layer of massive dunite resulted in pronounced or accelerated thermomechanical erosion of the underlying pegmatitic dunite. Peaks in platinum-group-element content, situated just below the upper chromitite and just above the lower chromitite, merge with reef thinning, becoming indistinct in reef that is less than 160 cm thick. With further thinning, until the point where the two chromitites are juxtaposed or merged, the single peak in PGE content "migrates" into the poikilitic orthopyroxenite hanging-wall. A sulfide lag, consisting of up to 20% sulfide by volume, occurs in reef less than 160 cm in thickness. Its presence is especially evident near the point where the Regional Pothole subfacies becomes manifest, and the upper chromitite or base of the Merensky Cyclic Unit transgresses the lower chromitite. Spatial distributions and graphical correlations of sampling data, related to reef thickness, indicate that there is a strong positive correlation between ΣPGE grams in the total reef sampled and the inter-reef pegmatite. A strong inverse relationship, relative to thinning, is observed between ΣPGE reef grade and ΣPGE grams. The ΣPGE grams content of the upper or Merensky chromitite of the reef is remarkably consistent over the extent of Normal Reef of the Merensky cyclic unit exposed at Northam, indicating that it is a drape or post-erosional crystal cumulate over an eroded and recrystallized pre-Merensky cyclic unit.

Keywords: Merensky Reef, platinum-group elements, sulfides, thermomechanical erosion, Northam Platinum mine, Bushveld Complex, South Africa.

SOMMAIRE

Le sous-faciès considéré "Banc normal" du faciès de Swartklip du banc de Merensky, le long de la séquence occidentale de la suite stratifiée de Rustenburg, telle qu'elle affleure à la mine Northam Platinum, fait preuve de variations latérales et verticales en types de roche intercalée entre le deux horizons de chromitite, en contenu et en teneurs en éléments du groupe du platine (EGP), et en aspects des sulfures présents. Où il est supérieur à 300 cm, le banc possède une base d'anorthosite mouchetée, que recouvre un niveau orthocumulatif de chromitite granulaire (la chromitite inférieure du banc) et, successivement, une dunite feldspathique pegmatitique, une dunite massive de 5 à 10 cm en épaisseur et à faible teneur en plagioclase, une harzburgite hétérogène pegmatitique, et ensuite une pyroxénite pegmatitique, le tout définissant une unité cyclique pre-Merensky. Vient ensuite la chromitite granulaire supérieure du banc, définissant la base de l'unité cyclique de Merensky, qui est recouverte d'une orthopyroxénite poecilitique homogène. Des grains de pentlandite, pyrrhotite et chalcopyrite sont disséminés ou regroupés partout

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dans les roches à texture pegmatitique inter-chromitites, mais ils semblent absents dans la dunite massive à faible teneur en plagioclase, typiquement rencontrée environ 100 cm par dessus la chromitite inférieure. Une recristallisation thermique et une migration vers le bas d'un front de reconstitution, ainsi qu'une érosion mécanique de la harzburgite hétérogène pegmatitique à grains moyens, ont accompagné l'atténuation de la séquence inter-chromitite supérieure à 300 cm en épaisseur. La percée de la couche massive et relativement imperméable de dunite massive a mené à une érosion thermomécanique prononcée ou accélérée de la dunite pegmatitique sous-jacente. Les anomalies positives en teneurs en éléments du groupe du platine, situées immédiatement sous la chromitite supérieure et par dessus la chromitite inférieure, s'unissent avec l'atténuation du banc, devenant méconnaissables là où l'épaisseur du banc est inférieure à 160 cm. A mesure que le banc s'amenuise, jusqu'au point où les deux niveaux de chromitite sont juxtaposés ou fusionnés, l'amplitude maximum en teneur des éléments du groupe du platine accuse une "migration" vers le toit, composé de l'orthopyroxénite poecilitique. Un dépôt décalé de sulfures, atteignant jusqu'à 20% par volume, apparait là où le banc est moins de 160 cm en épaisseur. Sa présence est particulièrement évidente près du point où le sous-faciès à "nid-de-poule" régional se manifeste, avec pour conséquence la trangression de la chromitite inférieure par la chromitite supérieure ou la base de l'unité cyclique de Merensky. Les distributions spatiales et les corrélations graphiques des données à propos des échantillons, en fonction de l'épaisseur du banc, indiquent une forte corrélation positive entre ΣEGP en grammes sur l'épaisseur totale du banc échantillonné et dans les roches pegmatitiques inter-chromitites. Une forte corrélation négative, par rapport à l'atténuation, caractérise la teneur ΣEGP du banc et ΣEGP exprimée en grammes. Le contenu ΣEGP en grammes de la chromitite supérieure (ou de Merensky) du banc est remarquablement constante sur l'étendue du faciès normal du banc de Merensky tel qu'il affleure à la mine Northam, indication qu'il s'agit d'un drapage de cristaux post-érosionnel par dessus l'unité cyclique pré-Merensky, érodée et recristallisée.

(Traduit par la Rédaction)

Mots-clés: banc de Merensky, éléments du groupe du platine, sulfures, érosion thermomécanique, mine Northam Platinum, complexe de Bushveld, Afrique du Sud.

Introduction

The world's largest known resource of platinum-group elements (PGE), the Rustenburg Layered Suite of the Bushveld Complex, boasts several mineralized horizons or intervals, the Merensky Reef being the best documented of these (Von Gruenewaldt 1977, Eales *et al.* 1993, Lee 1996, Viljoen 1994, 1999). Viljoen (1999) broadly defined the Merensky Reef as "a mineralized zone within, or closely associated with, an unconformity surface within the ultramafic cumulate at the base of the Merensky Cyclic Unit". Cawthorn & Boerst (2002) indicated that the Merensky Cyclic Unit comprises a lower chromitite horizon, a feldspathic pyroxenite that may have a lower pegmatitic portion containing a thin stringer of chromitite, a thin layer of norite, which is followed by a layer of anorthosite.

There is significant scope to laterally connect or correlate the features documented in many studies on the Normal Reef. Such research invariably provides "snapshots" of the reef, either in limited exposures along stopes or from borehole samples. Underground observations at the Northam Platinum mine, combined with an extensive mapping and sampling database containing information on the thickness of the Normal Reef, PGE content and grade, provide a continuous, coherent picture of the effects of reef thinning from thick, through intermediate, to thin reef types, and the resulting inter-chromitite recrystallization and PGE remobilization. The data therefore allow for a qualitative assessment of primary features, secondary (recrystallization) effects, and the processes that may have caused them. In this paper, we argue for a thinning and recrystallization process to account for the observed lithological, textural and mineralization effects in proximity to the transition from Normal Reef to Regional Pothole Subfacies at the Northam Platinum mine.

Description of the Reef

The Merensky Reef in its highest or "normal" stratigraphic position typically comprises a heterogeneous pegmatitic feldspathic pyroxenite bounded by narrow stringers of chromitite. The pegmatite varies and may comprise very coarse-grained feldspathic harzburgite or even medium-grained melanorite (Viljoen 1999). PGE grades apparently increase with increased coarsening of the inter-chromitite lithology (Viljoen & Hieber 1986, Viring & Cowell 1999, Viljoen 1999). The PGE are concentrated near the chromitite stringers, and in particular the upper chromitite, a feature termed "top loading" (Viljoen & Hieber 1996, Viljoen 1999, Scoon & Mitchell 2002, Wilson & Chunnett 2002). The footwall to the reef is typically noritic or anorthositic, although it may rarely comprise feldspathic pyroxenite or harzburgite. In contrast, the hanging wall is uniform, comprising poikilitic pyroxenite to feldspathic pyroxenite, which grades upward into norite and anorthosite (Viljoen & Schürmann 1998).

The reef has a known extent of at least 145 km in the Western Limb of the Bushveld Complex and is mined over approximately 80 km of this length (Viljoen 1999). Dips range from 9° to 22° in the western and northwestern limbs of the Bushveld Complex. Recent research has highlighted the variability in the reef's petrographic character, thickness and PGE content and its transgressive nature with respect to the underlying layered cumulates of the Upper Critical Zone (UCZ) (Kruger & Marsh 1982, Kruger 1990, 1994, Carr *et al.* 1994). Consequently, the reef has been divided into several facies, subfacies and reef types, in order to provide a working scheme of classification for the mining industry, particularly in the western limb of the Rustenburg Layered Suite, in the vicinity of Rustenburg (Fig. 1). At the facies level, subdivision of the western limb is based on lateral differences within UCZ stratigraphy (Fig. 2), such as the vertical separation between the Normal Reef of the Merensky unit and other seams of chromitite (*e.g.*, UG2), the stratigraphic thickness of UCZ units, the extent of olivine-bearing rock-types, and cryptic mineralogical and geochemical trends (Wagner 1929, Eales & Cawthorn 1996, Maier & Eales 1997). Wagner (1929) subdivided the Merensky Normal Reef into the Swartklip Facies to the north of the Pilanesberg Complex and the Rustenburg facies to the south of the complex (Fig. 1); the Swartklip Facies shows abundant olivine-bearing layers and a notably reduced separation between the UG2 and Merensky Normal Reef (Wagner 1929, Viljoen 1994).

Variations in the nature and size of pothole structures, and thickness and lithological variations of the Normal Reef of the Merensky unit, led Viljoen (1994) to subdivide the Rustenburg Facies into four subfacies or reef types (Contact Reef, Rolling Reef, Potholed Thin Reef and Non-Pegmatitic Wide Reef), and the Swartklip Facies into two subfacies or reef types (Normal Reef and Regional Pothole Reef). The study area, the Northam Platinum mine, located approximately 120 km north of Rustenburg, occurs within the Swartklip Facies, and contains type examples of its two component subfacies (Fig. 1; Viljoen 1994, 1999, Viring & Cowell 1999). The Normal Reef Subfacies occurs where the base of the Merensky Cyclic Unit (MCU) does not transgress the lower chromitite (Fig. 3), whereas regional-scale (10^3 to 10^4 m^2) transgressions of the lower chromitite by the base of the MCU define the Regional Pothole Subfacies (Fig. 3; Viljoen 1999). Variations in the nature of PGE mineralization have been attributed to reef thinning and MCU transgression (Kinloch 1982, Kinloch & Peyerl 1990, Bonel 1992, Lee 1996, Penberthy & Merkle 1999, Teigler 1999, Viljoen 1999, Wilson *et al.* 1999, Ballhaus & Sylvester 2000). Smaller-scale (10 to 10^2 m^2) variations in the elevation of the base of the MCU with respect to the underlying stratigraphy have led to the further definition of several types of reef (Viljoen 1994, Viring & Cowell 1999; Fig. 3).

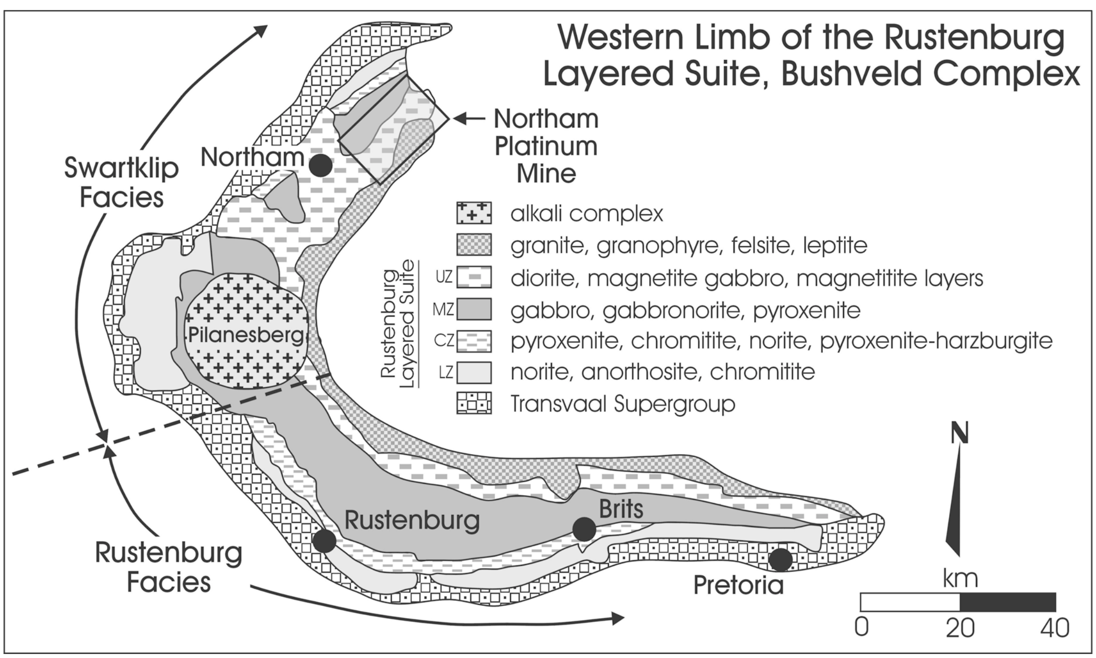


FIG. 1. The western limb of the Bushveld Complex, showing the two main facies (Wagner 1929) of the Rustenburg Layered Suite, the Swartklip Facies and the Rustenburg Facies. The study area, the Northam Platinum mine, occurs within the north-eastern portion of the Swartklip Facies (after Viljoen 1994, 1999).

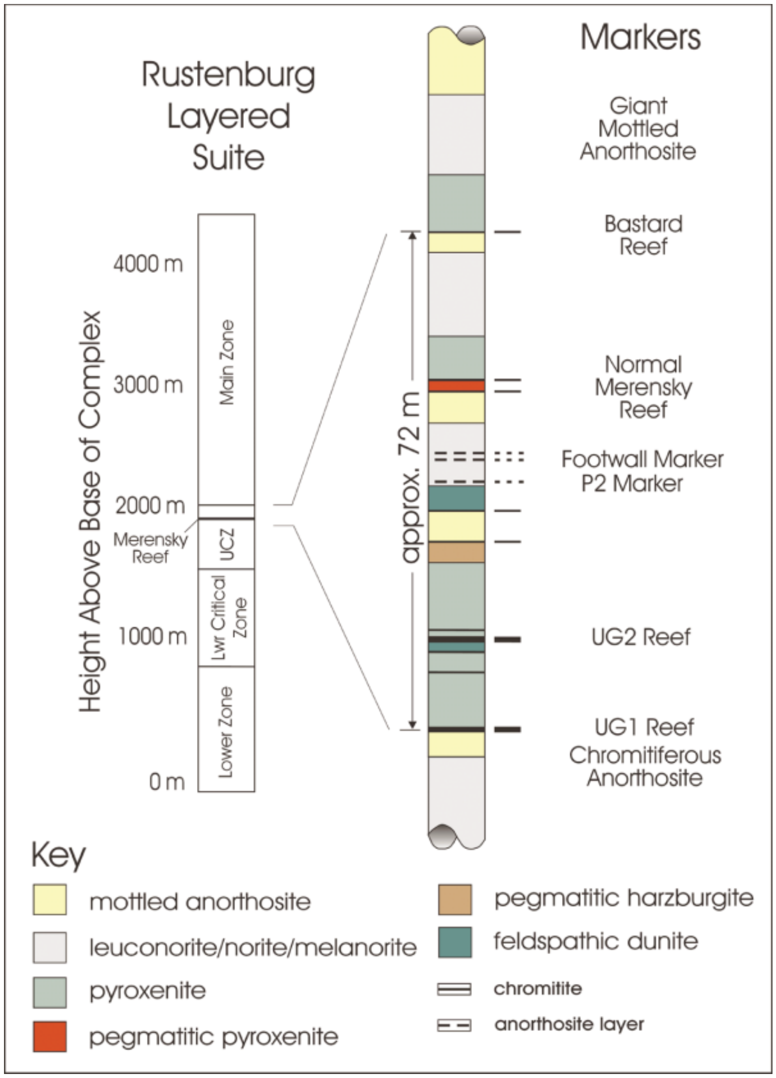


FIG. 2. Simplified stratigraphy of the Rustenburg Layered Suite. The upper portion of the Upper Critical Zone contains several chromitite-rich layers, including the Merensky Reef.

The thickness and nature of the inter-chromitite lithology are possibly the most variable features of the Normal Reef, such variation resulting in the following terminology, with the quoted thickness referring to the separation between the two chromitite stringers: "pegmatitic" and "pyroxenitic" reef (Impala Platinum Mine; Barnes & Maier 2002, Cawthorn & Boerst 2002); "wide reef facies or type" [1.8 m, Winnaarshoek, eastern limb of the Bushveld Complex, Scoon & Mitchell (2002), 6–8 m, western limb, Viljoen (1994), Wilson & Chunnett (2002)], "intermediate reef type" (2–3 m, Wilson & Chunnett (2002) and "thin reef facies or type" [0.15–0.25 m, Viljoen (1994), Scoon & Mitchell (2002); <0.35 m, Wilson & Chunnett (2002), 0.06 m, Barnes & Maier (2002)]. It is evident that the terms "wide", "intermediate" and "thin" are useful only in the context of certain mines or within certain facies. Transitions between the "reef types" within the Merensky Normal Reef are poorly defined.

Normal Reef Subfacies at Northam Platinum Mine

According to the regional characteristics of the Merensky Reef in its normal stratigraphic position, the Normal Reef Subfacies at the Northam Platinum mine occurs where the base of the MCU does not transgress the lower chromitite, although the degree of reconstitution, petrographic character, and PGE mineralization of the inter-chromitite pegmatite and cryptic changes in the footwall lithology vary with degree of reef thinning. The Normal Reef at Northam has a footwall of Upper Pseudoreef Cyclic Unit mottled (troctolitic) anorthosite overlain by an undulating granular orthocumulate

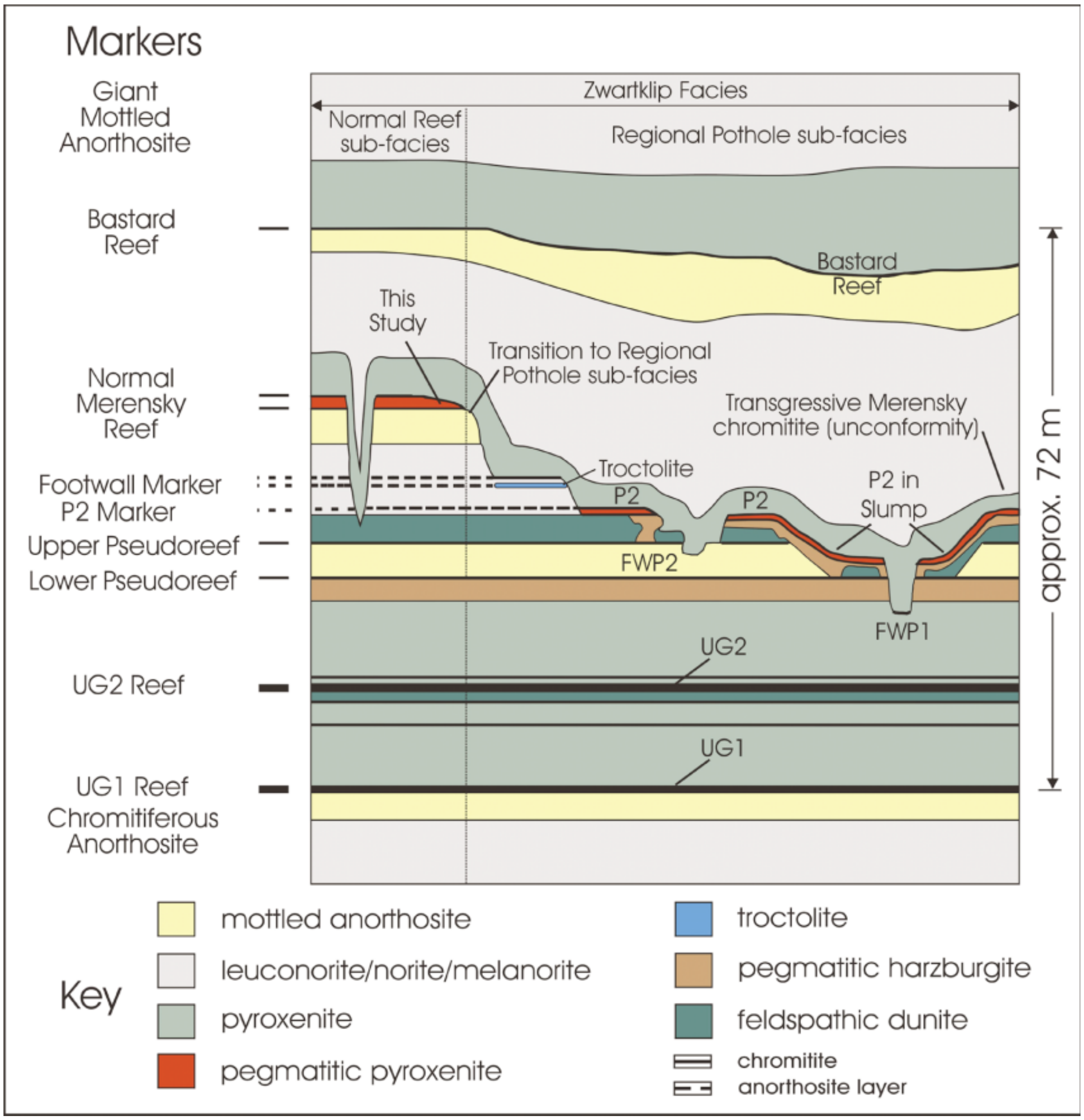


FIG. 3. Schematic cross-section of the upper portion of the Upper Critical Zone, Rustenburg Layered Suite, at the Northam Platinum mine. The Normal Reef Subfacies occurs where the Merensky Reef is in its normal stratigraphic position. Reef types in the Regional Pothole Subfacies are defined where the Merensky Cyclic Unit is conformable to footwall lithologies. Transitions between the reef types occur where the Merensky Cyclic Unit truncates the underlying stratigraphy. This study focuses on the Merensky Normal Reef in proximity to the Regional Pothole Subfacies.

chromitite (here termed the lower chromitite), followed by reconstitution pegmatites and medium- to coarse-grained pyroxenite and harzburgite in the thicker reef (160–300 cm). This is overlain by the MCU, which consists of a basal, commonly planar stringer of refractory chromitite (here termed the upper chromitite), in turn succeeded by a medium-grained poikilitic pyroxenite to feldspathic pyroxenite (Fig. 4; Viring & Cowell 1999, Reid & Basson 2002, Smith *et al.* 2002).

Regional Pothole Subfacies at Northam Platinum Mine

Transgression of the lower chromitite and underlying stratigraphic markers by the MCU produces a number of measurable features. These include a step-like transgression of the MCU within the Regional Pothole Subfacies, wherein a conformable relationship with the footwall units is potentially mineable (Figs. 3, 5; Viring & Cowell 1999). The intervening unconformable relationships are termed "transition zones" (Fig. 3; de Klerk 1982, Kinloch & Peyerl 1990, Viljoen 1994, 1999, Viljoen & Schürmann 1998, Viring & Cowell 1999), which form the margins to potholes. Potholing affects the extent of reconstitution and the distributions of PGM and base-metal sulfides in inter-chromitite pegmatite and the reef footwall (de Klerk 1982). Potholing also causes zoning, with Pt–Pd tellurides at pothole edges and Pt–Fe alloy at pothole centers (Campbell *et al.* 1983, Kinloch & Peyerl 1990). Furthermore, potholes show more reduced conditions of mineralization and recrystallization, suggesting the localization of C- and S-rich reducing fluids during footwall erosion and MCU deposition (Buntin *et al.* 1985, Campbell 1986).

Subdivision of the Normal Reef Subfacies

On the basis of underground observations, three broad subdivisions of the Normal Reef of the Merensky unit in proximity to the transition to the Regional Pothole Subfacies are here defined in terms of the inter-chromitite separation, with an attendant change in inter-chromitite lithology and texture (Smith *et al.* 2002; Fig. 6). A fourth subdivision, wherein the upper chromitite merges with the lower chromitite, is included for completeness. Note that the rock types and textures described grade into one another vertically, whereas the four subdivisions, established on the basis of reef thickness and characteristics of the inter-chromitite pegmatite, also display gradational relationships with one another. The subdivisions are therefore intended as guides to the observable effects of variable thickness of the reef, which may readily be correlated with changes in PGE grade and content, presented in a later section. The footwall mottled anorthosite and the MCU poikilitic orthopyroxenite are ubiquitous in all subdivisions described below. However, both the degree of mottling (due to crystallization of clustered microcrysts of olivine, which has been referred to as "troctolization") of the footwall, and the proportion of PGE-enriched sulfides in the hanging wall, increase with reef thinning (Fig. 6).

Chromite separation >300 cm

A basal pegmatitic dunite grades upward into a medium-grained heterogeneous harzburgite, which in turn, grades upward into a coarse-grained, pegmatitic orthopyroxenite of approximately 60 cm thickness. The sulfide mineralogy varies throughout the section. Coarse-grained, clustered pyrrhotite – chalcopyrite – pentlandite and finely disseminated pyrrhotite, with lesser chalcopyrite and pentlandite, are present in a zone approximately 20 cm above the lower chromitite. Minor disseminated very fine-grained intergrowths of pyrrhotite – chalcopyrite – pentlandite are present in the medium-grained heterogeneous pegmatitic pyroxenite. Coarse clusters and fine disseminations of pentlandite – pyrrhotite – chalcopyrite are present in the upper coarse-grained pegmatitic pyroxenite. Sulfide and concomitant PGE contents typically display two distinct peaks, one centered 10–20 cm above the lower chromitite, and the other coincident with or just below the upper chromitite.

Chromitite separation 160–300 cm

The section consists of a basal pegmatitic dunite, which is relatively barren of sulfide mineralization except for a zone of finely disseminated pyrrhotite with lesser pentlandite and chalcopyrite approximately 20 cm above the lower chromitite. This zone is overlain by a locally discontinuous but regionally persistent ultramafic layer, approximately 5–10 cm thick (generally not visible in the thicker reef owing to mining-width constraints). This consists of approximately 95% olivine, contains no observable sulfide phases, and is positioned approximately 100 cm above the lower chromitite. A heterogeneous harzburgite above the mafic layer contains zones of large, subhedral, glomeroporphyritic orthopyroxene in a dominantly coarse dunitic matrix. The abundance of clusters of orthopyroxene crystals increases upward into a coarse-grained pegmatitic pyroxenite in the immediate 60 cm below the upper chromitite. Potentially relict to cryptic lamination is evident in the form of discrete layers of orthopyroxene, olivine and plagioclase. Pentlandite – pyrrhotite – chalcopyrite clusters are preferentially associated with the orthopyroxenite-rich portions of the heterogeneous harzburgite and, thereby, the upper orthopyroxenite. Chromitite-related PGE and sulfide peaks become progressively more indistinct with thinning.

Chromitite separation <160 cm

The section consists of coarse-grained, pegmatitic pyroxenite, with or without minor olivine. Intercumulus pentlandite – pyrrhotite – chalcopyrite occur as randomly distributed, irregular clusters and fine disseminations. Chromitite-related PGE and sulfide peaks become progressively more indistinct with thinning.

Chromitites juxtaposed

A single stringer of chromitite rests conformably upon the mottled anorthosite footwall. The chromite grains of the individual stringers are amalgamated, thereby making the upper and lower chromitite stringers indistinguishable, and no inter-chromitite pegmatite remains. Pentlandite – pyrrhotite – chalcopyrite occur as fine disseminations, intercumulus with respect to the granular chromite. As previously described, the limit of the Regional Pothole Subfacies occurs where the MCU transgresses the lower chromitite (Fig. 3).

SAMPLE COLLECTION

Grid sampling of Normal Reef of the Merensky unit adjacent to the southern, deepest edge of the Regional Pothole Subfacies (Fig. 5) has produced a database of 1889 data points, each of which is referenced on an *XYZ* coordinate system. The grid, reduced to the plane of the reef, which dips 20° to the southeast, comprises points at a spacing of 5 m along dip and 10 m along strike, each point representing a single sampling channel composed of a number of individual samples. Only channels exposing a full section of pegmatitic reef, and unaffected by replacement, intrusion or intense alteration, were selected for this study. This grid sampling of data enables a consideration of PGE variation, both parallel and orthogonal to the reef surface (*i.e.*, lateral and stratigraphic variation). Data are represented spatially in the form of contoured plots, as graphs and as potentially significant correlations in the text.

Prior to channel cutting, the face is measured orthogonal to reef dip to obtain the thickness of the following lithologies: exposed hanging-wall pyroxenite, upper chromitite, inter-chromitite pegmatite (inter-chromitite separation), lower chromitite, and exposed mottled anorthosite footwall (Fig. 4, inset). The face is then marked, for the purposes of cutting the channel sample, into lengths of approximately 10 cm straddling the two layers of chromitite, and approximately 20 cm in the inter-chromitite pegmatite, together with 10 cm of the exposed hanging-wall and footwall lithologies. Channel widths and depths are approximately 5 cm. The thicknesses of the upper chromitite, inter-reef pegmatite and lower chromitite are combined to produce a Total Normal Reef thickness. The samples then are cut and subsequently bagged for in-house analysis.

ANALYTICAL TECHNIQUE

Channel samples are air-dried, crushed to fragments of approximately 0.6 cm diameter and passed through a spindle pulverizer, which produces 80 μm powder. Masses of 50 g (standard silicate-rich samples) and 25 g (Cr-bearing or Cr-rich samples) then undergo fluxing, fusion and cupellation. The separated masses of silicate- and Cr-dominated samples are then mixed with a borax – sodium carbonate – litharge (Pb) – silica-reducing agent flux (R0700) and fused in a furnace for 60 minutes at 1200°C. The resultant Pb-free button (termed a "prill") contains Pt, Pd, Rh and Au (3 PGE + Au). Ir, Ru, Os and Ag are lost. The Pb-free prills then undergo cupellation at 1300°C for 90 minutes to separate the three PGE + Au. They are then analyzed for Pt, Pd, Rh and Au by dissolution ICP–MS, the latter utilizing an internal Sc standard. The weight and density of the prill, the three PGE + Au grade, and density of the initial sample are then used to determine a concentration in grams for a representative centare or area. For the purposes of this study and to preserve confidentiality with respect to mine grades, the grade and derived grams are then normalized to the arithmetic mean of the grade and grams of the 3PGE + Au values for total Normal Reef. These are simply referred to as "grams" and "grade" in the text.

SPATIAL REPRESENTATION OF DATA

The study area trends NE–SW, encompassing lines 27 to 42 and levels 10 to 13 at the Northam Platinum mine (Figs. 5, 7). The upper–lower chromitite separation decreases toward the northwest up to the limit of the data distribution, wherein the base of the MCU transgresses the lower chromitite (transition to Regional Pothole Subfacies, termed the NP2 Upper Transition at Northam; Fig. 3). Although the Normal Reef is at its thickest in the southeastern portion of the Northam study area, where the maximum reef thickness is approximately 330 cm, in other areas such as the Amplats Union section to the southwest (pers. commun., E. Venter), it is up to 7 m thick, similar to the "thick" reef type defined by Viljoen (1994) and Wilson & Chunnett (2002). Even the thickest exposed reef at Northam thus exhibits some degree of thinning.

Total thickness of the Normal Reef, contour range: 27 to 219 cm

The Normal Reef (Fig. 7a) thins notably toward the Regional Pothole Subfacies. Thinning, in terms of reef thickness (cm) per horizontal distance (m), is marginally more gradual (0.88 cm/m) where the edge of the transition trends approximately northeast (point i). The rate of thinning is greater (1.15 cm/m) where the transition curves toward a NW–SE trend (Pilanesberg trend) in the western portion of the study area (point ii). More irregular thinning and a resultant amoeboid margin are evident in areas where the local strike of the regional transition changes markedly (point iii). Northwest-trending lows, containing relatively thin reef, are evi-

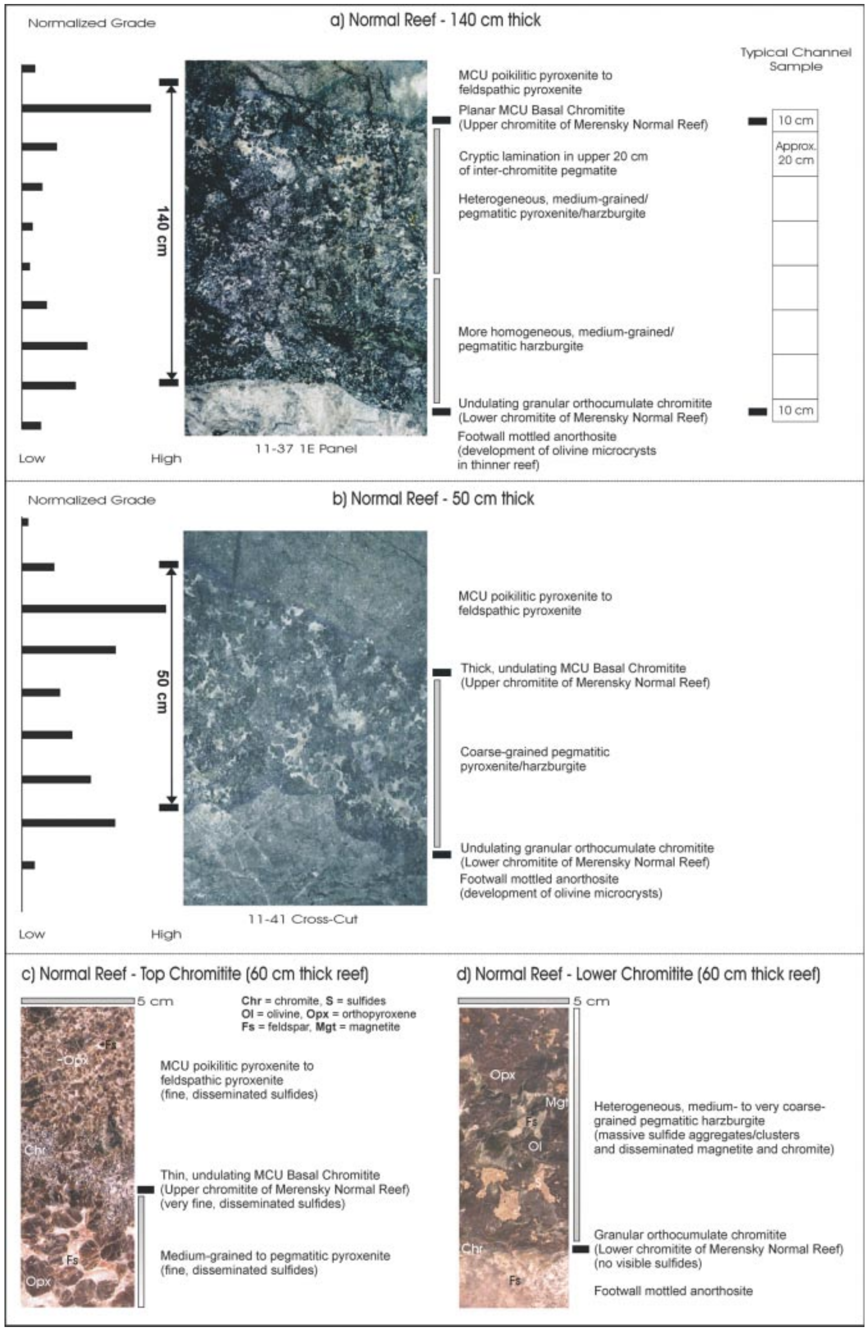


FIG. 4. Features of the Normal Merensky Reef, Northam Platinum mine. a) Typical <160-cm-thick Merensky Normal Reef (11–37 1E Panel), showing the distribution of normalized PGE grade and textural and lithological characteristics. The inset shows a channel sampling cut, samples of which are commonly 5 cm wide and approximately 10 cm deep. b) Normal Merensky Reef with a 50 cm thickness of pegmatitic pyroxenite–harzburgite between the upper and lower chromitites (11–41 Cross-Cut). Note the highly undulating lower chromitite and irregular footwall anorthosite. c) Detail of the upper chromitite, showing the inter-chromitite pegmatite (pyroxenite) and the overlying poikilitic Merensky Cyclic Unit pyroxenite (60-cm-thick Normal Merensky Reef). d) Detail of the lower chromitite, showing clustered, coarse-grained sulfides within a medium- to coarse-grained pegmatitic pyroxenite (60-cm-thick Normal Merensky Reef).

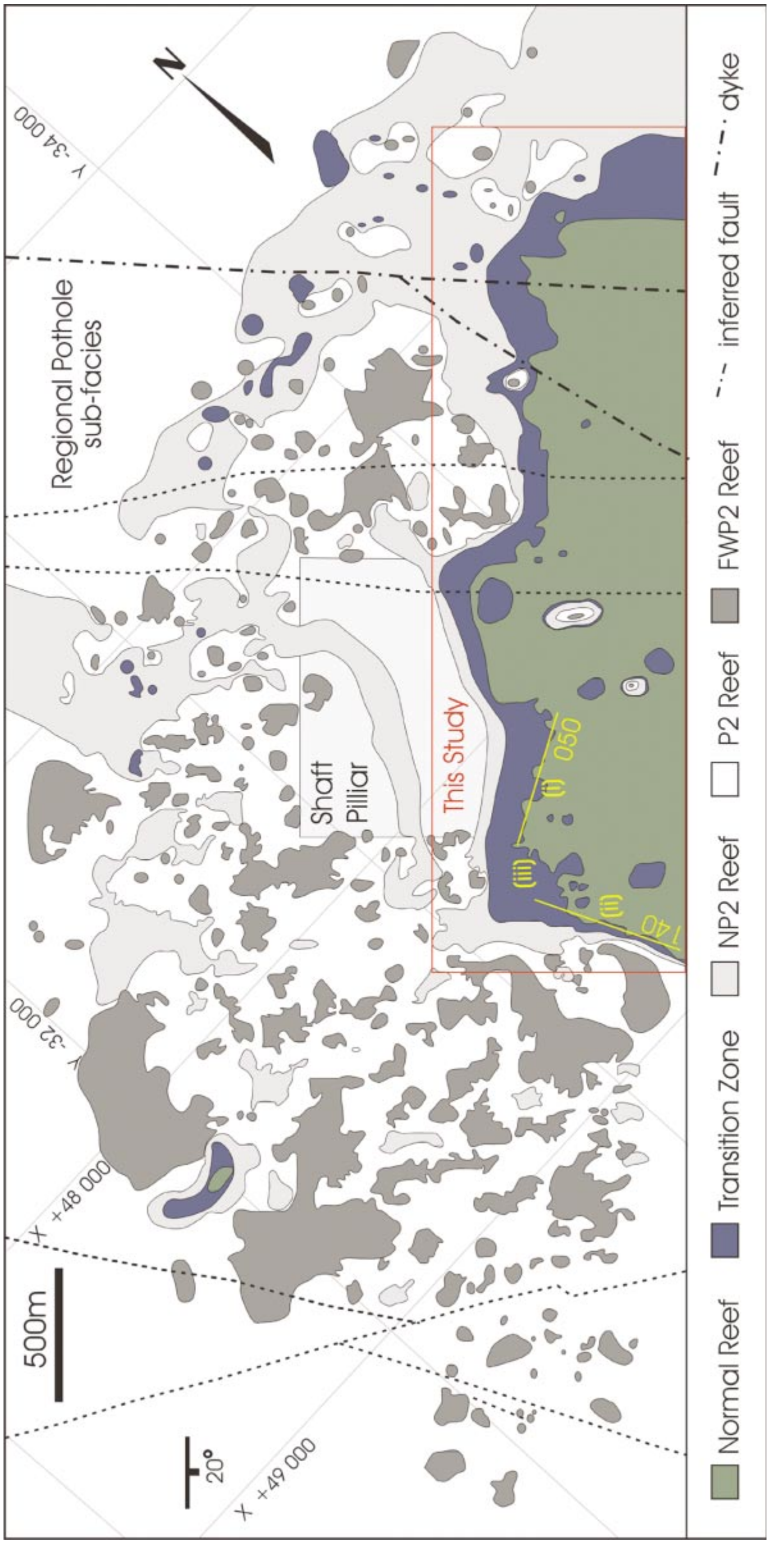


FIG. 5. Subfacies distribution at the Northam Platinum mine, represented on the plane of the reef, which dips at approximately 20° to the southeast. The study area, which occurs at the margin of the Regional Pothole Subfacies, is delineated, as are the main structural features. The margin of the Normal Reef Subfacies is reflected in the spatial distribution of the data in Figure 7. Note the relative width of the transition zone along the 050° and 140° trends (points i and ii, respectively) and the amoeboid margin of the Normal Reef Subfacies (point iii).

dent, particularly along the 35 Line in proximity to the Little John Dyke.

Normalized ΣPGE content of the upper chromitite, contour range: 0 to 0.8 cm

There is no discernable change in the normalized ΣPGE content of the upper chromitite (Fig. 7b) toward or into the Regional Pothole Subfacies. The majority of the study area displays an even distribution of ΣPGE. Lows in ΣPGE occur within scattered, deep, highly localized potholes across the study area.

Normalized ΣPGE content of the inter-chromitite pegmatite, contour range: 0.09 to 1.23 cm

The distribution of normalized ΣPGE values in the inter-chromitite pegmatite (Fig. 7c) mimics the overall trend of the total Normal Reef thickness in that it decreases toward the Regional Transition. Very localized highs and lows coincide with highs and lows in the distribution of total Normal Reef ΣPGE (Fig. 7e). A northwest-trending low, corresponding to relatively thin reef, is evident along the 37 Line Fault, as are localized lows along the eastern margin of the Little John Dyke and adjacent to the diagonal fault. Although there is some evidence for an inverse relationship between the ΣPGE content of the upper chromitite and inter-chromitite pegmatite, this relationship is not spatially consistent and is better demonstrated by a comparison of distribution histograms and lognormal relationships in subsequent sections.

Normalized ΣPGE content of the lower chromitite, contour range: 0.02 to 0.35 cm

The distribution of the ΣPGE values in lower chromitite displays an inverse relationship with the total reef thickness, in that the ΣPGE in the lower chromitite increases toward the Regional Transition (Fig. 7d). Low values of ΣPGE are also present in proximity to known structures (faults, dykes), which may imply a secondary structurally related process of PGE (re)distribution. This distribution may be due to preferential magmatic erosion in the vicinity of these features, as is evident in the spatial distribution of ΣPGE in the inter-chromitite pegmatite, or it could be related to fluid migration along long-lived structural conduits.

Normalized ΣPGE of the total Normal Reef, contour range: 0.45 to 1.45 cm

The distribution of normalized ΣPGE values in the Total Normal Reef mimics the overall trend in total thickness of the Normal Reef (Fig. 7e). Local variations in the main body of the Normal Reef are generally controlled by very local variations in the nature of the inter-chromitite pegmatite, and structurally related lows are evident.

PGE grade in the total Normal Reef, contour range: 0.2 to 1.7 cm

The PGE grade in the Total Normal Reef displays a general inverse relationship with the number of grams in the total Normal Reef, and consequently its thickness (Fig. 7f). However, the effect of the presence of potholes on PGE grade is more marked. Two notable exceptions to the general trend are a low-grade trough on the 33 Line between pothole-centered highs and an elongate low-grade area adjacent to the eastern margin of the Little John Dyke, which corresponds to an area of relatively thin Normal Reef, with a low PGE content. These low-grade areas may be evidence for a partial structural control on reef development and mineralization.

Graphical Representation of Data

The dataset for the Normal Reef at Northam is described by means of simple histograms and bivariate plots (Fig. 8). The 160-cm limit in reef thickness is indicated on selected graphs as a vertical dotted line.

Distribution of Normal Reef thickness

Although contours of this parameter range between 27 and 219 cm, the histogram shows that where sampled, the Normal Reef thickness ranges from 40 to 280 cm and is apparently skewed toward lower thickness of the total reef (Fig. 8a). This effect is partly a product of the proximity of present mining-induced exposures of the Regional Pothole Subfacies and the potential for exposure of the entire reef package in restricted stoping widths of 150 cm, which largely limits the exposure of the Normal Reef to thicknesses of less than 140 cm. The statistical mean of reef thickness is 111 cm, the median is 110 cm, whereas a "spatial median" (see previous section on spatial representation of the data) is 116 cm.

Normalized ΣPGE distribution in the Normal Reef

The distribution of ΣPGE in the Normal Reef is skewed toward lower values (Fig. 8b), partly owing to a concentration of sampling in areas of relatively thinned reef, in the up-dip portions of the Normal Reef Subfacies.

Normalized ΣPGE in the upper chromitite versus total thickness of the Normal Reef

The majority of data cluster below the 160-cm limit in reef thickness (Fig. 8c), and data range from 0 to 0.87

of the mean ΣPGE in the Total Normal Reef. The best-fit curve to the data shows no correlation between grams and thickness. A flat line with a near-constant normalized ΣPGE value of 0.28 represents the relationship.

Normalized ΣPGE in the inter-chromitite pegmatite versus total thickness of the Normal Reef

Data range from 0 to 2.49, and the best-fit curve to the data shows a natural log correlation between grams and thickness: grams = 0.3902 ln(thickness) – 1.203. The rate of change of the gradient of the best-fit curve increases markedly below reef thicknesses of 160 cm (Fig. 8d).

Normalized ΣPGE in the lower chromitite versus total thickness of the Normal Reef

Data ranges from 0 to 0.90, and the best-fit curve to the data displays a natural log correlation between grams and thickness: grams = –0.0926 ln(thickness) + 0.5544. The rate of change of the gradient of the best-fit curve increases markedly below reef thicknesses of 160 cm. Conversely, the gradient tends to zero as reef thickens (Fig. 8e).

Normalized ΣPGE in the total Normal Reef versus normalized ΣPGE for inter-chromitite pegmatite

A strong positive correlation is found between normalized ΣPGE in the total Normal Reef and normalized ΣPGE in the inter-chromitite pegmatite, with the array of data predictably falling below the 1:1 correlation line (Fig. 8f). The expected disparity between an ideal correlation and the negative *y* intercept is due to the missing PGE contribution of the upper and lower chromitites, relative to the ΣPGE content of total Normal Reef.

Ratio of ΣPGE in the lower chromitite to ΣPGE for inter-chromitite pegmatite versus total thickness of the Normal Reef, <160 cm thickness

The relative concentration of the PGE and Au into the lower portions of the inter-chromitite pegmatite with progressive thinning of the reef is demonstrated in Figure 8g. Here the lower chromitite : pegmatite ratio in the reef, where the thickness ranges from 20 to 160 cm, increases toward decreasing thickness of the reef according to the exponential relationship: LwrChr:Peg Ratio = $1.4475\exp^{-0.0205(\text{thickness})}$. The relationship has no correlation or is described by a flat line where the thickness of the reef exceeds 160 cm. This situation is partly due to the sampling technique, wherein the 10-cm-long sample straddling the lower chromitite contains a progressively greater degree of mineralized pegmatite as the reef thins, indicating the formation of a basal accumulation of sulfides, as observed in underground mapping. As reef thickness increases, ΣPGE in the lower chromitite and the inter-chromitite pegmatite tend toward background values, causing the gradient of the best-fit curve for the lower chromitite : inter-chromitite pegmatite ratio to tend toward zero.

The contribution of the upper and lower chromitite and inter-chromitite pegmatite to ΣPGE of the total Normal Reef

Figure 8h comprises a Merensky Normal Reef profile, expressed as normalized ΣPGE, for the dataset from the Northam mine. A constant contribution of PGE from the upper chromitite is readily evident, as is the increased contribution from the lower chromitite and decreased contribution from the inter-chromitite pegmatite as reef thickness decreases. This is especially notable for reef widths of less than 160 cm. The relationship between the three reef components is strikingly represented as percentage contributions to total PGE content in Figure 8i. It is important to note from Figure 8i that there is a linear increase in PGE contribution from the upper chromitite, together with a lognormal increase in PGE contribution from the lower chromitite with decreasing reef thickness. The ΣPGE signature for thinned reef is dominated by the contributions from the two chromitites, whereas the thicker reef is dominated by the PGE contribution of the pegmatite.

Normalized ΣPGE grams and grade versus total thickness of the Normal Reef

The number of ΣPGE grams for the total Normal Reef follows a very similar trend to the ΣPGE for the inter-chromitite pegmatite (Figs. 8d, f), and is described by the equation: normalized grams = 0.2924ln (thickness) – 0.3551, within the range 0.6 to 1.3 times mean ΣPGE in grams in the total Normal Reef (Fig. 8j). The PGE grade of the Normal Reef shows an inverse relationship with respect to ΣPGE grams in the range 0.1 to 0.45 times mean grade of ΣPGE in the total Normal Reef.

Discussion

A number of features are observable, concomitant with reef thinning, toward the edge of the Regional Pothole Subfacies. At a high inter-chromitite separation (greater than 300 cm), the inter-chromitite interval consists of a sequence of medium-grained dunite, grading upward into a medium-grained harzburgite, topped by a pegmatitic pyroxenite. As the inter-chromitite separation decreases, this unit becomes increasingly pyroxenitic and pegmatitic, and grades downward from a megacrystic pegmatitic pyroxenite, directly below the upper chromitite, into a heterogeneous pegmatitic pyroxenite–harzburgite containing clusters (glomeroporphyrocrysts) of pyroxene. This transition indicates the

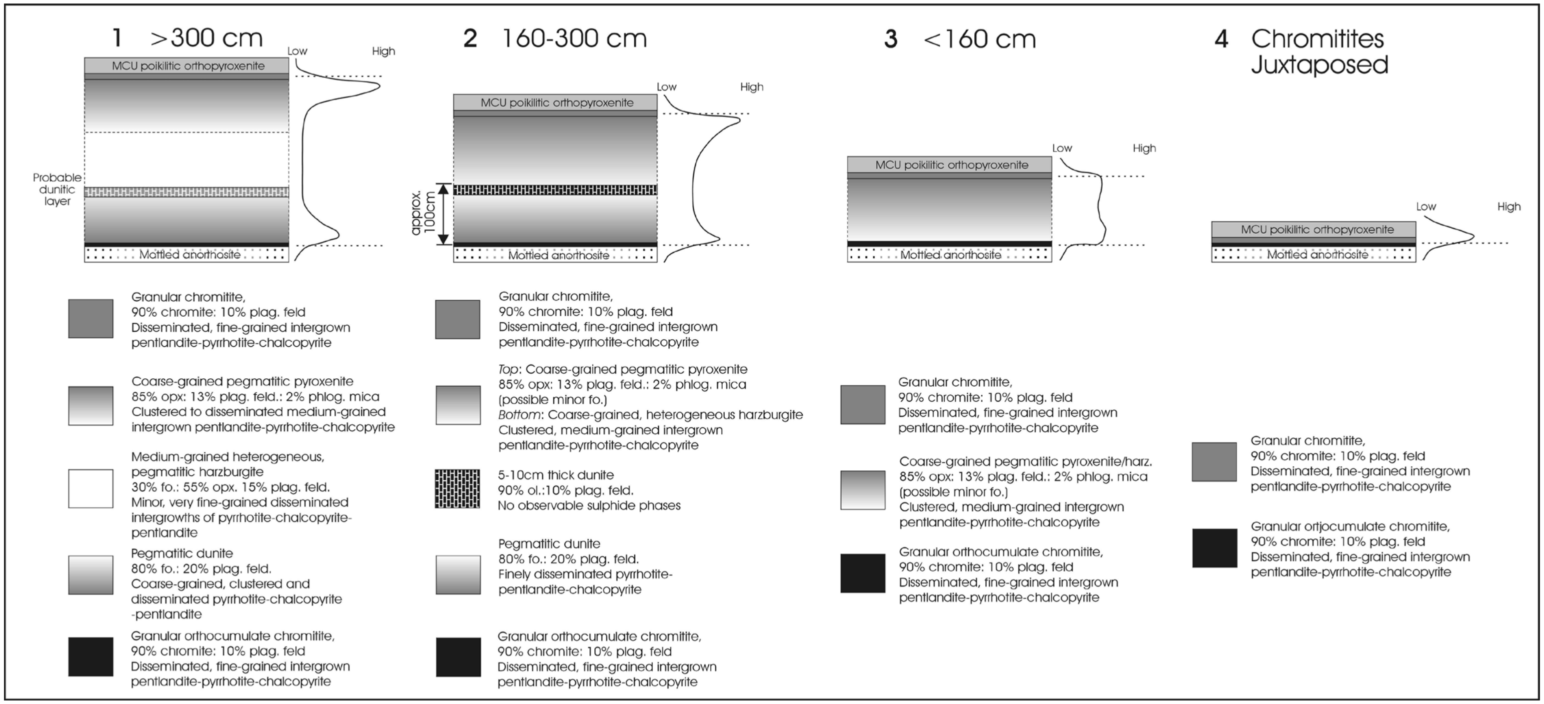


FIG. 6. Schematic representation of lithological and textural characteristics of the four subdivisions of the Normal Reef at the Northam Platinum mine. The depiction of these changes is accompanied by typical profiles of grade, demonstrating the merging of distinct peaks with reef thinning. Grade peaks are not coincident with the bounding chromitites in the thicker reef, although the peaks do tend toward coincidence with the chromitites upon reef thinning. The grade peak, in the case of merged chromitites, occurs in the orthopyroxenite hanging-wall.

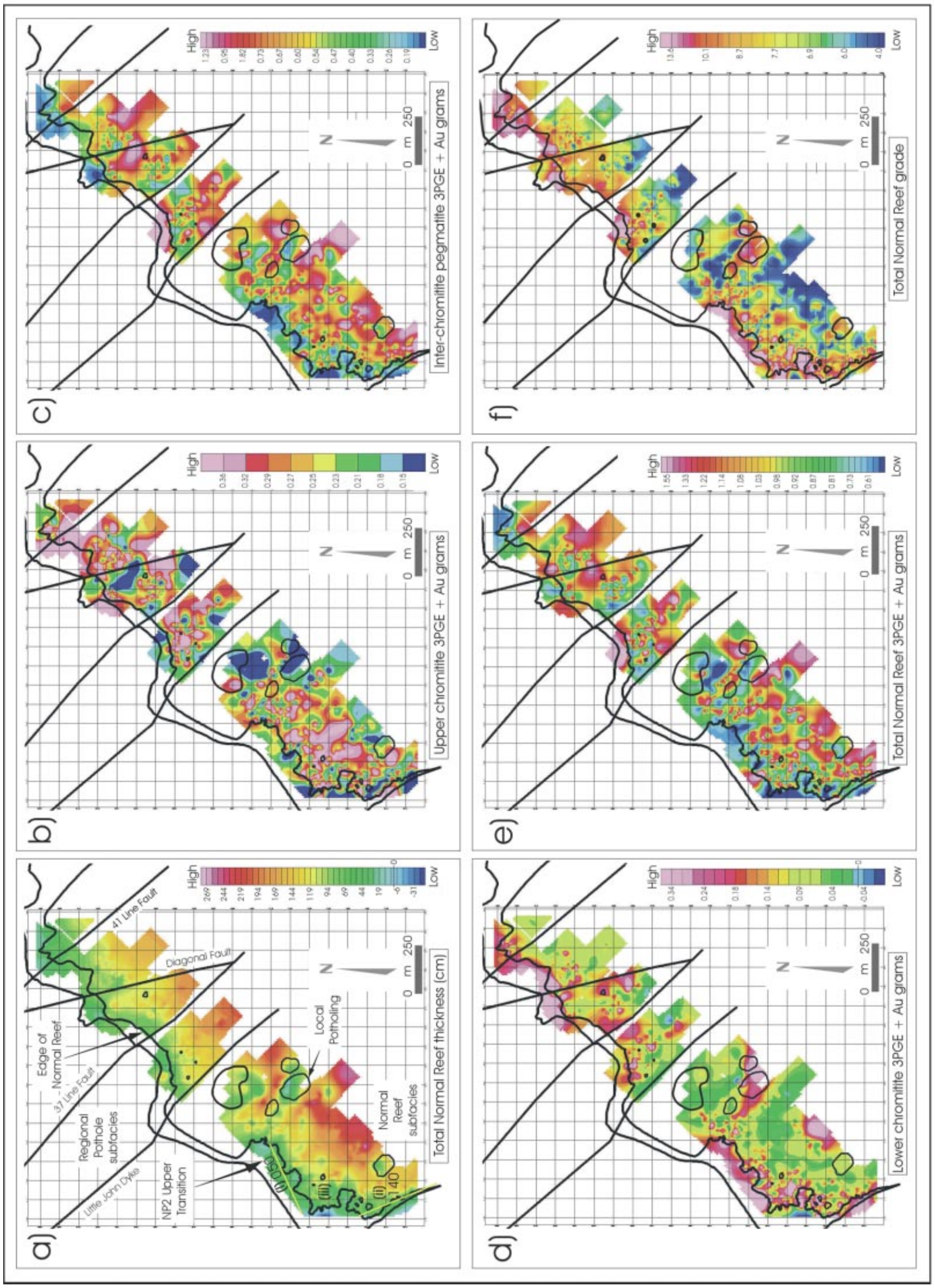
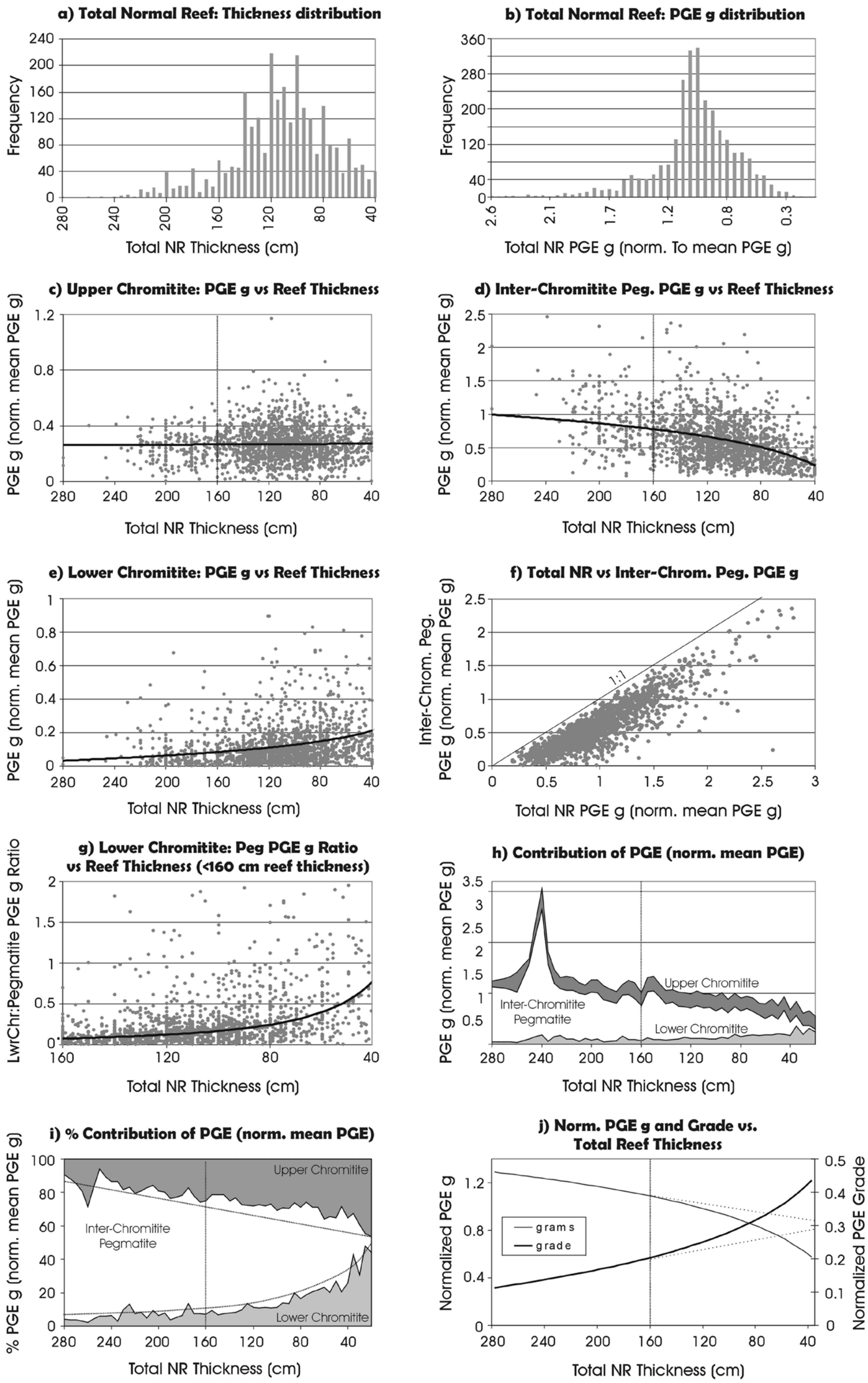


FIG. 7. Spatial representation of gridded sampling data. For reference purposes, the limit of the Normal Reef Subfacies is shown in each plot. All data, except reef thickness, are normalized to their mean value. a) Total thickness of the Normal Reef, b) 3PGE + Au in grams in the upper chromitite, c) 3PGE + Au in ms in the inter-chromitite pegmatite, d) 3PGE + Au in grams in the lower chromitite, e) 3PGE + Au in grams in the total Normal Reef, and f) grade in the Total Normal Reef.


a) Total Normal Reef: Thickness distribution
Frequency
Total NR Thickness (cm)
b) Total Normal Reef: PGE g distribution
Frequency
Total NR PGE g (norm. To mean PGE g)
c) Upper Chromitite: PGE g vs Reef Thickness
PGE g (norm. mean PGE g)
Total NR Thickness (cm)
d) Inter-Chromitite Peg. PGE g vs Reef Thickness
PGE g (norm. mean PGE g)
Total NR Thickness (cm)
e) Lower Chromitite: PGE g vs Reef Thickness
PGE g (norm. mean PGE g)
Total NR Thickness (cm)
f) Total NR vs Inter-Chrom. Peg. PGE g
Inter-Chrom. Peg. PGE g (norm. mean PGE g)
1:1
Total NR PGE g (norm. mean PGE g)
g) Lower Chromitite: Peg PGE g Ratio vs Reef Thickness (<160 cm reef thickness)
LwrChr:Pegmatite PGE g Ratio
Total NR Thickness (cm)
h) Contribution of PGE (norm. mean PGE)
PGE g (norm. mean PGE g)
Upper Chromitite
Inter-Chromitite Pegmatite
Lower Chromitite
Total NR Thickness (cm)
i) % Contribution of PGE (norm. mean PGE)
% PGE g (norm. mean PGE g)
Upper Chromitite
Inter-Chromitite Pegmatite
Lower Chromitite
Total NR Thickness (cm)
j) Norm. PGE g and Grade vs. Total Reef Thickness
Normalized PGE g
Normalized PGE Grade
grams
grade
Total NR Thickness (cm)

progressive recrystallization of olivine to pyroxene, partly due to the addition of feldspar. Downward transgression of the upper chromitite, which forms the base of the Merensky Cyclic Unit, and the relict primary layering, exemplified by a massive dunite layer preserved in thicker reef (160–300 cm), argues for thinning of a pre-MCU cyclic unit consisting of the lower chromitite overlain by a dunitic layer to a pyroxenite cumulate (Smith *et al.* 2002). The zone of recrystallization, or zone of partial melting, existing at the solidus–liquidus interface, has a relatively consistent thickness despite the absolute thickness of the reef, extending downward from the upper chromitite for approximately 60 cm. The lower limit of this zone of recrystallization is best considered as a "recrystallization front", below which portions of the original cyclic units are partially preserved in the thicker reef. Thinning and mineralogical changes were apparently initiated by this recrystallization front, which disrupted silicate layering, substantially increased grain-sizes and reworked or remobilized PGE-rich sulfide phases.

Sulfides in the thicker reef (>300 cm and 160–300 cm) are disseminated as intercumulus phases throughout the inter-reef silicate and are reflected by two distinct PGE peaks; one just below the upper chromitite, and the other just above the lower chromitite. PGE peaks merge, and sulfides become more aggregated or clustered, with progressive thinning of the reef. In reef thinner than 160 cm, massive sulfides are concentrated in a "sulfide lag" centered approximately 10–20 cm above the lower chromitite, within the heterogeneous, coarse-grained pegmatitic pyroxenite (commonly with minor olivine). The anorthosite–leuconorite footwall to the reef becomes increasingly troctolitic with reef thinning. The ΣPGE value of the total Normal Reef mimics ΣPGE of the Inter-Chromitite Pegmatite, displaying a lognormal relationship to reef thickness, according to ΣPGE = 0.2924ln(thickness) – 0.3551, converging to a constant (maximum) value of 1.3 (normalized). The PGE grade of the Normal Reef displays an inverse relationship with respect to total grams.

There is no clear relationship between reef thickness and ΣPGE in the upper (Merensky) chromitite, indicating that this is a drape, or post-erosional crystal cumulate overlying the relict, partially reconstituted sub-Merensky cyclic unit. In contrast, ΣPGE in the lower chromitite increases with reef thinning, according to the relationship ΣPGE = –0.0926ln(thickness) + 0.5544, whereas the ΣPGE content of the inter-chromitite pegmatite decreases with reef thinning according to ΣPGE = 0.3902ln(thickness) – 1.203, both being a result of the progressive development of the basal sulfide lag. The ΣPGE value of the total Merensky Normal Reef and the inter-chromitite unit essentially display a strong positive relationship. The single PGE peak in thinner portions of the reef (<160 cm) "migrates" upward to occupy the hanging-wall orthopyroxenite, possibly owing to the impermeability of the lower chromitite.

The lognormal decrease in ΣPGE of the reef is relatively gradual where the reef thickness is greater than 160 cm, but markedly more pronounced in reef that is thinner than 160 cm. This "cut-off" attests to the combined thickness of the recrystallization front (approximately 60 cm) and the olivine-rich layers (an approximately 10-cm-thick layer of massive dunite and the underlying approximately 90-cm-thick pegmatitic dunite). Once the dunite layer is breached, erosion, reconstitution and sulfide remobilization are pronounced or more active, to the point where the MCU transgresses the lower chromitite and the other footwall lithologies in the Regional Pothole Subfacies.

The spatial trends described above provide valuable insights into the mechanisms of reef thinning toward the Regional Pothole Subfacies. Thinning is more gradational at an 050° trending transition, whereas it is relatively marked at a 140° (Pilanesberg) trending transition, indicating that Pilanesberg-parallel structures may have provided a preferential orientation for the initiation and subsequent scouring of potholes of the Regional Pothole Subfacies. Major structures, such as faults and dykes, disrupt the trends in reef thinning and PGE distribution, indicating that their precursor structures or movement may have been contemporaneous with the formation of the MCU and its related thermomechanical

FIG. 8. Graphical representation of sampling data from the Normal Reef Subfacies at the Northam Platinum mine. "PGE g" refers to 3 PGE + Au in grams (normalized to mean values). a) Thickness-distribution histogram, showing values skewed toward lower values. b) PGE g distribution, showing values skewed toward lower PGE g values in the total Normal Reef. c) ΣPGE in g in the upper chromitite *versus* Normal Reef thickness, showing no relationship. d) ΣPGE in g in the inter-chromitite *versus* Normal Reef thickness; a best-fit lognormal relationship is indicated [PGE g = 0.3902 ln(thickness) – 1.203]. e) ΣPGE in g in the lower chromitite *versus* Normal Reef thickness; a best-fit lognormal relationship is indicated [PGE g = –0.0926 ln(thickness) + 0.5544]. f) ΣPGE in g in the inter-chromitite *versus* PGE g in total Normal Reef, showing a strong positive correlation, with the discrepancy between an ideal 1:1 relationship being accounted for by the PGE g in the upper and lower chromitites, data from which are not included on this plot. g) Ratio of PGE in g in lower chromitite *versus* inter-chromitite, showing the relationship LwrChr:Peg Ratio = $1.4475\exp^{-0.0205(\text{thickness})}$ in the thickness range from 20 to 160 cm. h) and i) Contribution of PGE g to PGE g profile and percentage contribution of PGE g to PGE g profile, indicating the relatively constant contribution of the upper chromitite. The PGE contribution of the lower chromitite increases notably below a reef thickness of 160 cm. j) Inverse relationship between PGE g [PGE g = 0.2924ln(thickness) – 0.3551] and PGE grade (lognormal relationships to reef thickness) with respect to reef thinning.

erosion. Regional observations (Viljoen 1999), data from adjacent mines and a thickness distribution that is skewed toward a thinner reef indicate that all the Merensky Normal Reef exposed at the Northam Platinum mine is thinned, relative to an original thickness of at least 700 cm [*cf.* the thick reef facies or type defined by Viljoen (1994) and Wilson & Chunnett (2002)].

Model

The evolution of the Merensky Normal Reef at the Northam Platinum mine may be summarized in a simple model, the stages of which are represented schematically, in a lateral sense, in Figure 9.

The formation of the reef types observed at the Northam Platinum mine started with the development of a pre-Merensky pulse (pre-MCU) footwall unit, consisting of a basal chromitite, which was deposited on the possibly truncated anorthosite of an earlier (upper pseudo-reef) cyclic unit. PGE mineralization, providing the lower PGE peak observed in channel-sampling data, occurred at this stage. The nature of the primary silicate sequence making up this pre-Merensky cyclic unit is difficult to identify, as syn-Merensky cyclic unit recrystallization is widespread. However, we suggest that the basal chromitite was succeeded by olivine-rich cumulates (essentially dunite) grading upward to harzburgite and orthopyroxenite. Disseminated sulfide-hosted PGE, as observed in the thicker types of reef, were distributed throughout these cumulates.

The emplacement of the Merensky magma disrupted and displaced or mixed with the residual magma overlying the dunite – harzburgite – orthopyroxenite cyclic unit and thereby brought these units into contact with the Merensky magma. Recrystallization of the upper portion of the pre-existing cyclic unit occurred within the 60-cm-thick zone of recrystallization, that is, above the recrystallization front (Fig. 9). This process was probably accompanied by mechanical erosion given a sufficiently turbulent pulse of Merensky magma, and relatively unconsolidated cumulates in the footwall to the magma chamber. The Merensky magma was initially undersaturated in orthopyroxene, resulting in consumption of orthopyroxene in the partially crystalline footwall. Olivine in these silicate lithologies would have remained, and its proportions perhaps even augmented by the newly crystallized olivine from the Merensky pulse. Continued interaction between the Merensky magma and the footwall cumulates probably led to its saturation in orthopyroxene and reaction with olivine, eventually producing pyroxenite after harzburgite.

Recrystallization was less vigorous where the Merensky magma encountered more olivine-rich ("massive") dunite layers, one of which occurs approximately

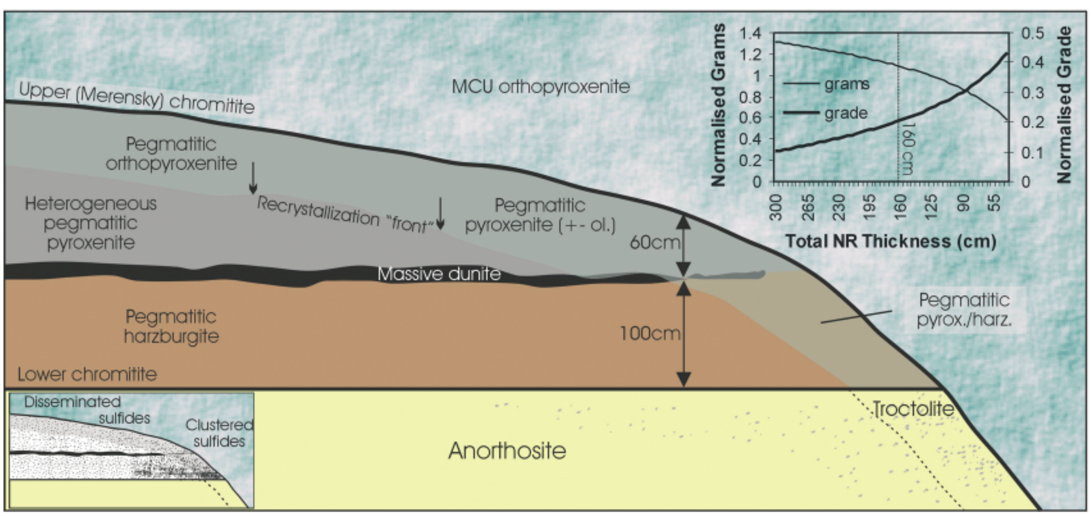


FIG. 9. Summary of proposed processes during reef thinning and recrystallization. The upper pegmatite, within a recrystallization front, transgresses the underlying cyclic unit, just as the MCU transgresses underlying lithologies in the Regional Pothole Subfacies. We propose that the key reef thickness of 160 cm, reflected on the graphical correlations, comprises a recrystallization thickness of 60 cm, and 100 cm of coarse-grained, pegmatitic dunite and the laterally persistent layer of massive dunite. Breaching of this dunite layer results in dramatic thinning of the reef and the progressive development of a lower PGE-enriched zone of coarse-grained, clustered sulfides. At this stage, the PGE peak "migrates" into the orthopyroxenite hanging-wall of the juxtaposed-merged chromitites. The mechanical removal of thermally recrystallized inter-reef pegmatite and its accompanying PGE must have occurred prior to or synchronously with the deposition of the MCU.

100 cm above the lower chromitite at Northam. In contrast, recrystallization and erosion were more pronounced in feldspar-rich or olivine-poor units. Where the footwall unit had been sufficiently thinned by erosion, the Merensky magma and its recrystallization front affected the leucocratic footwall underlying the lower chromitite. This interaction resulted in the decomposition of the orthopyroxene to form clustered olivine microcrysts in the footwall anorthosite and leuconorite, thereby generating a troctolite. The sequence of events terminates with the deposition of the basal (Merensky) chromitite of the Merensky Cyclic Unit and its associated sulfides. The combined PGE peak apparently "migrates" into the hanging wall in very thin reef or where the upper and lower chromitites are juxtaposed and merged. The Merensky chromitite therefore "drapes" over a recrystallized and thermomechanically eroded pre-Merensky cyclic unit. The Merensky chromitite was succeeded by the ubiquitous Merensky pyroxenite. Where the lower chromitite was finally breached, the underlying footwall was strongly altered to troctolite. Recrystallization and removal of the leucocratic lithologies below the lower chromitite heralded the full-blown development of the Regional Pothole Subfacies.

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