

# Mostly solidified hardground at the top of the crystal pile in the Bushveld magma chamber

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## ABSTRACT

Mafic layered intrusions show abundant evidence for the formation through the progressive inwards growth of a mushy solidification layer, with a central body of nearly crystal-free resident melt. The thickness and permeability of the mushy layer play a vital role in operation of several petrogenetic processes but remain poorly constrained in layered intrusions. To address this issue, we have re-examined the cumulate sequence in the Upper and Critical Zones of the Bushveld Complex. Although some observations (e.g., soft-sediment deformation) are indicative of cumulate rocks being mushy and having experienced interstitial melt percolation (e.g., metasomatic anorthosites), other field and textural evidence suggest the contrary. Some of the clearest evidence comes from sections through chromitite and magnetite layers as well as through the Merensky Reef, layers that were deposited on the eroded rocks of the temporary chamber floor. Below the erosional surface, the layered rocks (1) were tilted and truncated without losing their internal coherence, (2) have knife-sharp contacts with the overlying rocks, (3) show minimal evidence of penetration by downward-percolating melt, (4) reveal sharp truncation of individual crystals, particularly beheading of pyroxene oikocrysts and intersecting of polysynthetic twinning in plagioclase, and (5) show resumed growth on the truncated crystals into the overlying rocks. These observations indicate that the cumulates of the inward-growing chamber floor were almost entirely solid at the time of the erosion and deposition of these layers. To reconcile these two sets of contrasting observations, we propose that only a few metres of the uppermost portion of the cumulate pile of the Upper and Critical Zones of Bushveld magma chamber were mushy, with other underlying rocks being almost totally solidified. The mushy layer tends to be thin and locally even non-existent (e.g., in magnetite layers) due to high efficiency of primary adcumulus growth at the crystal-liquid interface of the temporary chamber floor. The solid chamber floor results from thermochemical erosion of the entire mushy layer by magmas replenishing the evolving chamber. The study implies that such petrogenetic processes as the hydrodynamic sorting of crystals and reactive porous flow may only operate within this very thin mushy portion of the cumulate pile and cannot therefore be responsible for any large-scale petrological features (e.g., platinum reefs, massive chromitites, stratiform anorthosite layers) of the Bushveld Complex.

## 1. Introduction

There is a wealth of petrological data indicating that mafic layered intrusions are formed by the inward growth of solidification fronts at the interfaces with a central body of crystal-free or crystal-poor resident melt (Cawthorn, 1996; Charlier et al., 2015; Latypov et al., 2024; Marsh, 1996; Parsons, 1987; Wager and Brown, 1968). Mushy layers at these solidification fronts are formed either by physical settling (Irvine et al.,

1998; Morse, 1988; Wager and Brown, 1968) or in situ nucleation and growth (Campbell, 1996, 1978; Latypov et al., 2020a, 2020b; Marsh, 2006, 1996; McBirney and Noyes, 1979) of crystals. A mushy layer represents a mechanically coherent mixture of crystals and melt, forming a framework of grains with variable cohesion to their neighbours (Marsh, 1996; Sparks et al., 2019; Weinberg et al., 2021). The amount of crystals in a mushy layer can vary widely and, in some cases, can be as low as 25–30% when crystals become linked together to form a

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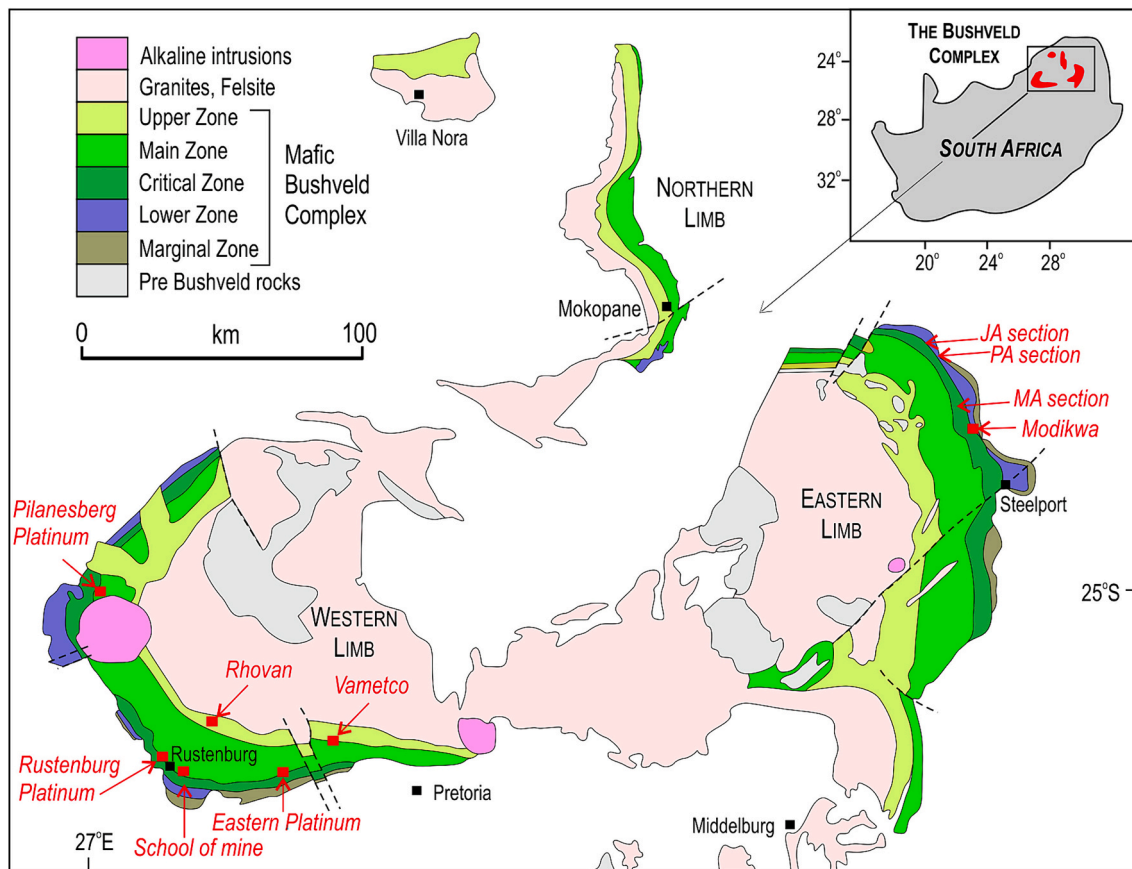


Fig. 1. Geographical location and a generalized geological map of the Bushveld Complex (Rustenburg Layered Suite) in South Africa. The places involved in this study are indicated on the map. MA - Maandaagshoek, JA - Jagdlust, PA - Paschaskraal. Modified from Latypov et al. (2017).

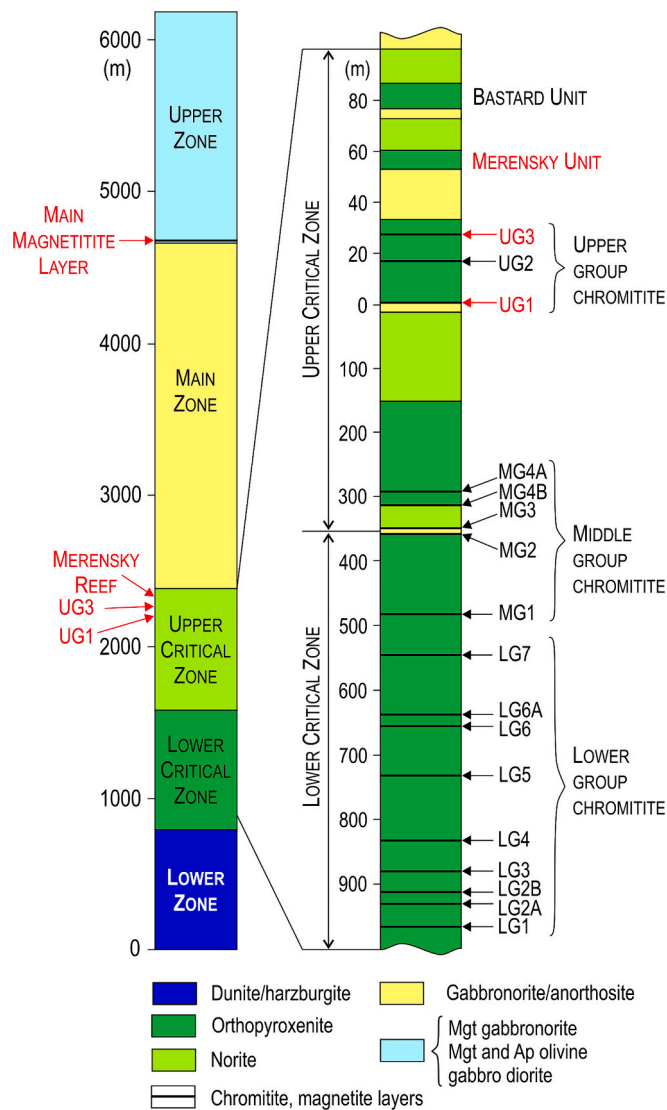
continuous 3D crystal framework; such frameworks have been noted in plagioclase-rich cumulates and in chromitites (Latypov et al., 2022a; Philpotts et al., 1998, 1999). There is a strong disparity in estimation of the thicknesses of mushy layers in layered intrusions. Some models assume a mushy layer on the chamber floor to be up to several hundreds of m in thickness (Boudreau, 2016, 2019; Boudreau and McCallum, 1992; Cashman et al., 2017; Irvine, 1980; Tait and Jaupart, 1992; Tegner et al., 2009). In contrast, other models argue for the thickness of a mushy layer to be only a few m thick (Hess, 1960; Holness et al., 2017a, 2017b; Irvine et al., 1998; Latypov et al., 2015; Thompson and Patrick, 1968) and sometimes even close to zero (Kruger and Latypov, 2020, 2021, 2022). The resolution of this discrepancy is important because operation of many petrological processes is strongly dependent on the thickness and permeability of a mushy layer in basaltic magma chambers. In particular, the cumulates of the inward-growing chamber floor, in some models, are required to be mushy to the depth of several dozens to hundreds of metres to provide sufficient volume of crystals and/or percolating melt/fluids for mineral sorting and/or metasomatic transformation of proto-cumulates, respectively. More specifically, large-scale slumping of a thick cumulate pile in response to central subsidence of the intrusion is proposed to result in segregation of sulphides and chromite/magnetite from silicate minerals by hydrodynamic sorting. This process is thought to be responsible for the formation of platinum-rich reef or chromitite/magnetitite at the base of the slumped cumulate pile (Maier et al., 2013, 2018, 2021a, 2023). Similarly, the thick mushy cumulate pile is considered to be a permeable medium through which interstitial melt/fluid can migrate upwards in response to compaction and/or high buoyancy of the melt (e.g., Boudreau, 2016, 2019) and this migrating fluid is considered to be the transport mechanism for platinum group elements and even chromium (Boudreau,

2019; Marsh et al., 2021). The permeability of a mushy layer thus controls the degree at which porous-media flow/convection may occur in magmatic bodies (Cheadle et al., 2004) and the thickness of a mushy layer dictates the volume of rocks that may potentially be subjected to reactive porous flow. In this paper we present and discuss new field and textural observations from the rock sequences hosting chromitite and magnetite layers and the Merensky Reef of the Bushveld Complex, that allow strict constraints to be put on the thickness of mushy layers, the extent of reactive porous flow and the potential degree of hydrodynamic sorting in gravity flows during the formation of these parts of the complex.

## 2. The Bushveld Complex

The 2.05 Ga Rustenburg Layered Suite of the Bushveld Complex in South Africa (Fig. 1) is the largest mafic-ultramafic layered intrusion in Earth's continental crust comprising about 600,000 km<sup>3</sup> of igneous rocks (Cawthorn, 2015; Cawthorn and Walraven, 1998; Latypov et al., 2022a, 2022b). The complex consists of several parts, the western, eastern, and northern limbs being the largest, and is subdivided stratigraphically into five major units - the Marginal, Lower, Critical, Main, and Upper Zones, comprising a total thickness of 7 to 9 km (Fig. 2; Cawthorn and Walraven, 1998; Cawthorn, 2015). The Bushveld Complex is widely considered to be a typical example of an open-system magma chamber (Cawthorn, 2015; Kruger, 2005; Latypov et al., 2022a, 2022b; Yao et al., 2021). Its principal zones are attributed to major replenishing events, with numerous smaller magma recharges contributing to the formation of these zones. During this process, the magma chamber incrementally increased in size through both vertical and lateral inflation (Eales, 2002; Kruger, 2005; Sharpe, 1985;





**Fig. 2.** Simplified stratigraphic section through the Bushveld Complex (Rustenburg Layered Suite) in South Africa and stratigraphic position of the Lower, Middle and Upper Group chromitites as well as the Merensky and Bastard Units in the Critical Zone. Also indicated by red scripts are objects (UG1, UG3, Merensky Reef, Main Magnetite Layer) involved in this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Willemse, 1959). All major replenishing events are marked by regionally extensive magmatic unconformities, local erosive unconformities into previous strata, significant isotopic shifts, and notable changes in whole-rock and mineral compositions (Cawthorn, 2015; Eales et al., 1990; Kinnaird et al., 2002; Kruger, 2005; Smith et al., 2013).

The Bushveld Complex hosts global resources of several critical metals. The Merensky Reef (MR; Fig. 2), together with two other principal deposits of the complex (UG2 chromitite and the Platreef), provide ~75% of the globally exploited platinum, ~35% of the world's Pd and > 80% of its Rh (Mungall and Naldrett, 2008). The MR usually occurs as a package of sulphide-bearing silicate rocks of broadly melanoritic to orthopyroxenitic composition (a few cm to a few m in thickness) that are extremely enriched in the platinum group elements (PGE). The package is normally easily recognizable because it occurs among cumulate rocks that are almost totally devoid of chromite and sulphide (Cawthorn, 2011; Hunt et al., 2018; Hutchinson et al., 2015; Maier et al., 2013; Naldrett et al., 2011).

The Bushveld Complex also contains >80% of the world's known

chromium resources (Cawthorn, 2010) which are hosted within 14 principal layers of massive chromitites (60–90 vol% chromite), mostly confined to the Critical Zone (Fig. 2; Scoon and Teigler, 1994; Schurmann et al., 1998; Naldrett et al., 2012). Three major groups of chromitites are recognised: the Lower (LG1 to LG7); Middle (MG0 to MG4); and Upper Groups (UG1 to UG3) (Schurmann et al., 1998). The thickness of individual chromitite layers ranges from a few centimeters to 2–3 m and some of them are traced across the entire complex (Hasch and Latypov, 2021; Schurmann et al., 1998).

Finally, the Bushveld Complex contains ~45% of the estimated world reserves of vanadium, which are mostly hosted in magnetite layers of the Upper Zone (Viljoen, 2016). About 21 magnetite layers ranging from massive titaniferous magnetite to disseminated and weakly disseminated magnetite occur within, or are associated with, magnetite gabbro, gabbro and diorite of the Upper Zone. Only the lowermost magnetite layers of 1 to 2 m thick (e.g., Bottom Seam Magnetite and Main Magnetite Layer; Fig. 2) with the highest vanadium content are currently mined in the Bushveld Complex and have been a subject of recent investigations (Kruger and Latypov, 2020, 2021, 2022).

### 3. Field observations

In this section, we present a comprehensive set of field and textural observations from chromitite and magnetite layers as well as the Merensky Reef that provide some strict constraints on the rheological state of the floor cumulates in the evolving Bushveld magma chamber (Figs. 1 and 2).

#### 3.1. Structures formed by soft-sediment deformation in the cumulate pile

##### 3.1.1. Recumbent folds within non-deformed strata

Fig. 3a and b show anorthosite, chromitite and norite layers that are plastically deformed into recumbent folds (with a sub-horizontal axial plane) that occur within a sequence of adjacent horizontal (non-deformed) layers of the same composition. The structures were probably formed when a sequence of layers detached from the layers below and above and began moving sub-horizontally (e.g., under the influence of gravity). The movement caused the soft layers to deform plastically, producing folded structures within a sequence of otherwise undisturbed cumulate layers. Fig. 3c illustrates another example of a complex fold consisting of plastically deformed orthopyroxenite and leuconorite layers. The overlying and underlying orthopyroxenite layers are only slightly deformed. Finally, in Fig. 3d, a thin chromitite seam is plastically deformed into a very small fold of an intricate shape which probably happened in response to a lateral flow of the hosting anorthosite. The deformation of anorthosite itself is not seen due to lack of any markers in this layer. The overlying and underlying chromitite layers do not appear to be deformed.

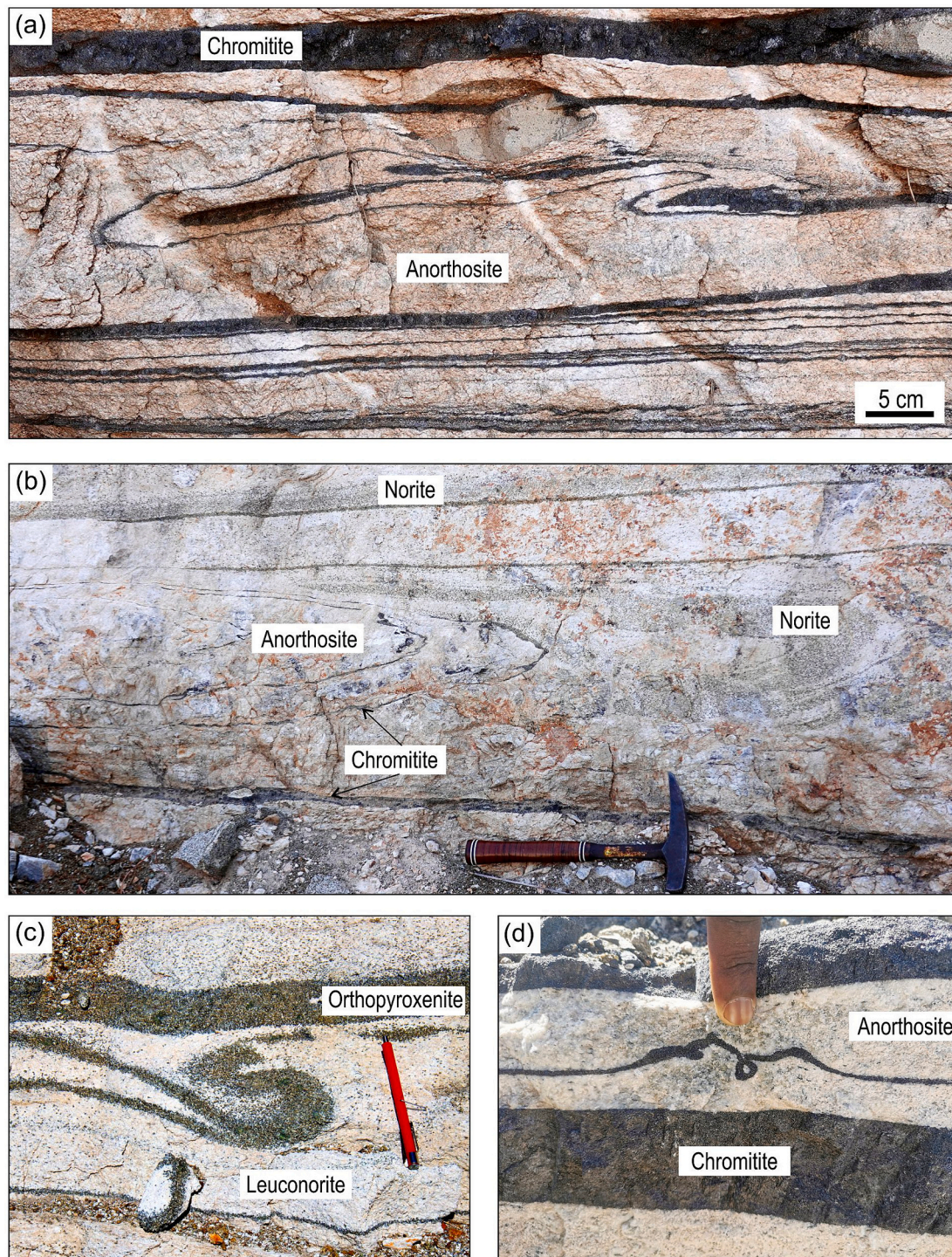
##### 3.1.2. Synclinal folds overlain by non-deformed strata

Fig. 4 shows two synformal folds that consist of plastically deformed anorthosite and chromitite layers. The structures are interpreted to have been caused by gravity-induced slumping of the layered sequence into the underlying cumulate pile. Importantly, the uppermost chromitite layer (only its base is visible in the photos; dotted yellow lines) is planar and non-deformed suggesting its deposition to have occurred after the underlying rocks were slumped and smoothed out by erosion from above.

##### 3.1.3. Shear boudinage of competent rocks within plastically deformed strata

Fig. 5a depicts locally developed asymmetric boudinage (or book-shelf boudinage) in an otherwise continuous orthopyroxenite layer that occurs within a plastically deformed leuconorite sequence. The orthopyroxenite layer has behaved in a brittle manner and has been broken





**Fig. 3.** Photographs of recumbent folds within non-deformed strata from the UG1 sequence. Upper Critical Zone, eastern Bushveld Complex. Anorthosite and chromitite layers that are plastically deformed into two recumbent folds that are sandwiched between a sequence of non-deformed, sub-horizontal layers of chromitites and anorthosites. Maandaagshoek section. (b) Anorthosite, chromitite and norite layers that are plastically deformed into a recumbent fold that is sandwiched between a sequence of non-deformed, sub-horizontal layers of the same composition. Head of the hammer is 17 cm. Jagdlust section (c) A recumbent fold that consists of plastically deformed orthopyroxenite and anorthosite layers. The overlying and underlying orthopyroxenite layers are only slightly deformed. Red pen is 13 cm. Jagdlust section. (d) A thin chromitite seam is plastically deformed into a very small fold of an intricate shape, with no deformation in the underlying and overlying rocks. Jagdlust section. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

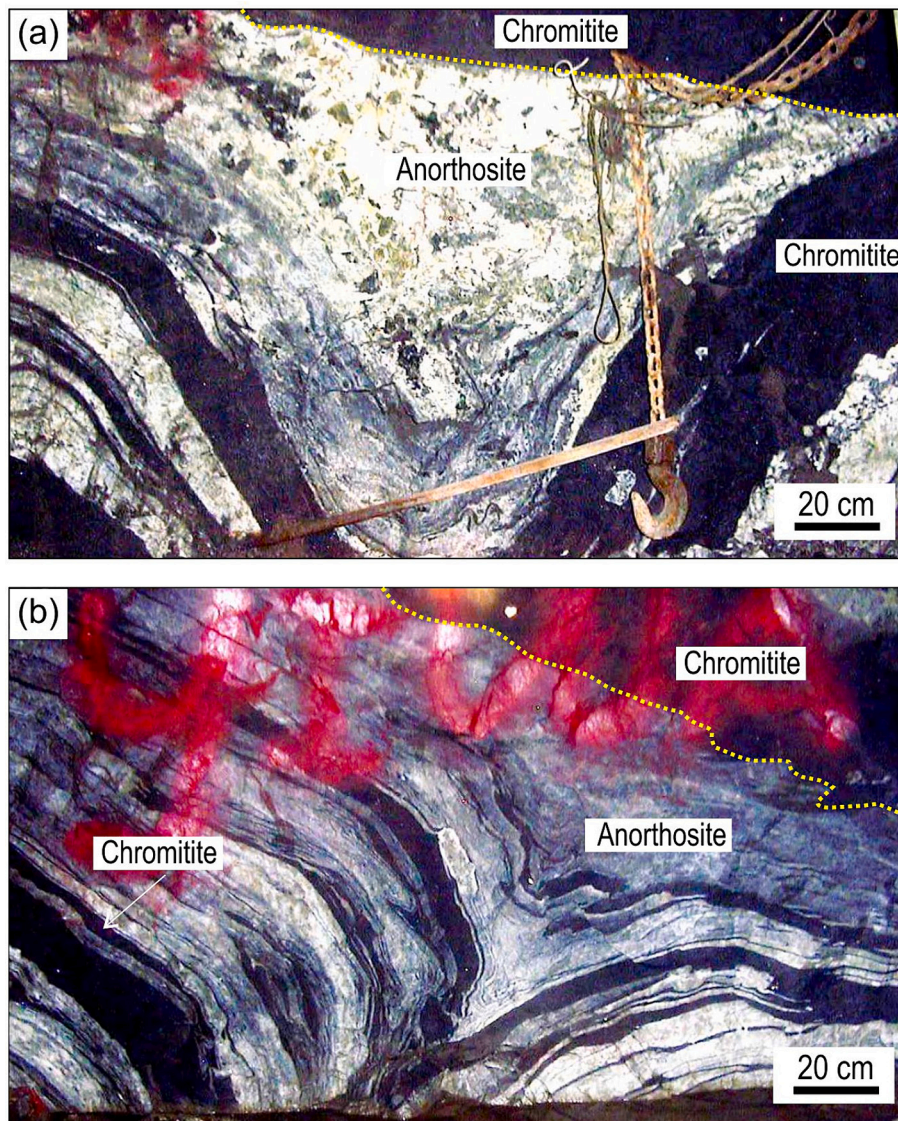
into boudins by asymmetric shear fractures while the anorthosite has deformed plastically. Some orthopyroxenite layers below and above the boudinaged orthopyroxenite layer are also plastically deformed. Fig. 5b shows boudins that are formed by the stretching of thin chromitite layers within a plastically deformed anorthosite layer. In this case, chromitite

behaved as a competent layer within the mushy anorthosite.

#### 3.1.4. Extensional boudinage of competent rocks within plastically deformed strata

Fig. 6 illustrates two examples of chromitite layers that are





**Fig. 4.** Photographs of syncline folds overlain by non-deformed strata from the UG1 sequence at Rustenburg Platinum Mine. Upper Critical Zone, western Bushveld Complex. (a) A syncline fold that consists of plastically deformed anorthosite and chromitite layers. Note that the uppermost chromitite layer (only its base is visible in the photo) is planar and non-deformed. A hinge zone of the fold is not exposed. (b) A syncline fold that consists of both plastically and brittily deformed anorthosite and chromitite layers. Note that the uppermost chromitite layer (its base is marked by a yellow dotted line) is planar and non-deformed. A hinge zone of the fold is not exposed. Photographs courtesy of Alan Page. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

fragmented into angular blocks by extension, with the adjacent anorthosites being mobilized to fill in the cracks between the blocks. In Fig. 6a the blocks of the thicker lower chromitite layer largely remain at their original position. However, one block of the upper chromitite layer appears to have sunk downwards and shifted with the mobilized anorthosite underneath its original layer. In Fig. 6b several blocks of one chromitite layer appear to have been displaced downwards and were shifted underneath this layer within mobilized anorthosite (red arrow). In addition, the upper anorthosite layer has also become mobile and has been intruded upwards as a subvertical cross-cutting body with sub-horizontal offshoots into the host melanorites (blue arrow).

### 3.1.5. Suction of plastically deformed strata into fractures within competent rocks

Fig. 7a shows an outcrop in which two thin chromitite stringers within anorthosite curve upward towards a crack in the overlying disrupted chromitite (red arrow). This likely testifies the low-pressure-induced sucking (entrainment) of anorthosite slurry (as indicated by

stringers) into the extensional crack within the overlying chromitite layer. In Fig. 7b, anorthosite was sucked upwards into the overlying strata through a fracture that extends into both chromitite and orthopyroxenite of the UG1 sequence. The anorthosite is plastically deformed and has a variable thickness and tapering edge towards the top.

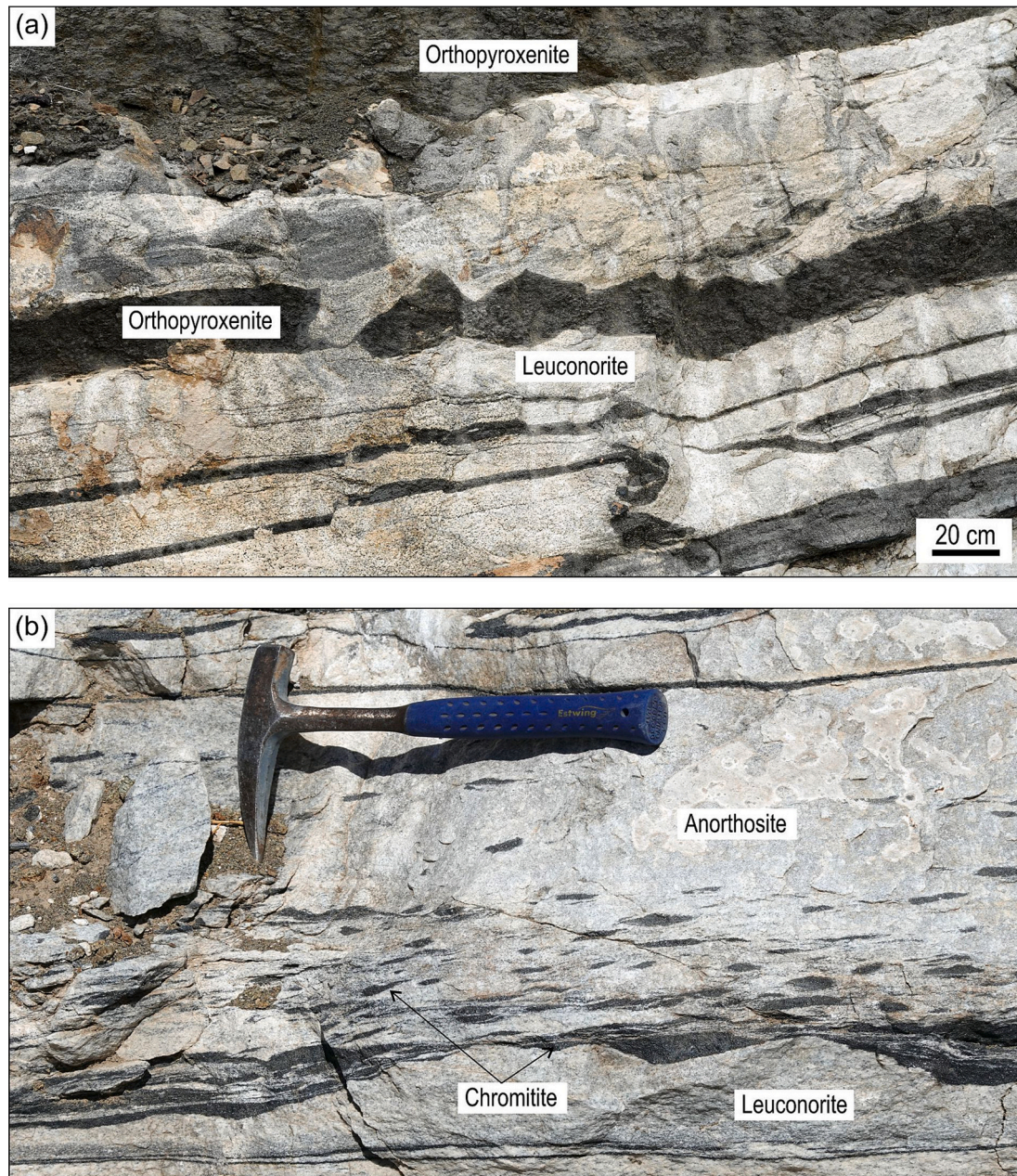
### 3.1.6. Sinking of chromitite blocks into the plastically deformable strata

Fig. 8 illustrates a spectacular example of fragmentation of a chromitite layer into angular blocks, with some of them sinking downwards into a plastically deformed anorthosite footwall. Note that the largest block has disrupted and displaced downwards from its original position a thin chromitite stringer within the underlying anorthosite (red arrow).

### 3.1.7. Upward and downward-oriented flames

Fig. 9 shows two examples of anorthosite layers that form irregular flames that extend either into the hanging wall melanorite of the UG2 sequence (a) or downwards into the underlying UG1 chromitite (b). The direction (up vs down) of movement is apparently not controlled by





**Fig. 5.** Photographs showing boudinage of some cumulate layers from the UG1 sequence. Upper Critical Zone, eastern Bushveld Complex. (a) Bookshelf boudinage in orthopyroxenite layer hosted within a plastically deformed leuconorite of the UG1 sequence at Maandaagshoek section. Below and above the boudinaged orthopyroxenite layers, other orthopyroxenite layers are also plastically deformed. (b) Locally developed boudinage of thin chromitite seams within a plastically deformed anorthosite from the UG1 sequence at the Jagdlust section.

gravity but rather by the effect of differential pressure of dilations in the rocks hosting the anorthosite. In addition, highly elongated schlieren of anorthosite within the melanorite (a) imply layer-parallel ductile deformation of both rock types that resulted in fragmentation of the originally continuous anorthosite layer into a large number of schlieren (red arrows).

### 3.1.8. Chaotically oriented blocks of competent rocks in plastically deformed strata

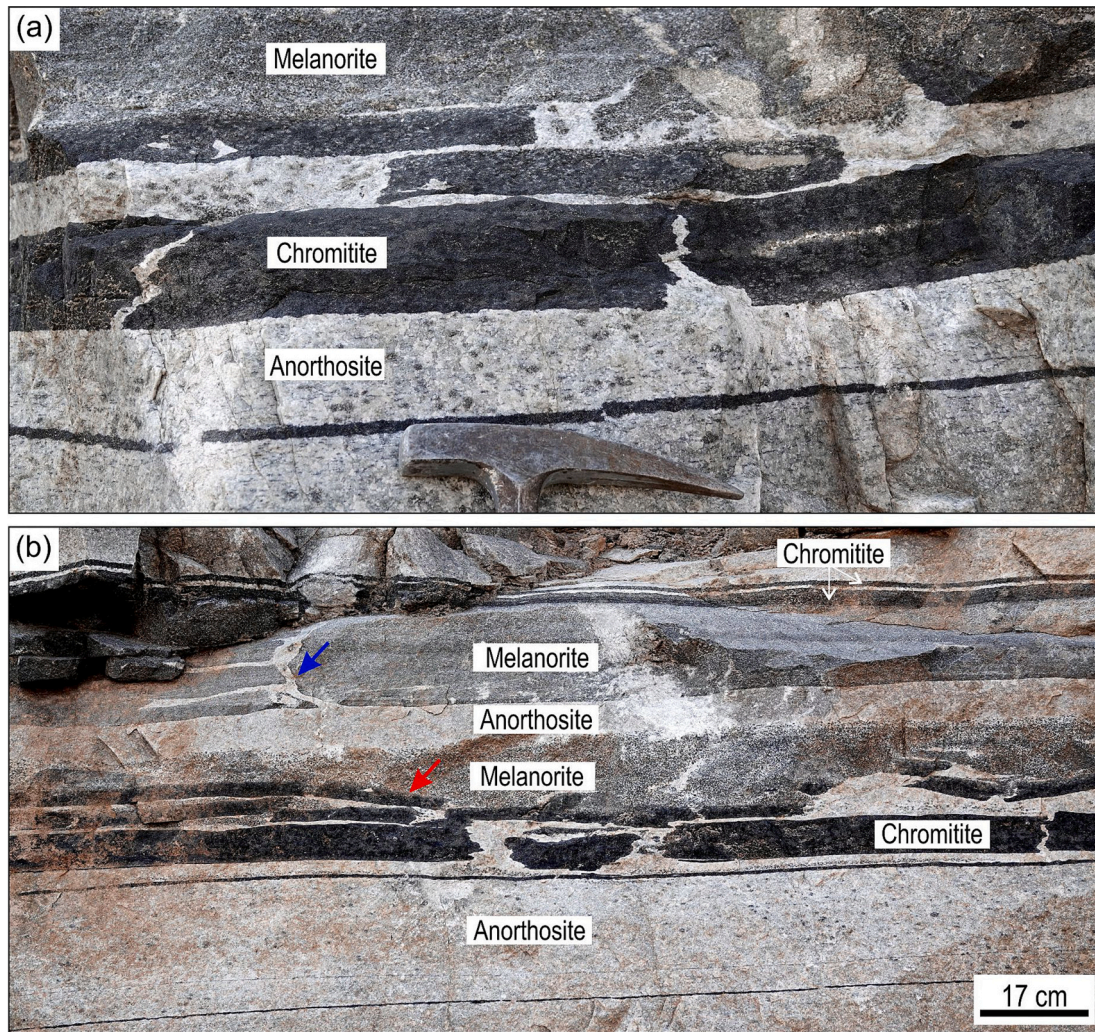
Fig. 10 exhibits an underground exposure with irregular and disoriented fragments of the UG1 chromitite of various sizes and shapes in plastically deformed anorthosites. Some fragments seem to have been derived from neighbouring exposures and transported into this place with laterally moving anorthosite. Fig. 11 shows an open pit outcrop

with a large depression produced by downward slumping of a gabbro/anorthosite sequence containing magnetitite layers. On the left side, the depression is marked by the Main Magnetitite Layer (MML) and the Magnetitite Layer 1 (ML1) that curve and plunge downwards, with the ML1 abruptly terminating. The central part of the depression contains several chaotically oriented blocks of magnetitite layers which are probably derived from the overlying Magnetitite Layer 2 (ML2; not seen in the photo) that was disrupted and collapsed downwards together with host gabbro/anorthosite.

### 3.2. Planar erosional surfaces truncating the structures formed by soft-sediment deformation in the cumulate pile

We present here three examples of soft-sediment deformation





**Fig. 6.** Photographs of extensional boudinage of competent rocks within plastically deformed strata from the UG1 sequence at Maandaagshoek section. Upper Critical Zone, eastern Bushveld Complex. (a) Fragmentation of chromitite layers into angular blocks, with underlying anorthosite being mobilized upwards to fill in a crack between the blocks. Note that a block of the upper chromitite layer sunk downwards and shifted underneath this layer with mobilized anorthosite. A visible part of head of the hammer is 15 cm. (b) Fragmentation of chromitite layers into angular blocks, with underlying anorthosite being mobilized upwards to fill in cracks between the blocks. The anorthosite has also been intruded into the overlying layer of melanorites (blue arrow). Note that one chromitite layer are broken into blocks that are shifted underneath this layer with mobilized anorthosite (red arrow). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

structures that, unlike the above considered examples (Figs. 3–11), have been truncated from above by planar erosional surfaces.

Fig. 12a shows melanorite and anorthosite layers that are plastically deformed into at least three small recumbent folds. One recumbent fold preserves (marked as 3 in Fig. 12a; Fig. 12c,) its original shape whereas two others (marked as 1 and 2 in Fig. 12a; Fig. 12b) are truncated by a planar erosional surface and overlain by non-deformed, sub-horizontal anorthosite-melanorite/orthopyroxenite layering (hinge zones of both folds remain preserved). The contact between the beheaded melanorite folds and overlying planar anorthosite is gradational as indicated by an increase in plagioclase content of the melanorite and in orthopyroxene content of the anorthosite towards the erosional surface (Fig. 12b).

Fig. 13a illustrates an example of a recumbent melanorite fold that was smoothed out by a planar erosional surface (again, with its synformal hinge zone being preserved, Fig. 13c) and overlain by non-deformed, sub-horizontal leuconorite-pyroxenite layering. The leuconorite-pyroxenite layering below the fold is depressed downwards resulting in an angular discordance between the depressed layering and the overlying sub-horizontal layering (Fig. 13b) that has been deposited on the erosional surface. Again, the contact between the eroded

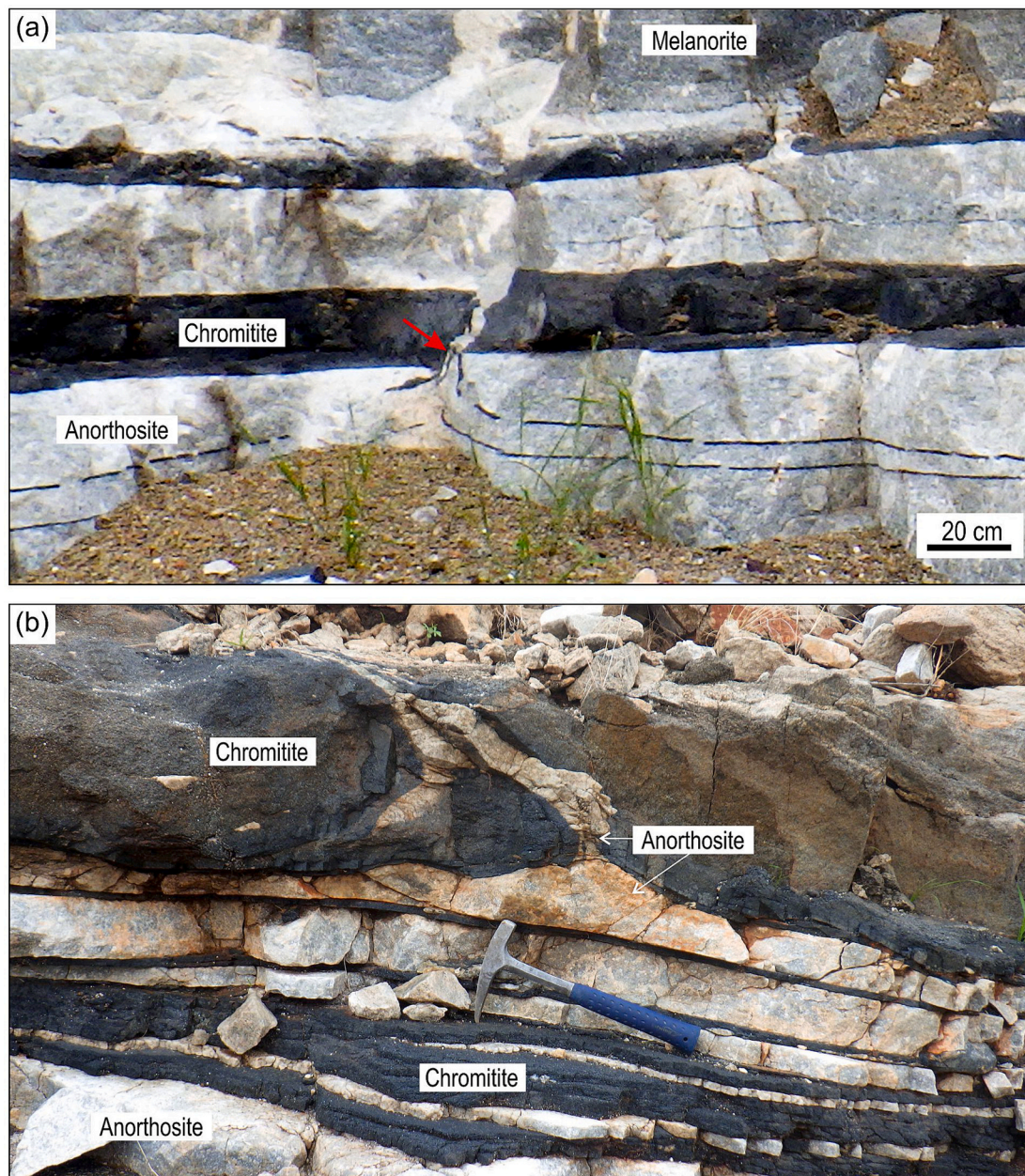
melanorite fold and overlying planar leuconorite is gradational, as indicated by an increase in plagioclase in melanorite and in orthopyroxene in leuconorite towards the erosional surface (Fig. 13b).

Fig. 14a exhibits yet another example of the deformed and locally folded leuconorite-orthopyroxenite strata (Fig. 14c) that is truncated by a planar erosional surface and overlain by non-deformed, sub-horizontal leuconorite-melanorite-orthopyroxenite layering. There is an angular discordance between this deformed layering and the overlying sub-horizontal layering (Fig. 14b) that has been deposited on the erosional surface. The contact between the eroded strata and overlying planar melanorite is gradational as indicated by increases in plagioclase in melanorite and in orthopyroxene in leuconorite towards the erosional surface.

### 3.3. Irregular erosional surfaces truncating the structures formed by hard rock deformation in the cumulate pile

The hard rock deformation structure is illustrated here using the Merensky Reef (MR) and its footwall rocks as an example (Fig. 15) although the similar field relations are characteristic of the UG1/UG2





**Fig. 7.** Photographs illustrating suction of plastically deformed strata into fractures within the overlying competent rocks, Upper Critical Zone, eastern Bushveld Complex. (a) Two thin chromitite stringers that were sucked together with anorthosite into an extensional crack (red arrow) in the overlying disrupted chromitite layer from the UG1 sequence at Maandaagshoek section. (b) An anorthosite layer that was sucked upwards into the overlying sequence of chromitite and orthopyroxenite from the UG1 sequence at Paschaskraal section. Note that the anorthosite layer becomes thicker towards the sucking point. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

chromitites and their underlying rocks (Latypov et al., 2017, their Fig. 11c). Fig. 15 shows an underground exposure of the MR that overlies with an angular discordance the layered sequence of footwall rocks. The field relations imply that the layered footwall rocks were tilted without losing their coherence and then eroded away before being covered by the MR. Of notice is the knife-sharp and scalloped nature of a contact between the footwall rocks and the overlying MR.

#### 4. Textural observations

##### 4.1. Truncation of fine scale anorthosite-chromitite layering by mini-potholes

Potholes are depressions at the base of a cumulate layer, roughly

circular in plan view, that truncate the layering beneath them. They can be anywhere from a few cm to tens of metres deep (Ballhaus, 1988; Hahn and Owendale, 1994; Schmidt, 1952; Van der Merwe and Cawthorn, 2005; Viljoen, 1999) and are common at the base of major cyclic units within the Critical Zone (Cawthorn, 2015; Chistyakova et al., 2019b; Latypov et al., 2015, 2019; Lomberg et al., 1999; Viring and Cowell, 1999). The UG1 sequence shows mini-potholes at the base of some chromitite layers which truncate the underlying, fine scale anorthosite-chromitite layering. Two examples of such mini-potholes in hand specimens are presented here. In one on them (Fig. 16a), a ~ 0.6 cm thick chromitite seam reveals a ~ 2 cm deep mini-pothole that sharply cuts through the underlying fine-scale layering of anorthosite and chromitite. Truncated layers are completely undisturbed all the way to the base of the mini-pothole at the scale of the grain size. The upper





**Fig. 8.** Photograph of a chromitite layer broken into angular blocks, with some of them sinking downwards into the underlying anorthosite from the UG1 sequence at Maandagshoek section. Upper Critical Zone, eastern Bushveld Complex. The local thickening of the lower chromitite layer is due to an occurrence of a melanorite autolith.

contact of the pothole-filling chromitite is straight and parallel to other layers in the specimen. An XRF element map of this specimen (Fig. 16b) reveals in addition that orthopyroxene oikocrysts only occur in the chromite-rich layers, and never in the plagioclase-rich layers. In another example (Fig. 17A), an ~8 cm deep mini-pothole truncates the underlying anorthosite-chromitite layering which includes among others one prominent chromitite stringer of ~0.6 cm thick. The upper contact of the potholing chromitite seam is not preserved in the specimen. Again, an XRF element map of this specimen (Fig. 17b) shows that orthopyroxene oikocrysts occur exclusively in the chromite-rich layers. There is no growth of oikocrysts across layer contacts as would be expected if the entire interval were mushy. It is quite conceivable that such mini-potholes may occur at the bases of all massive chromitites of the complex, but the prominence of the fine scale chromitite-anorthosite layering makes them particularly noticeable in the UG1 sequence.

#### 4.2. Truncation of pyroxene oikocrysts in anorthosites by the UG3 chromitite/Merensky Reef

The magmatic erosion of the footwall anorthosites by chromitite becomes especially clear where the anorthosites are mottled, i.e., have oikocrysts of clinopyroxene/orthopyroxene that are commonly of a rounded shape (Figs. 15b and 18). In this case, their truncation is evident from beheading of the rounded oikocrysts (i.e., only the lower part of the oikocrysts is preserved). This observation is important because oikocrysts fill interstitial space and cement a population of small plagioclase chadacrysts of anorthosite (Fig. 18c). The beheaded oikocrysts are separated from the overlying chromitite by a rind of larger plagioclase crystals that is only 1–2 grains wide. The rind is usually interpreted as representing the residual (and recrystallized) phases that are left at the site after complete melting/dissolution of clinopyroxene/orthopyroxene oikocrysts (together with some plagioclase) from anorthosite in response to thermochemical erosion (Latypov et al., 2015; Smith et al., 2021). Similar observations on truncation of pyroxene oikocrysts in anorthosites by the MR have been reported elsewhere (Hutchinson et al., 2015; Latypov et al., 2015).

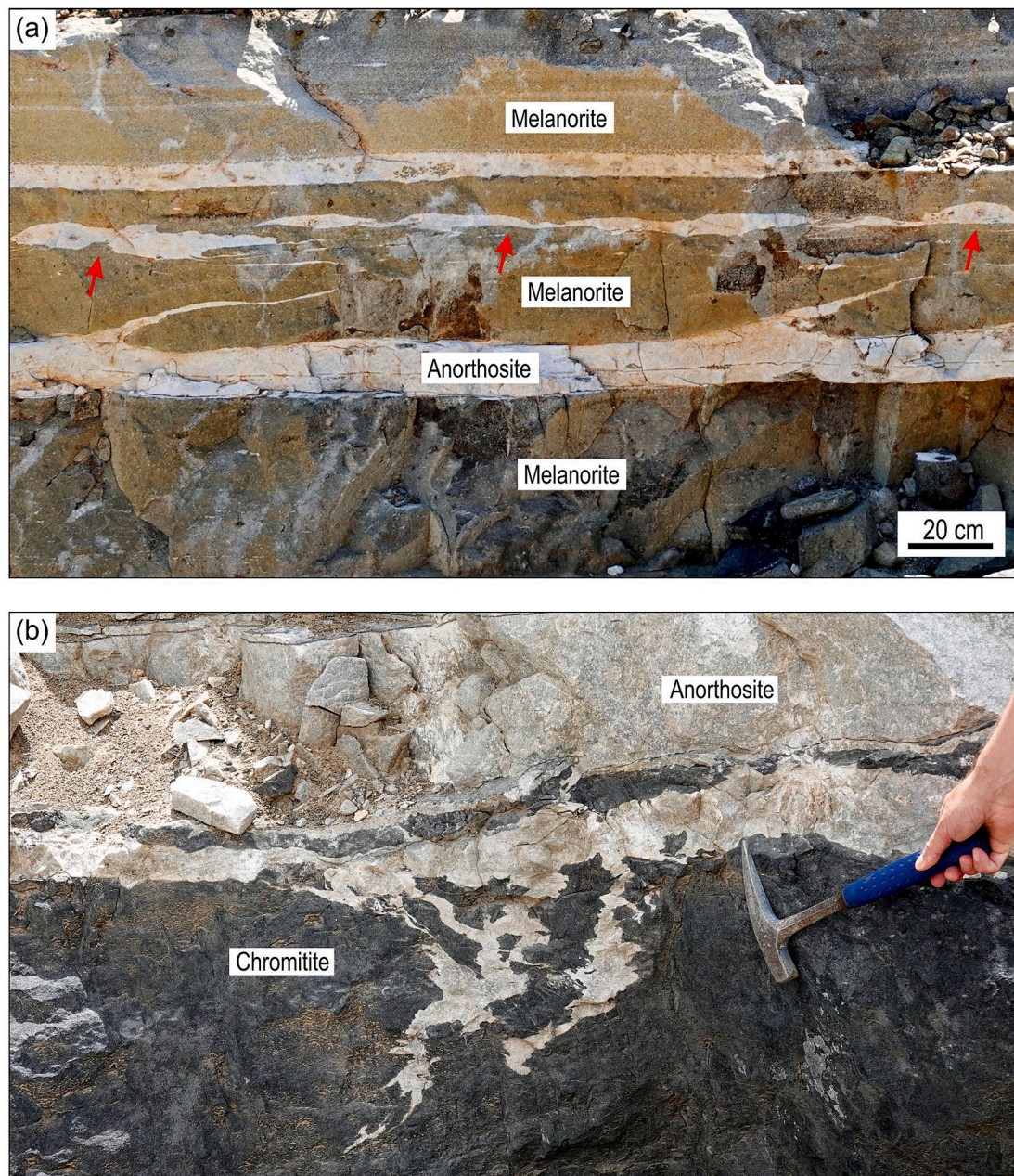
#### 4.3. Resumed growth on truncated oikocrysts/primocrysts from anorthosite into the overlying UG3 chromitite

The sharpness of the erosional surface is additionally emphasized by truncation of large orthopyroxene crystals (Fig. 19) and by the fact that these crystals as well as truncated oikocrysts of clinopyroxene/orthopyroxene and plagioclase primocrysts (Fig. 20) commonly act as seeds for the resumed growth of these minerals into the overlying chromite mush. Where a plagioclase rind is poorly developed, we observe the localized and highly selective growth of orthopyroxene on orthopyroxene, clinopyroxene on clinopyroxene and plagioclase on plagioclase (Fig. 20c). In cases where a plagioclase rind is present, only plagioclase grows as oikocrysts into the overlying chromite much (Fig. 18b, c) – i.e., in the absence of orthopyroxene and clinopyroxene seeds, no growth of these minerals occurs at the basal contact.

#### 4.4. Termination of downward percolation of a sulphide liquid at the base of the Merensky Reef

The base of the MR is normally marked by ~1–2 cm thick chromitite seam (up to 50–60 vol% chromite) which shows sharp upper and lower contacts (Fig. 21a). In this seam, plagioclase forms large oikocrysts which occupy the interstitial space in its lower part whereas oikocrystic orthopyroxene mainly occurs in the upper part of the chromitite seam (Fig. 21b). Orthopyroxene oikocrysts in the upper part of the seam are continuous with the overlying orthopyroxene-rich layer that is a few crystals thick. The relations of this chromitite seam with the footwall mottled anorthosite are similar to those of massive chromitites with their footwall rocks (e.g., truncation of pyroxene oikocrysts, a few grains wide plagioclase rind, resumed growth of crystals into the overlying chromite mush). Unlike the massive chromitites, the MR is rich in base metal sulphides. Base metal sulphides tend to occur in both the chromitite layer and overlying orthopyroxenite of the MR, although they tend to be much smaller in a chromitite seam. Sulphides in a chromitite seam concentrate along the contacts between plagioclase and orthopyroxenite oikocrysts, with very little to no sulphide inside the oikocrysts themselves. This suggests that a sulphide liquid started percolating through the interstitial space of a chromite mush after the oikocrysts had





**Fig. 9.** Photographs of upwards and downward-oriented flames from anorthosite layers from the UG1 sequence at Maandaagshoek section. Upper Critical Zone, eastern Bushveld Complex. (a) An anorthosite layer that shows irregular flames that extend into the overlying melanorites. Note that another anorthosite layer was dismembered and deformed into many elongated schlierens (red arrows). (b) An anorthosite layer that forms irregular flames that extend downwards into the underlying UG1 chromitite. Head of the hammer is 17 cm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

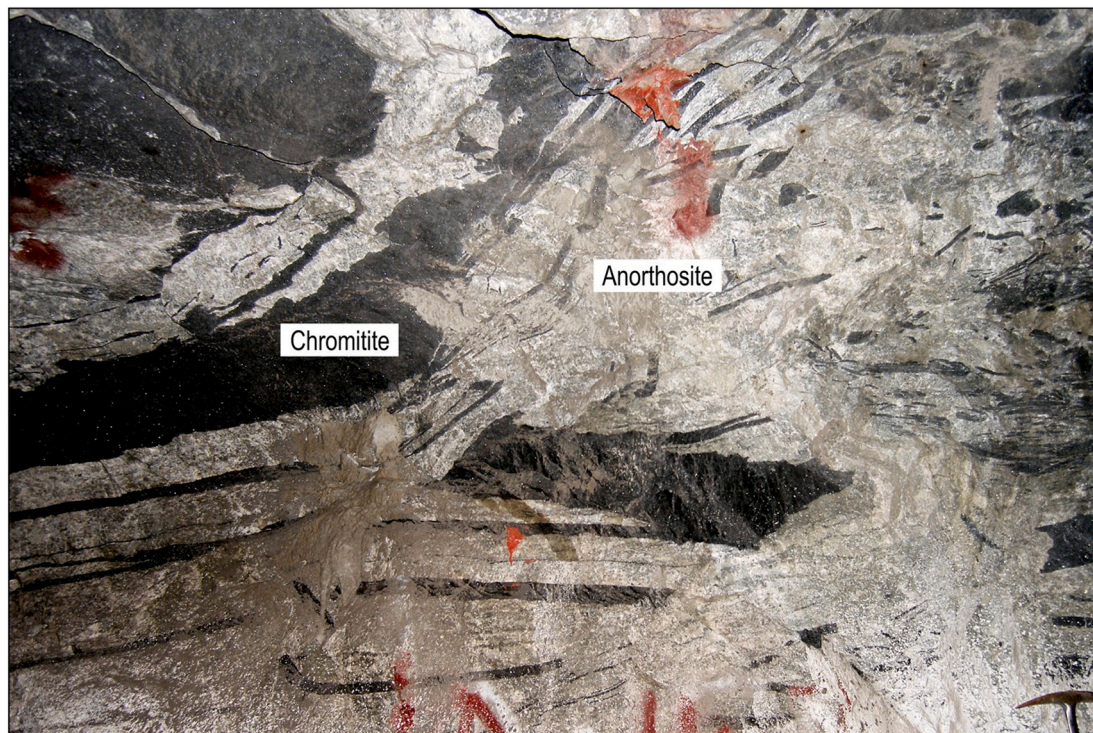
already formed. Most importantly, the sulphides do not extend into the footwall mottled anorthosites (Fig. 21c). Similar textural observations on distribution of the base metal sulphide within the MR have been reported elsewhere (Barnes et al., 2021b; Smith et al., 2021). In some places, however, base metal sulphides may occur for 30 cm (Barnes and Maier, 2002) and even for 1–2 m (Cawthorn, 1999) below the chromitite layer of the MR, but 2 m is the upper limit.

#### 4.5. Truncation of plagioclase crystals in anorthosite by massive magnetitite

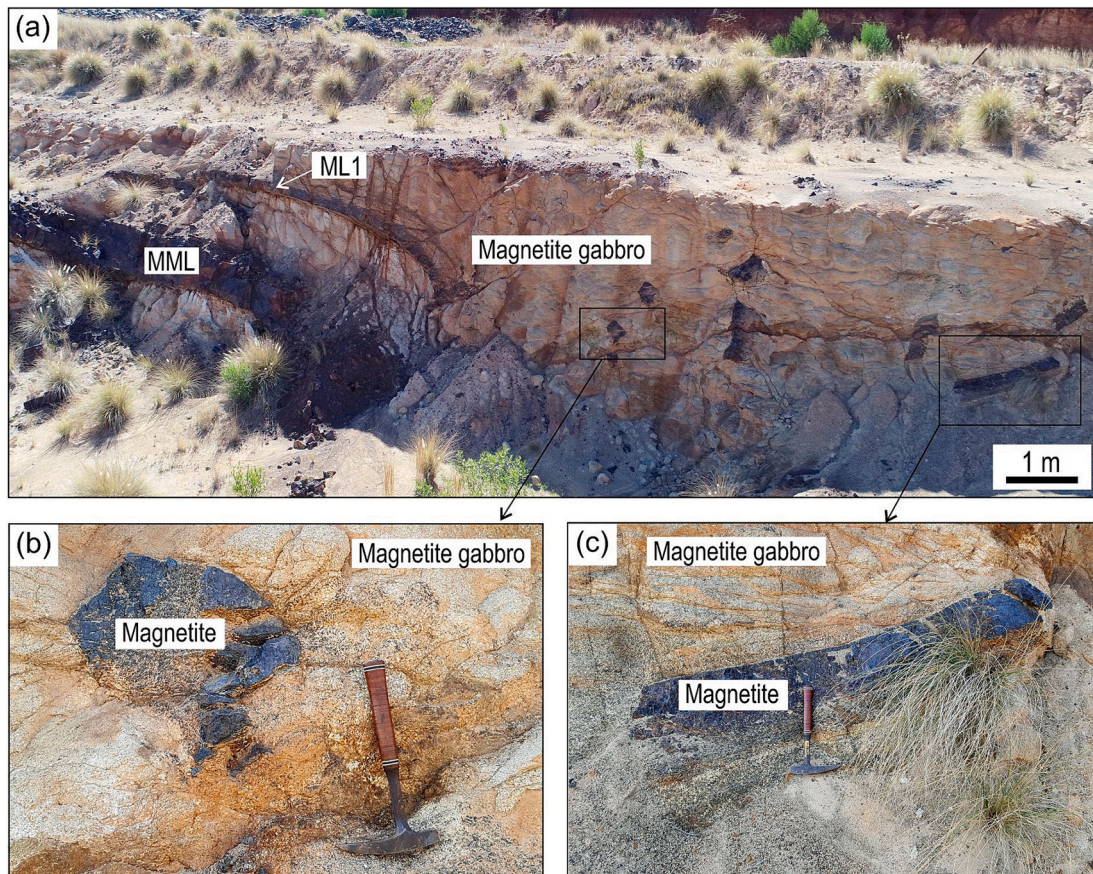
Unlike UG1/UG3 chromitites that contain, at best, up to 50–60% of chromite, massive magnetitites are nearly monomineralic (~100%

magnetite) which makes their relations with the underlying anorthosite/gabbro especially visible (Figs. 22, 23). In drill-core (Fig. 22a), the anorthosite-magnetitite contacts are typically knife-sharp and highly irregular, with small angular erosional remnants of the underlying anorthosite/gabbro in the basal magnetitite. The sharpness of these contacts is indicative of the anorthosites being in the solid state at the time/level of their truncation. Magnetitites also commonly contain remnants (i.e., in situ autoliths) of anorthosite that are interpreted to have formed by partial thermochemical erosion of the underlying anorthosite in a phenomenon that has been termed as magmatic karst (Kruger and Latypov, 2021). A part of one such in situ autolith can be observed in the top half of Fig. 22b. The autolith itself has experienced a large extent of thermochemical erosion indicated by the presence of



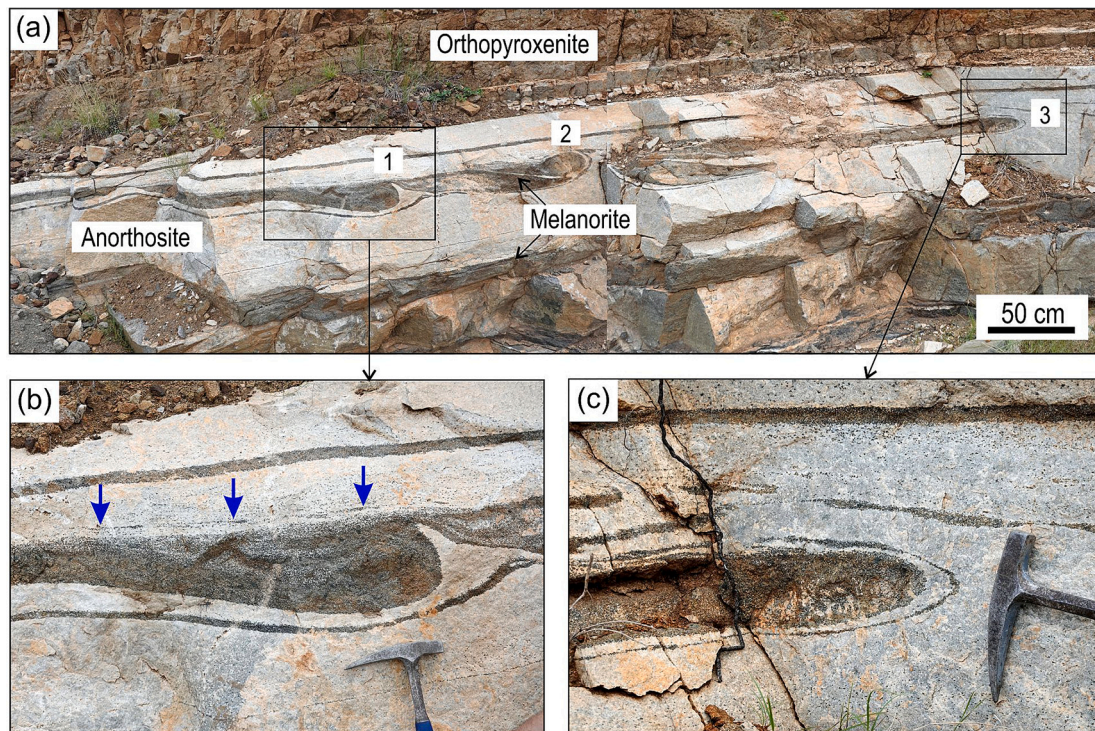


**Fig. 10.** Photograph of a chromitite layer within anorthosite that has been fragmented into many chaotically oriented blocks of various sizes and shapes. Underground exposure of UG1 sequence in the School of Mine, Upper Critical Zone, western Bushveld Complex. Head of the hammer in the bottom right corner is 17 cm.

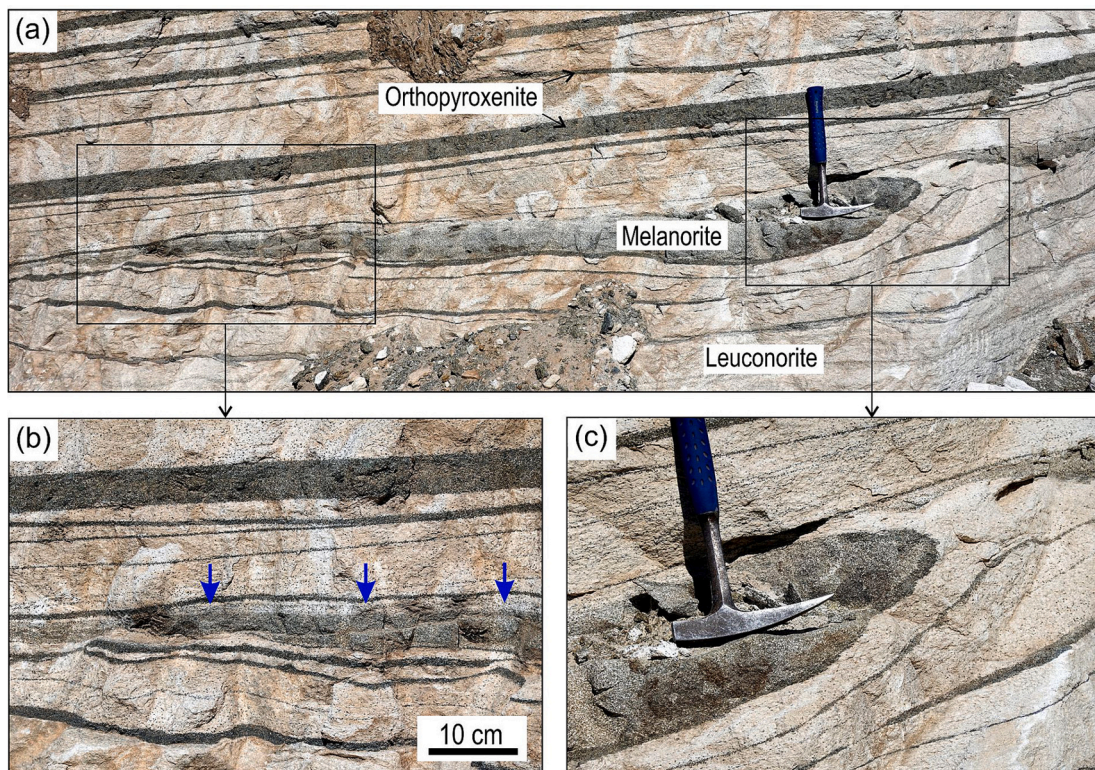


**Fig. 11.** Photographs of disrupted magnetitite layers from the Upper Zone, western Bushveld Complex. (a) An exposure of a large depression with the slumping Main Magnetitite Layer (MML) and Magnetitite Layer 1 (ML1) (b) Close up view of the depression containing several chaotically oriented blocks of magnetite layers which are likely derived from the overlying Magnetitite Layer 2 (ML2, not seen in the photo). (c) Close up view of one fragment of the ML2 from this depression. Head of the hammer in (b) and (c) is 17 cm. Rhovan mine, Open Pit 1 West.



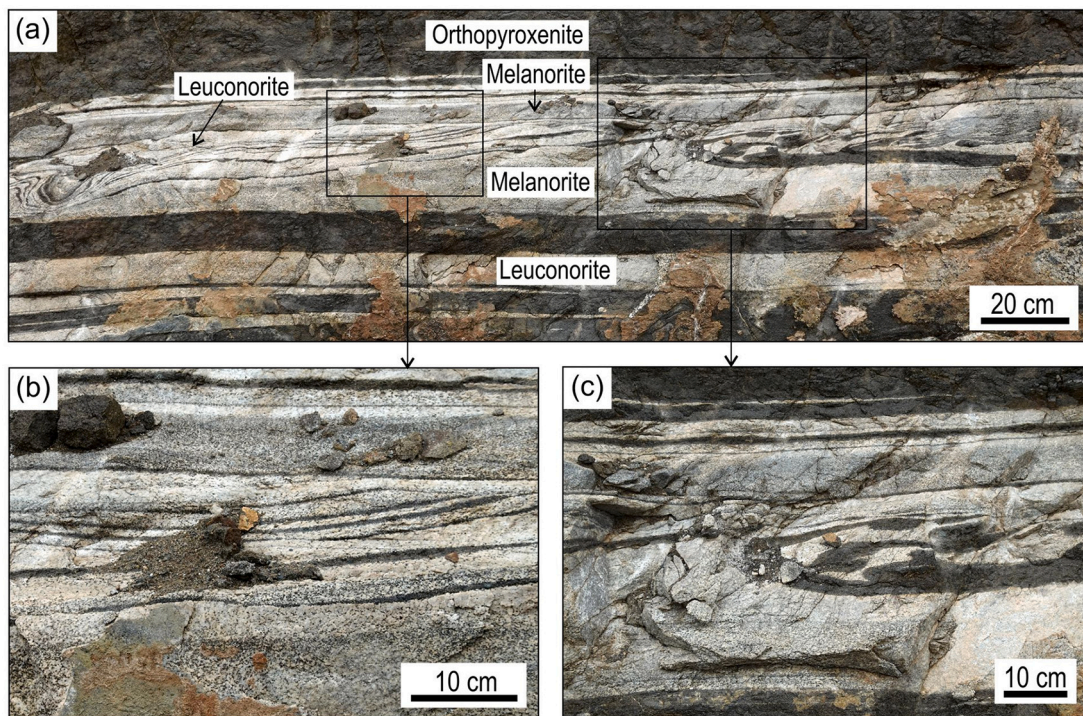


**Fig. 12.** Photographs of a planar erosional surfaces truncating the soft sediment deformation structure from the UG1 sequence at Maandaagshoek section. Upper Critical Zone, eastern Bushveld Complex. (a) A soft sediment deformation structure with three melanorite recumbent folds. (b) The folds 1 and 2 are partially smoothed out by a planar erosional surface whereas the fold 3 preserves its original shape (c). Note that the erosional surface at the top of the beheaded melanorite fold (b, blue arrows) is gradational over a distance of a few cm. Head of the hammer in (b-c) is 17 cm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



**Fig. 13.** Photographs of a planar erosional surface truncating the soft sediment deformation structure from the UG1 sequence at Jagdlust section. Upper Critical Zone, eastern Bushveld Complex. (a) A soft-sediment deformation structure with a melanorite recumbent fold that is partially truncated by a planar erosional surface. Head of the hammer is 17 cm. (b-c) The layering below the melanorite fold is depressed that resulted in an angular discordance between the deformed layering and the overlying sub-horizontal layers of norite/melanorite that have been deposited on the erosional surface. Note that an erosional surface between the fold and overlying norite is gradational over a distance of a few cm (b, blue arrows). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)





**Fig. 14.** Photographs of a planar erosional surface truncating the soft sediment deformation structure from the UG1 sequence at Maandaagshoek section. Upper Critical Zone, eastern Bushveld Complex. (a) The deformed and locally folded anorthosite-orthopyroxenite strata that is smoothed out by a planar erosional surface and overlain by non-deformed, sub-horizontal leuconorite-norite-pyroxenite layering. (b) Close up view of deformed norite/melanorite layering that is truncated by a planar erosional surface. (c) Close up view of one recumbent fold that is partially truncated by a planar erosional surface. Note that an erosional surface is gradational over a distance of a few cm (b-c).

abundant magnetite. A thin layer of mostly pure magnetite underneath the autolith indicates where the liquid cuts laterally into the footwall to separate the autolith from the footwall to which it was originally attached. In thin sections (Figs. 22b, c; 23b), magnetite cuts through the individual plagioclase crystals in the underlying anorthosite as well as develops as separate magnetite ‘inclusions’ within individual plagioclase crystals (Fig. 23c-d). Apart from the areas where a few cm long offshoots of magnetite intrude into the underlying anorthosites, at planar portions of the chamber floor magnetite penetrates the underlying anorthosite no deeper than 1 cm (Figs. 22, 23). Similar textural observations on the sharpness of a basal contact of magnetite layers with the underlying anorthosites have been reported elsewhere (Kruger and Latypov, 2021; Vukmanovic et al., 2019).

## 5. Discussion

### 5.1. Key inferences on the rheological state of a cumulate pile

Two sets of field and textural observations provide contrasting insights into the rheological state of a cumulate pile at the time of the formation of chromitite and magnetite layers as well as the Merensky Reef of the Bushveld Complex.

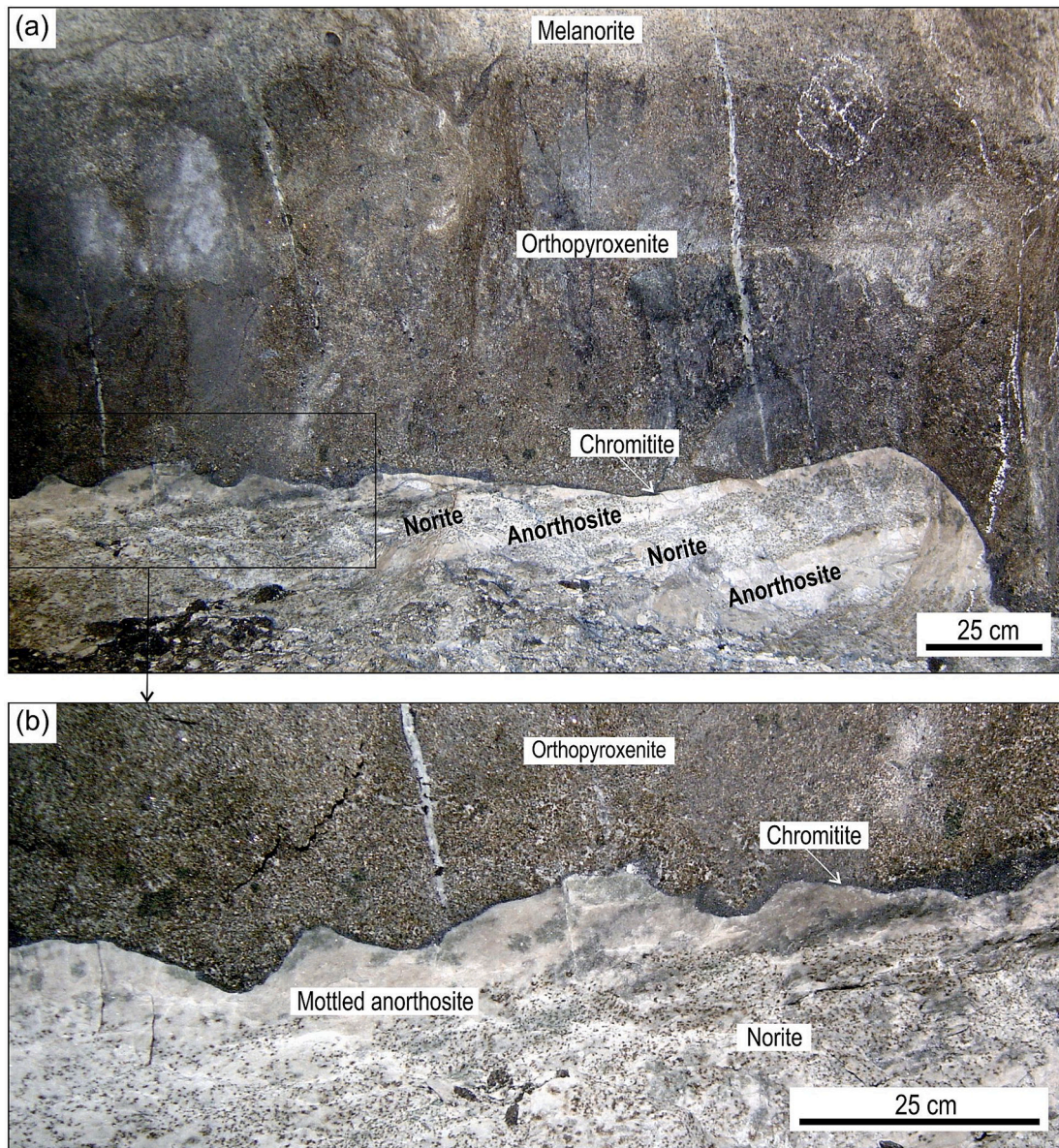
The first set which includes mostly soft-sediment deformation (ductile) structures (Figs. 3–11), indicates that anorthosites of the cumulate pile were in a mushy (unconsolidated) state and susceptible to plastic deformation, whereas intervening pyroxenite/chromitite layers were more competent and deformed in a predominantly brittle way. Similar soft-sediment deformation structures in the Bushveld Complex have been previously described by Lee (1981), Nex (2004) and Pebane and Latypov (2017). Both brittle and ductile layers are intercalated at decimetre scale with planar layers showing no deformation at all. These observations (Figs. 3–11), however, do not reveal exactly how deep within the cumulate pile these rocks were at the time of their

deformation. In other words, they give us no clue with regards to the thickness of the mushy layer on the inward-growing chamber floor at that time.

On the other hand, Figs. 12–14 show other examples of soft-sediment deformation structures which also indicate a mushy state of the cumulate pile but allow us to draw conclusions about the potential thickness of the mushy layer on the temporary chamber floor. The erosion of the chamber floor cumulates in the Bushveld Complex has been attributed to replenishing of the chamber by new pulses of hot/superheated magma (Campbell, 1986; Chistyakova et al., 2019a, 2019b; Eales et al., 1988; Hunt et al., 2018; Latypov et al., 2019; Lomberg et al., 1999; Mukherjee et al., 2017; Smith and Basson, 2006; Viljoen, 1999; Viring and Cowell, 1999). The ability of such magmas to erode the rocks of the chamber floor mechanically/thermally is limited and has been estimated both geologically (Latypov et al., 2015; Viljoen, 1999) and thermodynamically (Latypov et al., 2022a, 2022b, 2022c) to be no larger than 15–20 m. From this it may be inferred that the thickness of observed eroded sequence fell within this range, i.e., it was close to the upward-growing chamber floor. At the time of erosion, the cumulates were still mushy, as inferred from the gradational nature of the erosional surface (Fig. 12b; 13b; 14b). It may also be noted that the truncation of igneous layering, observed over a range of scales from mm to tens of metres, by erosional surfaces indicates that the layering is of primary origin, i.e., it has not been formed by any late-stage recrystallization of deeply buried non-layered rocks as argued in some studies (e.g., Boudreau and McBirney, 1997). Instead, we suggest, following (Irvine et al., 1998), that the igneous layering has been fully developed very close to or even directly at the crystal-liquid interface of the inward-growing chamber floor.

The second set of observations, comprising hard rock deformation structures and various textural data on sharp erosive surfaces, suggests that the cumulate pile was mostly solid (Fig. 15). The following sequence of events can be deduced from the observed field relations: (1) crystallization of a norite-anorthosite layered sequence; (2) tilting of the





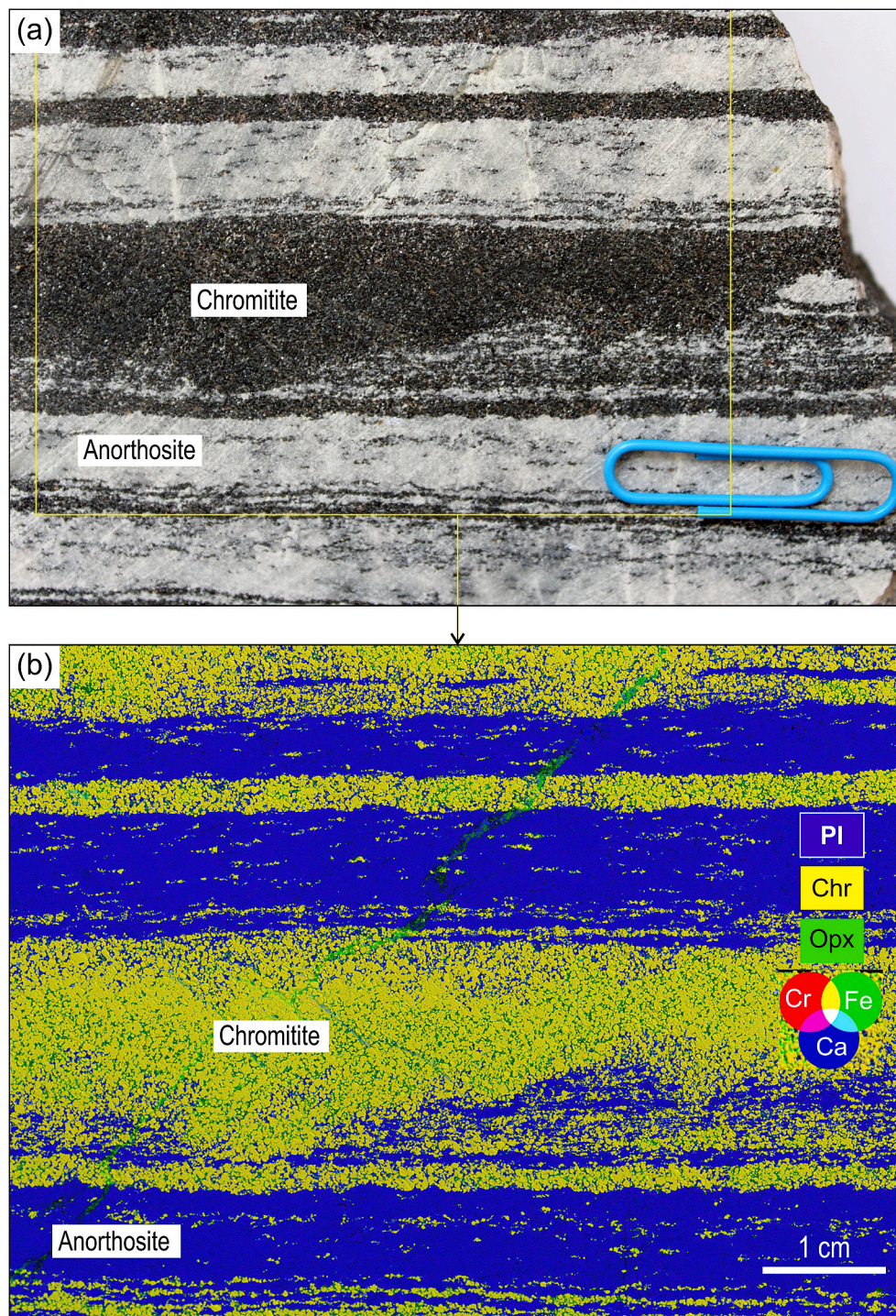
**Fig. 15.** Photographs of an underground exposure with the Merensky Reef (MR) from Eastern Platinum Mine. Upper Critical Zone, western Bushveld Complex. (a) MR orthopyroxene that overlies on the tilted and eroded footwall layered rocks. (b) The abrupt truncation of the footwall layered rocks by an erosional surface resulting in the knife-sharp and scalloped basal contact of the MR. Note the truncation of pyroxene oikocrysts in footwall anorthosites. Photograph courtesy of Jan Van der Merwe.

layered sequence; (3) erosional truncation of this sequence by a new magma pulse accompanied by the local transformation of the uppermost cumulates into mottled anorthosite; (4) deposition of the MR chromitite and orthopyroxenite on the irregular erosional surface followed by formation of the overlying melanorite; and (5) late stage formation of pegmatitic veins crosscutting the MR orthopyroxenite. A key inference to draw from the exposure in Fig. 15 is that the rocks on which the MR was deposited were nearly solid, otherwise the internal layering would not have preserved its coherence during their tectonically induced tilting. The abrupt truncation by an erosional surface of the layered rocks, resulting in the knife-sharp and scalloped contact with the overlying MR (Fig. 15b), also strongly implies the nearly solid state of the floor cumulates at the time of their erosion. Again, to be eroded in this way, the igneous layering in this rock sequence must have been produced very close to or directly at the inward-growing chamber floor.

Similarly, abrupt truncation of fine-scale chromite-anorthosite layering by mini-potholes (Figs. 16–17) indicates that the igneous

layering in the footwall units must have been fully developed, and the layers must have been almost totally solidified at the chamber floor. The solid nature of the temporary chamber floor at the time/level of its erosion is also strongly indicated by the following textural features: (a) truncation of pyroxene oikocrysts in anorthosites that underlie the MR/massive chromitites (Fig. 18), (b) resumed growth on truncated oikocrysts/primocrysts in these anorthosites (Figs. 19–20), (c) termination of downward percolation of a sulphide liquid immediately beneath the MR (Fig. 21), (d) truncation of individual plagioclase crystals (Fig. 22c) and occurrence of magnetite ‘inclusions’ within these crystals in anorthosites that underlie massive magnetitites (Fig. 23c–d). We conclude that sulphide liquid was not able to percolate through the footwall mottled anorthosites (or a pure plagioclase rind) because they were already solid prior to the percolation of the sulphide liquid (Fig. 21c). In a similar way, the Fe-rich melt parental to magnetitite was able to penetrate the underlying anorthosite no deeper than 1–3 mm (Fig. 22) because the anorthosite was essentially completely solid. Otherwise, one would





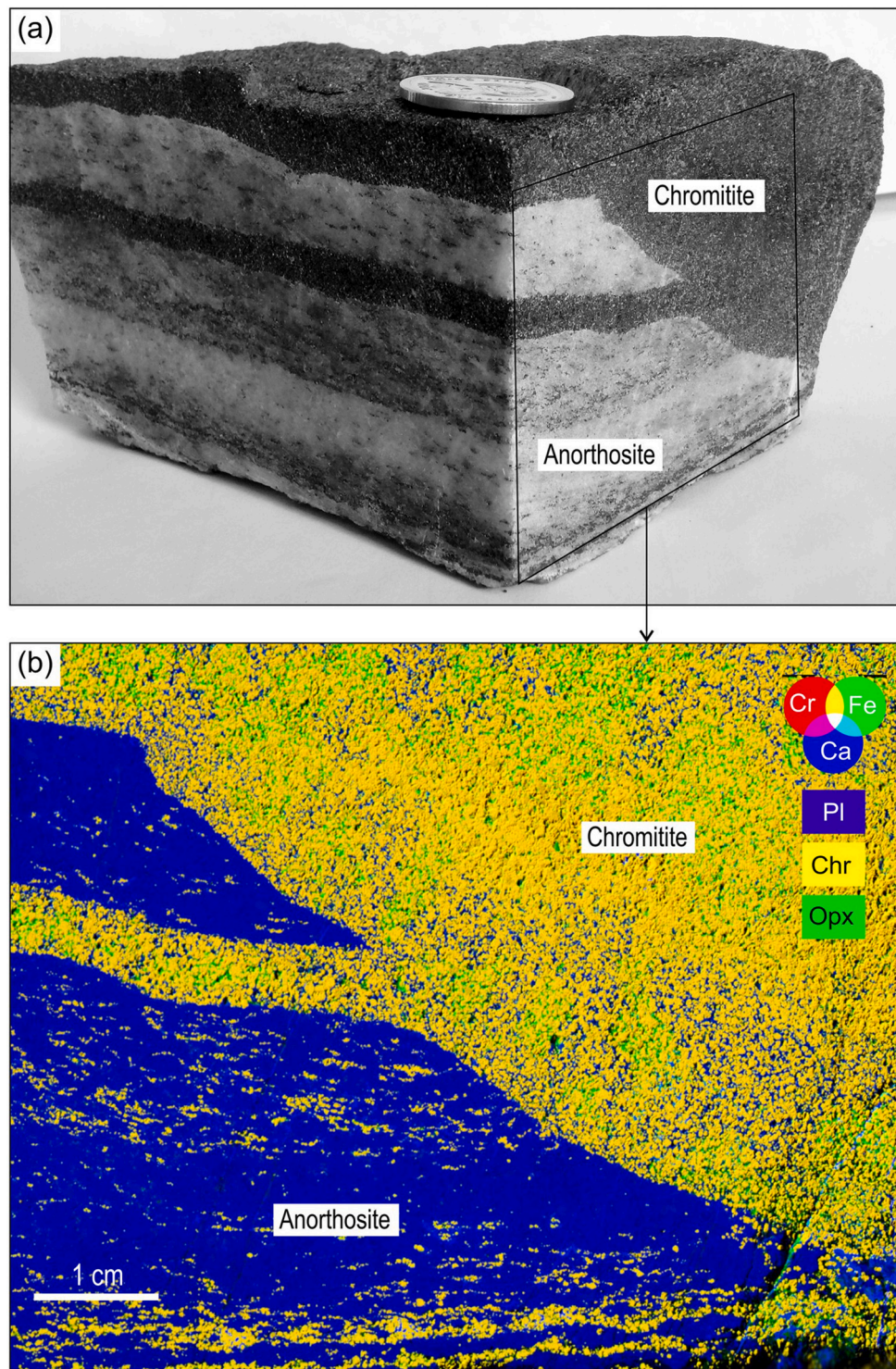
**Fig. 16.** Truncation of fine scale anorthosite-chromitite layering by mini-potholes from the UG1 sequence at Pilanesberg Platinum Mine. Upper Critical Zone, western Bushveld Complex. (a) Photograph and (b) XRF element map of a specimen JO-1 in which a  $\sim 0.6$  cm thick chromitite seam shows a  $\sim 2$  cm deep mini-pothole that sharply cuts through the underlying fine-scale layering of anorthosite and chromitite. The upper contact of the chromitite seam is planar and parallel to other layers in the specimen. XRF element map reveals that orthopyroxene oikocrysts only occur in the chromite-rich layers, and never in the plagioclase-rich layers. Pl – plagioclase, Chr – chromite, Opx – orthopyroxene. Clip is 3 cm long in (a).

observe the Fe-rich melt to percolate much deeper (perhaps, a few meters) through the open space between plagioclase grains composing the porous 3D framework of a crystal-rich mush. It should be noted that the magnetite ‘inclusions’ in plagioclase (Fig. 23c-d) are not chadacrysts because texturally plagioclase crystals are not oikocrysts, but primocrysts. Also, magnetite does not appear to co-crystallize with plagioclase because in such cases it usually occurs between the plagioclase crystals,

not within them. Instead, the magnetite ‘inclusions’ are interpreted as resulting from the local replacement of plagioclase crystals by magnetite-only-saturated melt percolating downwards.

Thus, field and textural observations indicate that the cumulate pile at the time of deposition of some units in the Upper and Critical Zones of the Bushveld magma chamber was either mushy (Figs. 3–14) or totally solid (Figs. 15–22) and although our data do not allow to define the





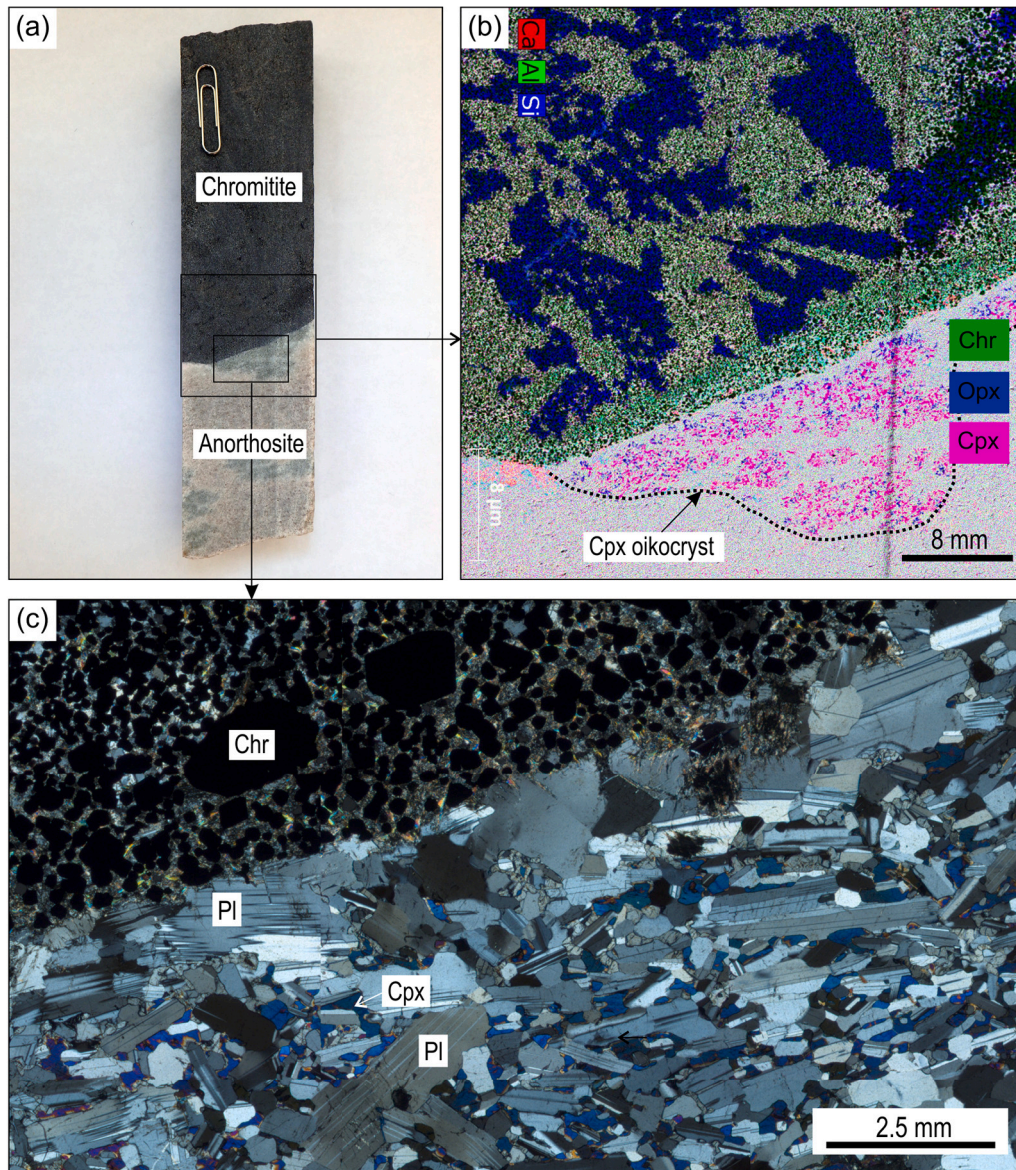
**Fig. 17.** Truncation of fine scale anorthosite-chromitite layering by mini-potholes from the UG1 sequence at Pilanesberg Platinum Mine. Upper Critical Zone, western Bushveld Complex. (a) Photograph and (b) XRF element map of a specimen JO-2 in which about 8 cm deep mini-pothole truncates the underlying anorthosite-chromitite layering which includes among others one prominent chromitite stringer of about 0.6 cm thick. The upper contact of the potholing chromitite seam is not preserved in the specimen. XRF element map of this specimen reveals that orthopyroxene oikocrysts only occur in the chromite-rich layers, and never in the plagioclase-rich layers. Pl – plagioclase, Chr – chromite, Opx – orthopyroxene.

thickness of a mushy layer, it allows us to infer, from the erosional ability of magma, that a mushy layer was likely quite thin, perhaps much <15–20 m in thickness. A pertinent question is how to reconcile observations indicating both mushy and hard floor behaviour in the Bushveld chamber in the frame of some general petrological model?

## 5.2. A thin mushy layer as a product of primary adcumulus growth

Our observations and related inferences imply that only the uppermost few metres of the cumulate pile in the Upper and Critical Zones were likely mushy, whereas the underlying cumulates were already





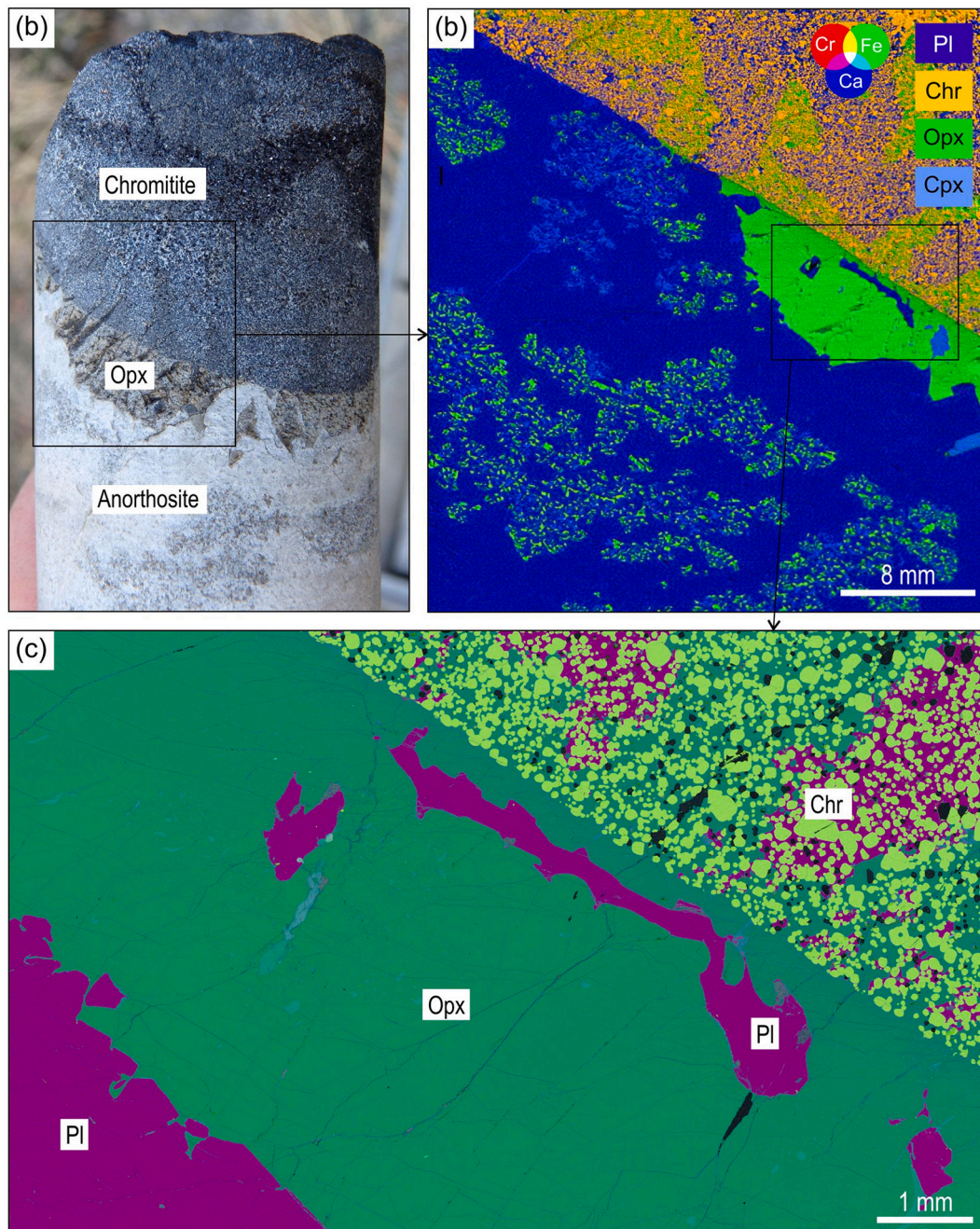
**Fig. 18.** Truncation of pyroxene oikocrysts in anorthosites by massive chromitites from Modikwa Mine. Upper Critical Zone, eastern Bushveld Complex. (a) Photograph of a basal contact of the UG3 chromitite which sharply truncates the underlying mottled anorthosite (sample OV-78-2). Note that the upper half of one pyroxene oikocryst has been eroded away. (b) XRF element map of the contact showing the beheaded pyroxene oikocryst that is separated from a chromitite by a 1–2 grain wide rind of plagioclase crystals. Note that only interstitial plagioclase develops in the basal part of the chromitite. (c) Photograph of a thin section in crossed polarized light that shows details of the contact with a 1–2 grain wide rind of plagioclase crystals. Note that clinopyroxene oikocryst (blue) contains a population of small plagioclase chadacrysts. Pl – plagioclase, Chr – chromite, Opx – orthopyroxene, Cpx – clinopyroxene. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

almost totally solidified (Fig. 24). Such architecture of a basaltic magma chamber is implied by an in situ crystallization concept that postulates the nearly complete absence of crystals in the main magma body (Fig. 24). In this concept, the magma chamber is considered to develop as a central body of the crystal-free melt which nucleates heterogeneously and crystallizes in situ along the margins of the chamber (e.g., Campbell, 1978, 1987, 1996; Jaupart and Tait, 1995; McBirney, 1995, 1996; McBirney and Noyes, 1979; Tait and Jaupart, 1996). This occurs because such magma chambers cool slowly and cannot, therefore, attain the degree of supercooling (several dozens of degrees; Campbell, 1996) that is necessary for homogeneous nucleation and crystallization within the convecting resident melt. The entire resident melt is also considered to be kept under metastable conditions, i.e., kinetically supercooled with respect to liquidus phases that crystallize along the chamber margins

(Campbell, 1987, 1978, 1996; Latypov et al., 2020b; Martin, 1990; Martin et al., 1987). This is consistent with the inference of Wager (1963), who was the first to recognize that melt in a basaltic chamber must be supercooled by at least, 5° to 10 °C to allow adcumulus crystallization to occur. The amount of such kinetic supercooling in a crystallizing magma chamber of basaltic composition that loses heat by conduction through its wall rocks, has subsequently been estimated to range between 1 °C and 20 °C (Martin, 1990; Martin et al., 1987). The resident melt transitions to solidifying rocks at the margins through an inward advancing solidification front (i.e., the mushy layer). The thermal and physical structure of a basal mushy layer that separates the crystal-free resident melt from the solid cumulate pile is shown in Fig. 24b.

The in situ crystallization concept provides a simple explanation to a



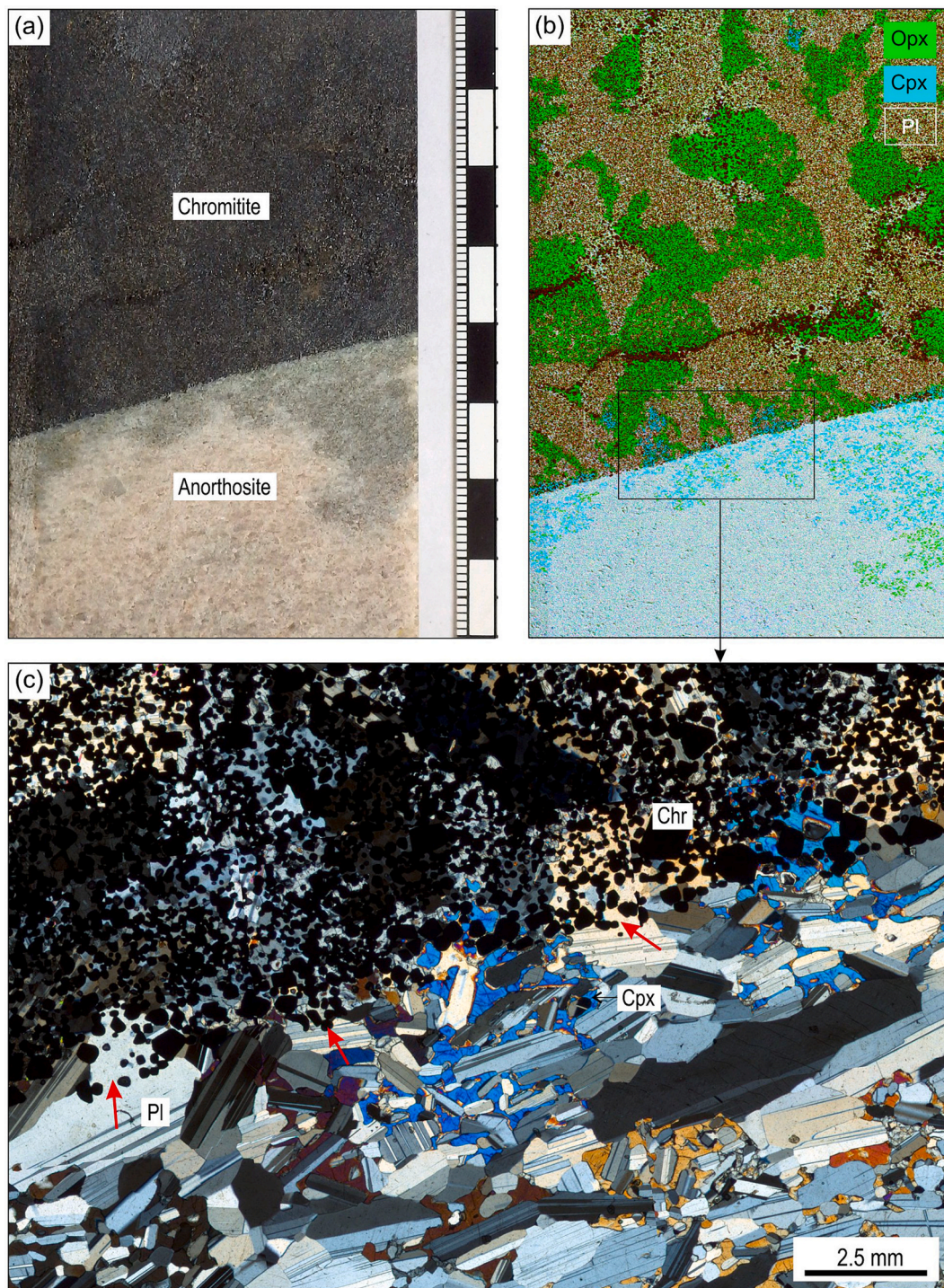


**Fig. 19.** Resumed growth on a truncated orthopyroxene crystal from anorthosite into the overlying UG3 chromitite from Modikwa Mine, Upper Critical Zone, eastern Bushveld Complex. (a) Photograph of a base of the UG3 chromitite that sharply truncates a large orthopyroxene crystal in the underlying mottled anorthosite (sample BU-27). (b) XRF element map showing that the truncated orthopyroxene crystal underwent further growth as an oikocryst into the overlying chromitite. (c) EPMA image of a portion of the truncated orthopyroxene crystal that emphasizes the extreme sharpness of the erosional surface. Pl – plagioclase, Chr – chromite, Opx – orthopyroxene, Cpx – clinopyroxene.

mushy layer in the Bushveld magma chamber being so thin and sometimes even non-existent. This can be understood in the context of the formation of primary meso- to adcumulates (Barnes et al., 2016; Campbell, 1968, 1987, 1996; Morse, 1986; Hill et al., 1995; Latypov et al., 2020a, 2020b). The concept implies that meso- to adcumulates (i. e., 0 to 25% of interstitial melt; Wager and Brown, 1968) may be formed directly at a crystal-liquid interface through fractional crystallization due to advective or convective removal of the parent liquid away from the growing crystals. (This liquid is slightly modified by growth of the cumulus phase and is termed the “rejected solute” following industrial crystal growth terminology). Cumulates forming in this way have a bulk

composition close to that of crystallizing cumulus minerals (e.g., plagioclase and orthopyroxene in norite). In this case, the solidus temperature of meso- to adcumulates in the mushy layer is only slightly lower than the liquidus temperature of the resident melt and very effective chemical exchange occurs between crystals and the overlying resident melt (see a review in Latypov et al., 2020b). If primary adcumulus growth is effective, the floor sequence may grow as nearly solid hardground of meso- to adcumulates from the very beginning. The process is enhanced by convective removal of the rejected solute, particularly where chemically and thermally-driven convection are operating (Morse, 1986). The formation of pure adcumulates (i.e., 0 to



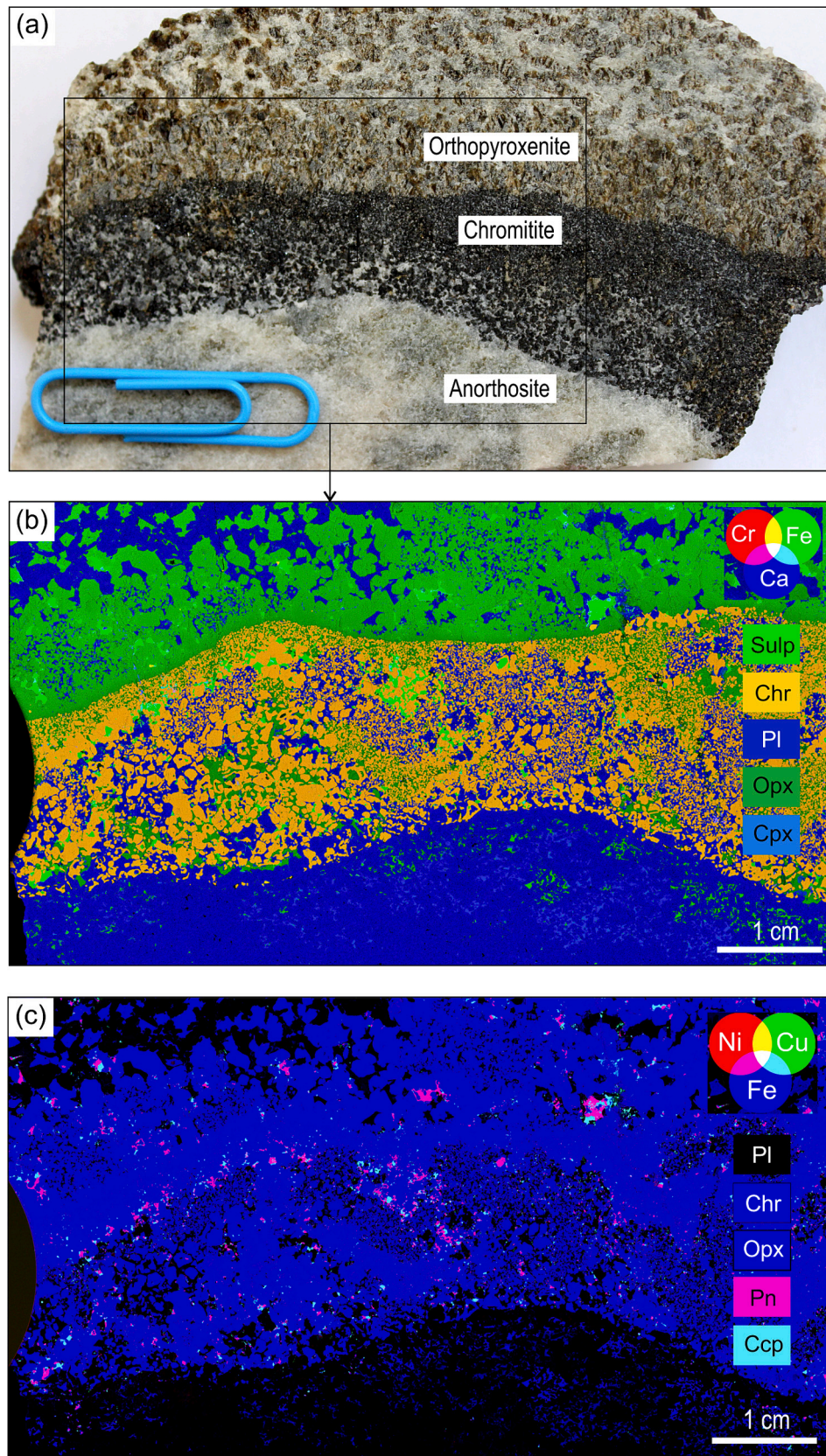


**Fig. 20.** Resumed growth on truncated pyroxene oikocrysts from anorthosite into the overlying UG3 chromitite from Modikwa Mine. Upper Critical Zone, eastern Bushveld Complex. (a) Photograph of a base of the UG3 chromitite that sharply truncates clinopyroxene oikocrysts in the underlying mottled anorthosite (sample HM-1-1). A vertical bar in cm. (b) XRF element map showing that in this case the oikocrysts are only locally separated from a chromitite by a thin plagioclase rind (see Fig. 18 for comparison). As a result, some of the clinopyroxene oikocrysts continue their growth as oikocrysts into the overlying chromitite. (c) Photograph of a thin section in crossed polarized light that shows that clinopyroxene oikocrysts (blue) and some plagioclase primocrysts (red arrows) grow as oikocrysts from anorthosite into the overlying chromitite. Pl – plagioclase, Chr – chromite, Opx – orthopyroxene, Cpx – clinopyroxene. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

7% of interstitial melt) seems to be a quite rare scenario in magmatic chambers (e.g., monomineralic magnetitites; Kruger and Latypov, 2020, 2021, 2022). By far the most common scenario would be a mushy layer in which some chemical exchange via both diffusion and convection takes place between its interstitial melt and a resident melt in the chamber and this exchange becomes progressively less effective as

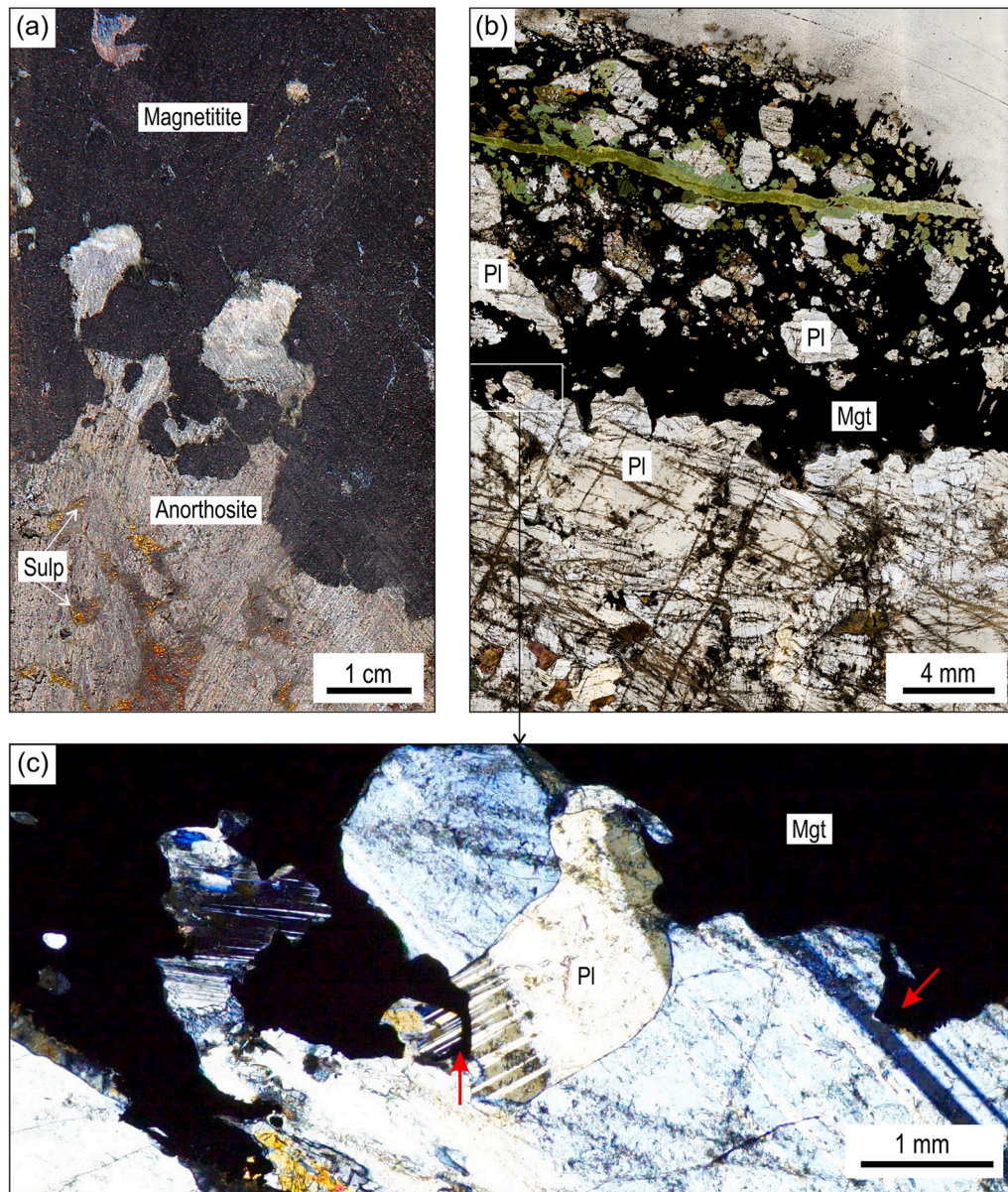
porosity of the cumulate reduces. The solidus isotherm of such a mushy layer depends on its porosity (i.e., amount of interstitial melt): a layer with the highest amount of interstitial melt will have the lowest solidus temperature, and vice versa. The solidus isotherm of a mushy layer is lower than the liquidus temperature of the parent melt, but above the solidus temperature of that melt ('true' solidus in Fig. 24b; Barnes and





**Fig. 21.** Sulphide distribution in the Merensky Reef that indicates termination of downward percolation of a sulphide liquid at the base of the lower chromitite. Rustenburg Platinum Mine, Upper Critical Zone, western Bushveld Complex. (a) Photograph of the basal part of the Merensky Reef, with its lower chromitite sharply truncating the underlying mottled anorthosite. Sample Rich-1 courtesy of Richard Hornsey. Clip is 3 cm long. (b) XRF element map showing the lower chromitite with overlying orthopyroxenite and underlying mottled anorthosite. Note a 1–2 grain wide rind of plagioclase crystals that separates mottled anorthosite from the overlying chromitite. (c) XRF element map showing that sulphides do not extend from the Merensky Reef chromitite into the underlying mottled anorthosites. Pl – plagioclase, Chr – chromite, Opx – orthopyroxene, Cpx – clinopyroxene, Sulp – sulphides, Pn – pentlandite, Ccp – chalcopyrite.





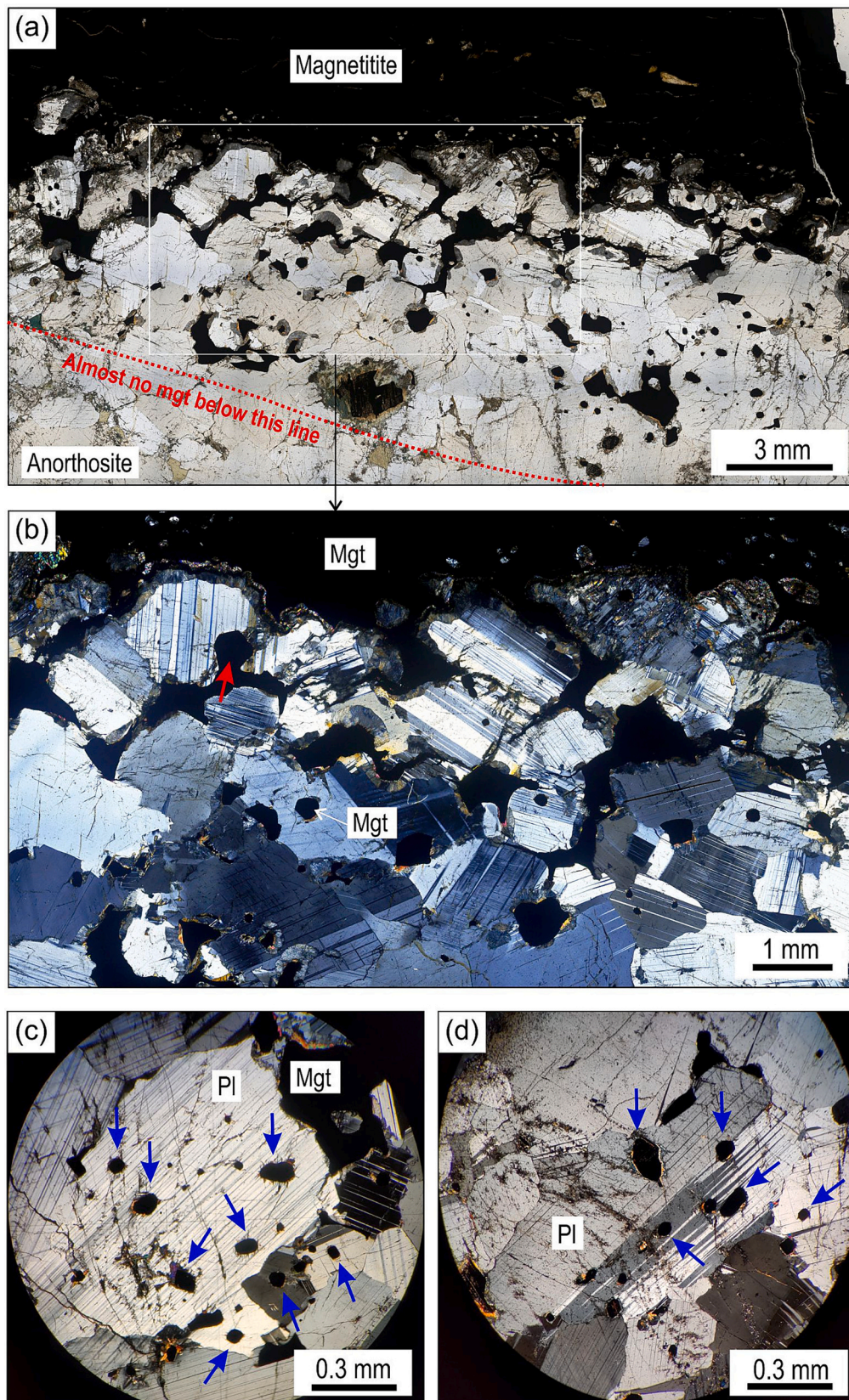
**Fig. 22.** Truncation of plagioclase crystals in anorthosite by massive magnetitite from Vametco Mine. Upper Zone, western Bushveld Complex. (a) Photograph of the drill-core illustrating an erosional character of the basal contact of the MML(?) with the underlying anorthosite/gabbro. The contact is sharp and highly irregular, with some highly scalloped erosional remnants of anorthosite that are entirely enclosed in magnetitite. (b) Photograph of a thin section (sample PB13t) in plane polarized light that shows the extreme sharpness and irregularity of the basal contact of one magnetite layer with the underlying anorthosite. (c) Close up view of the same photograph in cross polarized light showing that magnetite cuts through polysynthetic twins of the individual plagioclase crystals (red arrows). Note in (b-c) that magnetite penetrates the underlying anorthosite no deeper than 1–3 mm. Pl – plagioclase, Mgt – magnetite, Sulp – sulphides. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Campbell, 1988); a pure adcumulate is 100% solid at the liquidus temperature of the parent melt. Such a mushy layer thus exists between isotherms defined by the liquidus temperature of the resident melt, and the solidus of the highest-porosity cumulate, and it may reach a few meters in thickness (Fig. 24b; Latypov et al., 2020b). It should be stressed that a thin mush scenario does not imply that the mush layer must be cooled by several hundred degrees (i.e., to reach ‘true’ solidus, Fig. 24b) from the top of the pile over just a few meters. Such a scenario can only be true for the formation of non-cumulate rocks in the context of crystal settling models (see discussion in Latypov et al., 2020b). Layered intrusions are mostly composed of meso- to adcumulates which may be fully solidified within a thin mushy layer at temperatures much higher than the solidus of the crystal-free parent melt (‘true’ solidus in

Fig. 24b), and in the case of pure adcumulates, at its liquidus temperature.

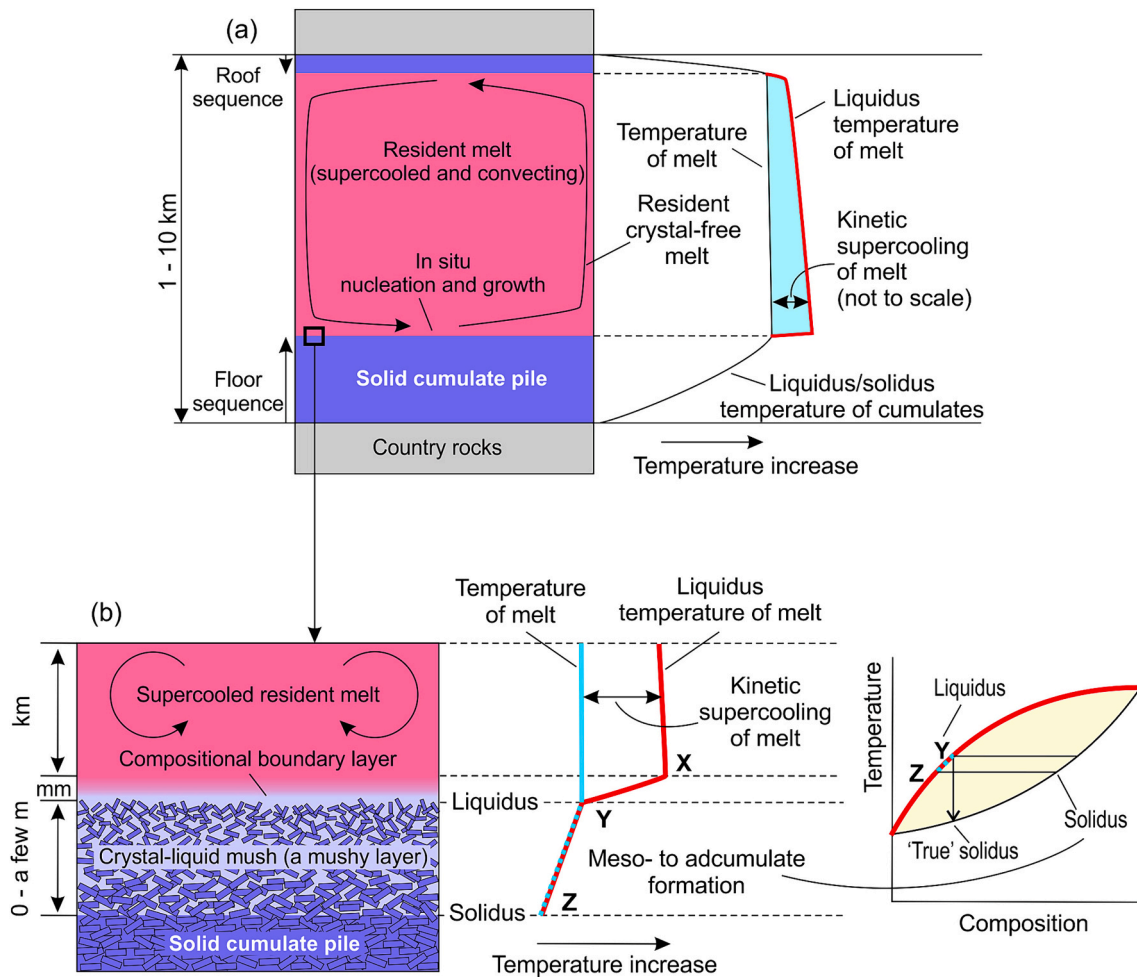
The process by which solid adcumulates or heteradcumulates may form at the chamber floor has been discussed in many previous publications (e.g., Campbell, 1978, 1987) and is illustrated schematically in Fig. 25. Adcumulus growth takes place by a highly efficient process of solute rejection, where the intercumulus liquid network is in diffusive contact with the main body of parent magma (Campbell, 1978; Morse, 1986). The simplest form of this model for monomineralic adcumulates involves nucleation at the temporary top of the crystal pile, followed by adcumulus overgrowth from of an adjacent boundary layer of magma very close to its liquidus temperature (Fig. 25 a, b), under conditions where the degree of undercooling is low such that growth is favoured





**Fig. 23.** Truncation of plagioclase crystals in anorthosite by massive magnetite from Vametco Mine. Upper Zone, western Bushveld Complex. (a) Photograph of a thin section in plane polarized light showing that magnetite penetrates the underlying anorthosite to the depth of <1 cm (sample W1-1C). (b) Close up view of the same photograph in cross polarized light showing that magnetite cuts through polysynthetic twins of the individual plagioclase crystals (red arrow). (c-d) Close up views of the same photograph in cross polarized light emphasizing the development of magnetite grains (blue arrows) within individual plagioclase crystals. Pl – plagioclase, Mgt – magnetite. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)





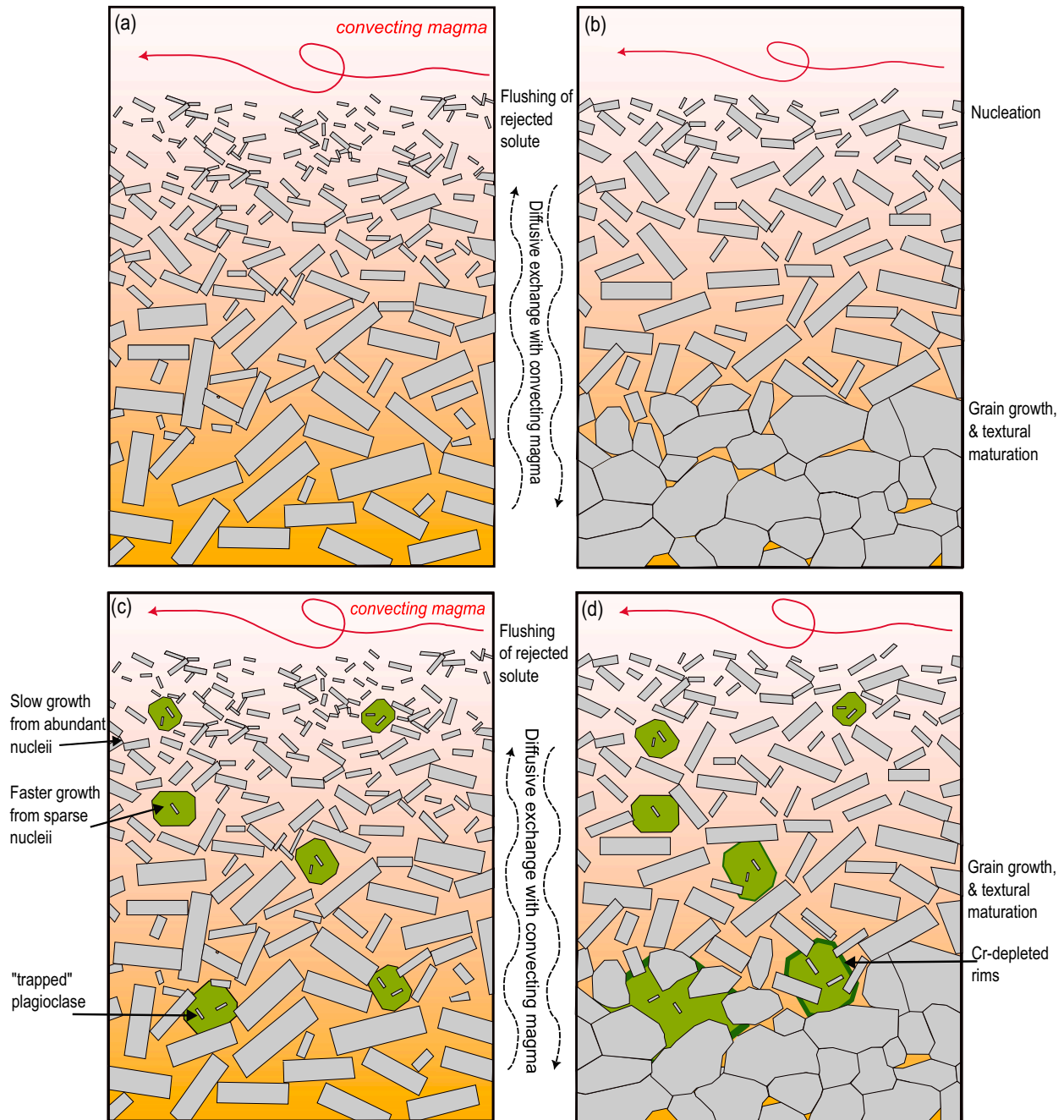
**Fig. 24.** A generalized view of a long-lived and largely molten basaltic magma chamber. (a) The magma chamber develops as a central body of the crystal-free resident melt which nucleates and crystallizes in situ along the margins of the chamber. This occurs because such magma chambers cool slowly and cannot, therefore, attain the degree of supercooling that is necessary for homogeneous nucleation within the resident melt. The resident melt passes to solidifying rocks at the margins through an inward advancing solidification front (a crystal-liquid mush). The resident melt is kept supercooled with respect to both newly arriving liquidus phases and the existing ones that are already crystallizing in a solidification front along the chamber margins. (b) A structure of a basal solidification front (a mushy layer) separating the crystal-free resident melt from the solid cumulate pile. Minerals in the mushy layer are in equilibrium with interstitial liquid Z-Y so that only very low supercooling occurs there (not shown). The mushy layer passes upwards into the resident melt through a few mm thick compositional boundary layer. With moving upwards from in situ growing crystals, the melt in the compositional boundary layer (from Y to X) becomes increasingly more supercooled with respect to liquidus minerals of the mushy layer. The effective chemical exchange of in situ growing crystals with the overlying resident melt keeps the mushy layer thin (from zero to a few meters) and mostly composed of meso- to adcumulates. A schematic binary diagram with complete solid solution between two endmembers (e.g., An-Ab) illustrates liquidus-solidus relationships in the mushy layer. Note that the solidus temperature of the mushy layer is only slightly lower than the liquidus temperature of the resident melt. Modified from Latypov et al. (2020b).

over nucleation and grains grow to fill space. This process gives rise to what is termed “primary adcumulates”, in contrast to “secondary adcumulates” that are thought to form by compaction and melt expulsion deep in the crystal pile. The process may be aided by physical recharge of the boundary layer, driven by thermal convection of the magma above, or by composition-driven convection where the rejected solute is relatively buoyant. It should be noted that adcumulus growth can be effective even without convective removal of ‘rejected solute’. Morse (1986) showed that in large magma chambers the characteristic transport distance for chemical diffusion alone (3–4 cm/year) is much higher than the rate of accumulation at the chamber floor (0.5–1.0 cm/year). This means that adcumulate with very low residual porosity can form directly at the crystal-liquid interface by diffusion alone. For poikilitic heteradcumulates, there is an additional complexity whereby the convecting magma is saturated with one phase but supersaturated with the other, such that a poikilitic texture arises from the difference in relative rates of growth of existing grains and nucleation of new ones (Fig. 25 c, d). This gives rise to a common observation that chadacrysts

(enclosed grains) commonly increase in size from the centres to edges of oikocrysts. In some cases, oikocrysts preserve the original nucleation and early growth history of the chadacryst phase, particularly plagioclase (Mathison, 1987). The characteristic texture of Bushveld Critical Zone norites (Fig. 26) is indicative of in situ heteradcumulate growth under conditions where the relative rate of growth of orthopyroxene is slightly faster than that of plagioclase and the rate of nucleation slower. This gives rise to a relationship whereby orthopyroxene has uniform Cr-rich, Ti-poor cores (Fig. 26a) that contain small, unzoned plagioclase crystals, grading out into Cr-poor, Ti-rich rims interstitial to plagioclase. These are separated by domains of texturally equilibrated plagioclase adcumulate where the plagioclase shows complex and often reverse zoning (Fig. 26b) indicative of variably compete diffusive equilibration with the resident melt above.

This mechanism is in line with earlier and more recent studies indicating that the mushy layer is commonly no more than a few metres thick in most mafic layered intrusions. In particular, field observations on deformation of igneous layering beneath blocks fallen from the roof



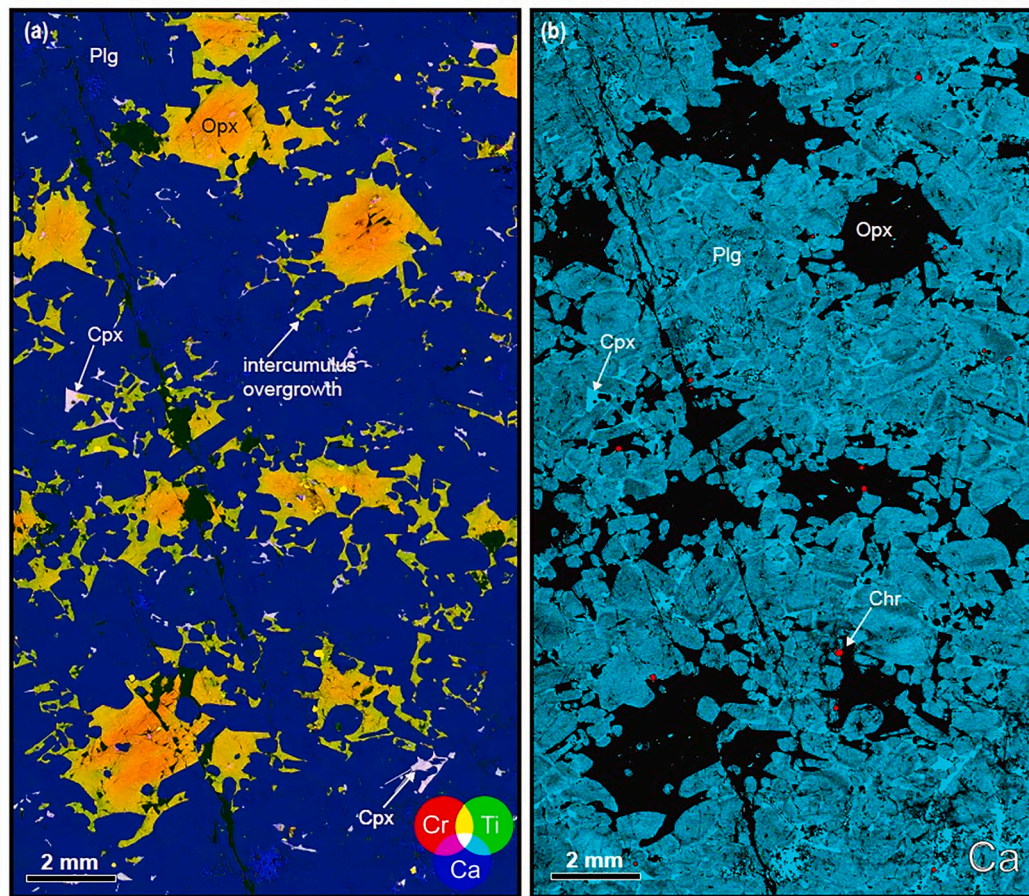


**Fig. 25.** Model (a, b) for origin of adcumulate texture by in situ nucleation and growth of cumulus plagioclase (grey) within a thin mushy boundary layer at the top of crystal pile, aided by convective removal of residual liquid (“rejected solute”) around growing cumulus grains. Grain growth and textural maturation develop with time (time a to time b) under conditions where the rate of advance of the crystal pile is slow or stagnant. Grain compositions remain essentially constant due to diffusive interchange between the boundary layer and convecting magma above. Development of heteradcumulate norite (c, d) due to differential growth and nucleation rates of plagioclase (grey) and orthopyroxene (green) in the boundary layer. Plagioclase grows slowly from abundant nuclei. Orthopyroxene grows relatively rapidly from sparser nuclei due to supersaturation of the liquid in this phase. Hence, small plagioclase grains become trapped with cumulus cores of orthopyroxene grains having Cr-depleted intercumulus rims due to continuing growth as the intercumulus liquid becomes depleted in strongly compatible components. Modified from [Barnes et al. \(2019\)](#). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

onto the inward-growing chamber floor, has been taken to indicate that a mushy layer was only 1 to 3 m thick in the Stillwater Complex ([Hess, 1960](#)) and a few meters thick in the Sarqata Qaqa Complex ([Thompson and Patrick, 1968](#)) and the Skaergaard intrusion ([Irvine et al., 1998](#)). [Cawthorn \(1999\)](#) examined the chemistry of the footwall rocks below the Merensky Reef of the Bushveld Complex and found that in some places the sulphide liquid was only able to penetrate downward for distances of no >1 to 2 m; in some cases, like in our study, this distance

was only a few cm ([Barnes et al., 2021b](#); [Smith et al., 2021](#)). This can be taken as reflecting the variations in the thickness of a mushy layer because a high-density, low-viscosity sulphide liquid is expected to migrate downwards when the cumulates are still mushy ([Barnes et al., 2018](#); [Chung and Mungall, 2009](#)). Sharp and essentially planar basal contacts of metre-scale layers of massive magnetitites in the Bushveld Complex with minimal disruption of the underlying anorthosite, are interpreted indicating deposition of these layers on a mostly solidified





**Fig. 26.** Synchrotron microXRF element maps of a norite from the immediate footwall of the Merensky Reef at the Karee mine, western Bushveld Complex. (a) False colour Cr-Ti-Ca map. Note the characteristic texture of the orthopyroxene (opx) showing continuous transition from Cr enriched cumulus cores and relatively Cr-poor, Ti-rich intercumulus overgrowths. Note also presence of small plagioclase inclusions in the cores of most grains. (b) Ca-element map enhanced to show complex oscillatory and reverse zoning in plagioclase in the texturally mature adcumulate domains, compared with lack of zoning at plagioclase margins in contact with orthopyroxene. Red grains are chromite. A model for the development of this texture is shown in Fig. 25. Pl – plagioclase, Chr – chromite, Opx – orthopyroxene, Cpx – clinopyroxene. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

hardground (Vukmanovic et al., 2019). Based on the distribution of intracrystalline dihedral angles in relation to new phase appearances, it has also been shown that the thickness of a mushy layer in both the Skaergaard intrusion and Bushveld Complex generally did not exceed 4 m (Holness et al., 2017a, 2017b). Even more revealing is the study of fine-scale chemical patterns at the base of magnetite layers in the Bushveld Complex which provide evidence for the growth of nearly pure magnetite adcumulate directly at the crystal-liquid interface in the absence of any mushy layer (Kruger and Latypov, 2020, 2021, 2022).

### 5.3. Hard chamber floor results from complete erosion of a thin mushy layer

In the frame of our conceptual model (Figs. 24, 25, 27a), the uppermost mushy portion of a cumulate pile may experience soft-sediment deformation (Fig. 27b) in response to some crustal instabilities (e.g., earthquakes) that would be expected to accompany magma replenishment events. Subsequently, the soft-sediment deformation structures may have either remained intact or been subjected to partial or complete thermochemical erosion by the replenishing magmas with the formation of planar erosional surfaces (Fig. 27c). The crystal deposition on these erosional surfaces would produce the sub-horizontal igneous layering (Fig. 27d). However, if the mushy layer was thin and/or thermochemical erosion was strong, then the entire mushy layer, be it intact or tilted/deformed (Fig. 27e), may have been eroded away (Fig. 27f), and the

newly formed crystals would have been deposited on the irregular surface of the solid chamber floor (Fig. 27g). Two scenarios in Fig. 27 explain the evidence for both ductile and brittle behaviour of the cumulate pile from nearly the same stratigraphic levels of the Bushveld Complex.

### 5.4. Strain-rate dependent rheology of a mushy layer

An intriguing aspect of the structures illustrated in Figs. 3 to 11 is that the thin mushy layer at the top of the crystal pile is evidently capable of rapid transition from ductile to brittle behaviour. This can be readily explained if crystal-rich mushes display strain-dependent rheology, i.e., they deform differently depending on how rapidly they are being sheared. Such non-Newtonian behaviour is a common phenomenon in nature (Barman et al., 2016). For example, water-saturated sand on a beach will become fluidised by gentle stirring but will crack on being rapidly compressed. Similarly, cornflour suspensions ('oobleck') behave as viscous fluids on gentle stirring, but show an increase in viscosity and shear strength when stirred rapidly, a phenomenon known as rheopexy or shear thickening (e.g., Barman et al., 2016; Roussel, 2012). The opposite property, thixotropy or shear thinning, occurs where fluids become less viscous with increased shear strain rate, as for example ketchup when the bottle is shaken. The rheology depends upon the nature of the solid particle interactions: rheopexy arises where the fluid is expelled from between the particles at high strain rates causing



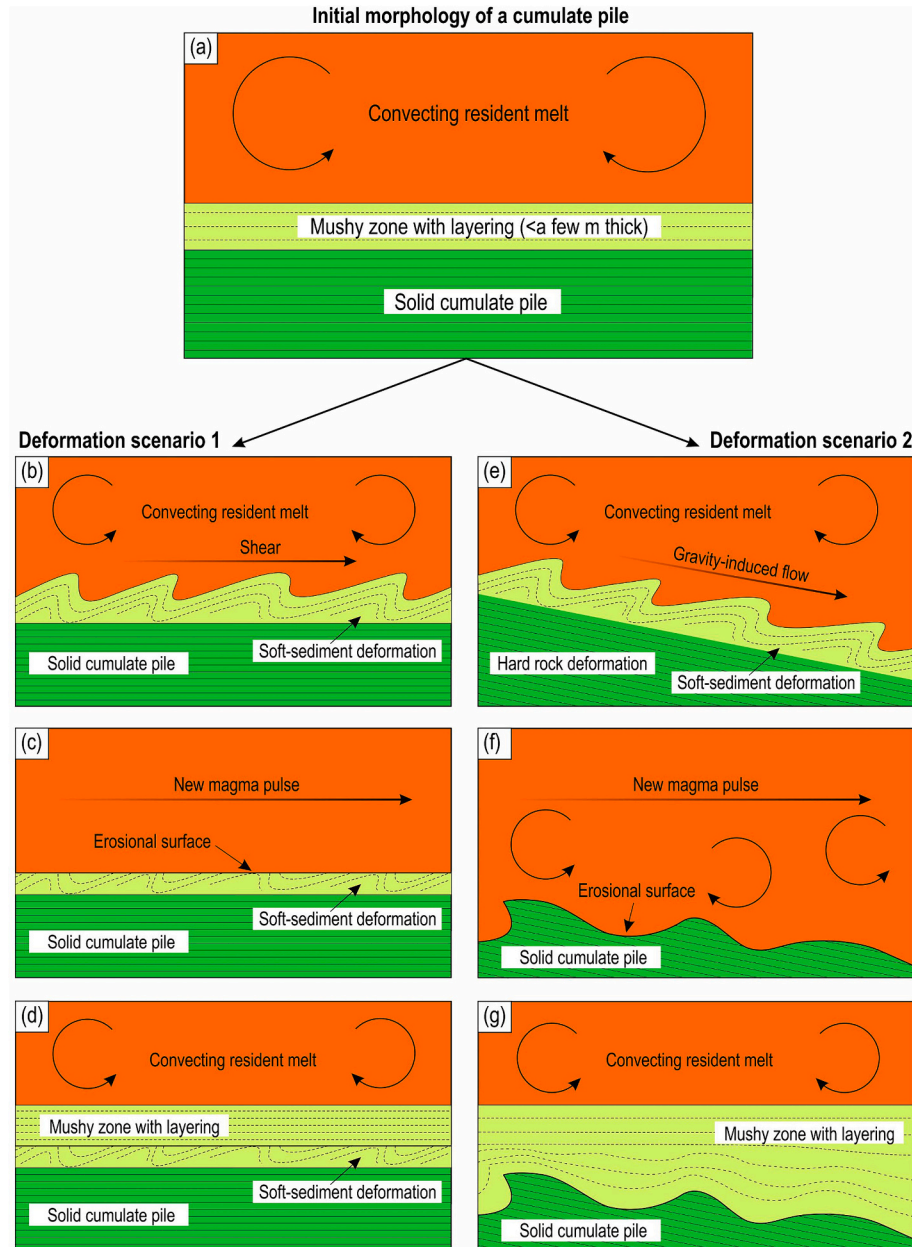
the particle to lock up as a rigid framework, whereas thixotropy is the opposite condition where the suspension dilates, and the solid particles interact less due to lubrication by the fluid. Both processes are time-dependent, i.e., the suspension recovers its original state of rheology with time after the strain ceases.

The observations presented here on partially solidified plagioclase-rich crystal mushes (Figs. 3–11) suggest that they are rheopectic. The transition between the structures observed in (for example) Fig. 5 may reflect rapid changes in strain rate due to intermittent earthquakes during the accumulation of successive layers. At moderate rates, the mush fluidises like wet sand; during rapid shocks, it strain-thickens and fractures. Rheopectic behaviour of mushes may explain other features

observed in cumulate rocks, for example the formation of sulphide-filled veins within bodies of olivine-sulphide liquid cumulates in Ni–Cu ore deposits. This model has been proposed for sulphide veins within the Nova and Savannah mafic-ultramafic intrusions (Barnes et al., 2018, 2020).

##### 5.5. Implications for reactive porous flow through a cumulate pile

An important implication for constraining a concept of reactive porous flow through crystal-rich mushes in magmatic systems arises from this study. Petrogenetic models that involve reactive porous flow normally postulate a mushy zone/layer to vary in thickness from several



**Fig. 27.** A proposed model for the evolving Bushveld chamber in which only the uppermost few metres of the cumulate pile is mushy, with other underlying cumulates being already almost totally solidified (a). The uppermost mushy portion experiences soft-sediment deformation in response to earthquakes associated with magma chamber replenishments (b). Subsequently, the soft-sediment deformation structures are subjected to partial thermochemical erosion by the replenishing magmas, with the formation of planar erosional surfaces (c). The crystal deposition on these erosional surfaces would produce sub-horizontal igneous layering (d). However, if the mushy layer is thin and/or thermochemical erosion is strong, then the entire deformed mushy layer (e), may be eroded (f), and the newly formed crystals would have been deposited on the irregular surface of the solid chamber floor (g). This model aims to explain field and textural evidence for both mushy and solid-state behaviour of the cumulate pile of the Bushveld Complex.



dozens to hundreds of metres (Boudreau, 2016, 2019; Boudreau and McCallum, 1992; Irvine, 1980; Maier et al., 2013; Tait and Jaupart, 1992; Tegner et al., 2009) through a few km (Bachmann and Bergantz, 2004; Bachmann and Huber, 2019; Bea, 2010) to up to several dozens of km (Blundy, 2022; Cashman et al., 2017; Jackson et al., 2018; Sparks et al., 2019). The thickness of the mushy zone is clearly the most critical parameter in these models because it acts as a key source of upward migrating interstitial melt/fluids that chemically interact and modify crystals in the mush. The field and textural observations presented here indicate that the mushy layer of the cumulate pile in the Bushveld chamber is unlikely to have been thicker than a few meters. If so, the extent of interstitial melt migration was trivial and its total volume was not sufficient to metasomatically produce any large-scale features of the Bushveld Complex such as the Merensky Reef (Boudreau, 2008, 2019), massive chromitites (Boudreau, 2019; Marsh et al., 2021) or stratiform anorthositic (Maier et al., 2021b) all of which occur as a few m thick layers extending for >350 km along strike (Cawthorn, 2015). Moreover, field and textural data indicate that chromitite and magnetite layers as well as the Merensky Reef were deposited onto the erosive surfaces below which the floor cumulates were almost solid, leaving no chance for these deposits to be formed via migrating interstitial melt/fluids. Reactive porous flow may, however, have played some role in chemical/textural modification of mushy cumulates in the uppermost portion of the cumulate pile of the Bushveld Complex. A question here is how to discriminate between the primary features of cumulates from those produced by reactive porous flow? Reactive flow through porous media is normally expected to be self-organised into channels or fingers, usually with fractal geometries (Jordan and Hesse, 2015; Renard et al., 1998). This is an inevitable consequence of the feedback loop where the percolating fluid locally increases the permeability of a cumulate pile. The metasomatic products should thus have a highly irregular advancing interface, as typically observed in hydrothermal replacement orebodies such as skarns (e.g., Lentz et al., 1995), rather than continuous planar features that are so characteristic of chromitite and magnetite layers in the Bushveld Complex. In this context, we think that it is quite possible that cross-cutting fingers extending upwards from the upper boundaries of some cumulate layers (e.g., Maier et al., 2013; Mitchell et al., 2019; Mitchell and Scoon, 2007) and irregular pods/patches of cross-cutting anorthositic (e.g., Carr et al., 1999; Maier et al., 2021a, 2021b) may represent products of reactive porous flow.

### 5.6. Implications for hydrodynamic sorting of crystals in a slumping cumulate pile

This study also places strict constraints on a concept of large-scale slumping of the mushy cumulate pile in response to central subsidence of mafic layered intrusions (Maier et al., 2013). The hydrodynamic sorting of crystals is thought by some to have been responsible for segregation of sulphides and chromite/magnetite from silicate minerals to form layers of platinum-rich reef or monomineralic chromitite/magnetite at the base of the slumped cumulate pile (Maier et al., 2013, 2018, 2021a, 2023). The production of such layers requires a large volume of crystal-rich slurries to be involved. For instance, assuming cotectic composition of phenocrysts (1–2% chromite and 98–99% silicate minerals), the formation of a 1 m thick chromitite layer requires, at least, a ~ 50–100 m thick column of an orthopyroxene-rich slurry to overlie this layer (see discussion in Latypov et al., 2017). The presented field and textural observations provide no support for existence of a mushy layer of such thickness at the time of chromitite layer formation, which questions the validity of this concept as an explanation for the origin of these ore deposits. Again, this is not to say that some localized crystal sorting may not have occurred in the uppermost mushy portion of the cumulate pile of the Bushveld Complex. For instance, a mobile crystal-rich slurry may be formed by new magma pulses when they enter the chamber as basal flows and cause a physical disruption of the uppermost mushy layer of the cumulate pile. This can be followed by

transportation of loose crystals along the floor of the chamber by flowing magma and their sorting and redeposition with the development of ‘secondary’ cumulates, commonly showing igneous lamination and lineation (Barnes et al., 2021a; Latypov et al., 2015). One of the potential examples of such sorting and redeposition is the chromite-rich and highly laminated MG3 layer exposed on the farm Jagdlust, eastern Bushveld Complex that contains abundant transported autoliths of pyroxenite, anorthosite, and chromitite (e.g., Maier et al., 2013). To conclude, it should be noted that our field and textural data have implications only for the mushy models (Maier et al., 2013, 2018, 2021a, 2023), not for the slurry models that mostly deal with the magma emplacement into the chamber (Eales, 2002; Eales and Costin, 2012; Maghdour-Mashhour and Hayes, 2021; Mungall et al., 2016; Voordouw et al., 2009).

## 6. Conclusions

The abundant field and textural observations from the Upper and Critical Zones of the Bushveld Complex points towards a very thin mushy layer on the upward-growing chamber floor, thereby restricting the operation of reactive porous flow and associated chemical/textural modification of rocks to the very top of the cumulate pile. The small volume of interstitial melt that can potentially be involved in reactive porous flow from such a thin mushy layer will not be sufficient to metasomatically produce such large-scale features of the Bushveld Complex as the Merensky Reef (Boudreau, 2008, 2019), massive chromitites (Boudreau, 2019; Marsh et al., 2021) or stratiform anorthositic (Maier et al., 2021b). In a similar way, a very thin mushy layer on the temporary chamber floor limits the potential operation of hydrodynamic sorting (in case of intrusion-scale slumping) to the very top of the cumulate pile and cannot, therefore, be responsible for the mentioned large-scale features of the Bushveld Complex. It seems more likely that these magmatic deposits were produced by accumulation of crystals on the inward-growing chamber floor from the overlying resident melt either by gravity settling (Campbell et al., 1983; Holness et al., 2023; Naldrett et al., 2009, 2012) or in situ crystallization (e.g., Latypov et al., 2015, Latypov et al., 2017, 2020a, 2022a; Kruger and Latypov, 2020). This does not mean that reactive porous flow or crystal sorting were not operative in the uppermost mushy portion of the cumulate pile of the chamber at all. It is quite conceivable, for instance, that reactive porous flow of fluid-rich interstitial melt may be responsible for some small-scale petrological features (e.g., cross-cutting fingers, irregular bodies of cross-cutting anorthositic) that locally complicate the primary magmatic stratigraphy of the cumulate rocks (Carr et al., 1999; Maier et al., 2013; Mitchell and Scoon, 2007). It is equally possible that transportation and crystal sorting of loose material from the disrupted cumulate pile may be responsible for some layers with igneous lamination/lineation and transported autoliths (Barnes et al., 2021a, 2021b; Latypov et al., 2015; Maier et al., 2013). One of the future challenges is to define a clear set of geological, textural and chemical parameters to rigorously distinguish the primary petrological features from secondary ones in the Bushveld Complex and other layered intrusions.

## CRedit authorship contribution statement

**Rais Latypov:** Conceptualization, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Sofya Chistyakova:** Conceptualization, Investigation, Validation, Writing – review & editing. **Stephen Barnes:** Conceptualization, Investigation, Software, Visualization, Writing – original draft, Writing – review & editing. **Christopher Letsoele:** Conceptualization, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Willem Kruger:** Conceptualization, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing.



## Declaration of competing interest

None.

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