Mineralium Deposita
https://doi.org/10.1007/s00126-024-01272-5

ARTICLE

Where are the feder channels for platinum reefs in the Bushveld Complex?

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Received: 15 January 2024 / Accepted: 23 April 2024
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Abstract

The Bushveld Complex in South Africa hosts the lion's share of the world's noble metal resources in platinum reefs – thin layers of silicate/chromite rocks containing platinum-rich sulphides. The reefs are widely attributed to multiple replenishments by ore-forming magmas that have been entering the evolving Bushveld chamber through numerous feeder conduits. The replenishment events are marked by regional and local disconformities/unconformities, significant isotopic shifts, and notable reversals in the whole-rock and mineral compositions. Surprisingly, however, so far no single feeder conduit for platinum reefs has been found despite extensive surface and underground mining for over a century. Feeder conduits appear entirely absent from the Bushveld Complex. This paradox has long been known but has never been specifically addressed. Here, we suggest that the absence of feeder channels is a natural consequence of the magma chamber replenishment through a cumulate pile. The fossilization of the feeder channels in the cumulate pile is likely impeded by two principal factors: (a) a cumulate pile is too hot to enable efficient cooling and crystallization of magma flowing through the channels, and (b) the channels are closed by an adjacent elastically deformable pile immediately after cessation of the magma emplacement. The feeding dykes are thus absent because there is little chance for the conduits to get preserved in a hot and deformable cumulate pile of layered intrusions.

Keywords Bushveld Complex · Merensky Reef · Cyclic units · Cumulate pile · Mobile hydrofractures · No crystallization · Feeder conduits closure · Layered intrusions

Problem statement

There is a general consensus among igneous petrologists that layered intrusions – the "fossilized" natural laboratories for diverse petrological studies (Wager and Brown 1968; Parsons 1987; Cawthorn 1996; O'Driscoll and VanTongeren 2017; Latypov et al. 2024) – do not form from a single large influx of magma. Rather, they grew to their present size incrementally, that is, via numerous magma pulses that refilled their chambers during almost the entire period of their evolution. This idea makes perfect sense because there is simply no terrestrial process capable of instantly generating and emplacing enormous volumes of basaltic magma (e.g., Marsh 2015). One of the most spectacular manifestations of multiple pulse activity in layered intrusions is cyclic units, which are commonly attributed to new magma pulses refilling the evolving magma chamber (e.g., Jackson 1970; Irvine 1975; Hunt et al. 2018). From the base to the top, the cyclic units commonly show a systematic change in crystallization sequence accompanied by progressive decrease in whole-rock MgO, Mg-number of mafic phases and An-content of plagioclase. The boundaries between cyclic units are commonly sharp and very distinctive and are marked by prominent reversals in phase, modal and cryptic layering as well as in trace and isotope geochemistry of rocks and minerals (see a review in Latypov and Chistyakova 2009). Discordant field relationships between the bases of cyclic units with the underlying cumulate rocks are also quite common. Examples include cyclic units in the Rum Complex (Emeleus et al. 1996), Muskox (Irvine 1970), Penikat (Alapieti and Lahtinen 1986), the Fox River Sill (Peck et al. 2002; Desharnais et al. 2004), Kap Edvard Holm Complex (Tegner et al. 1993), Bushveld Complex (Eales and Cawthorn 1996;

Editorial handling: E. Mansur

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Published online: 30 April 2024

Cawthorn 2015) and many other layered intrusions. Some of these cyclic units in layered intrusions (e.g., in Bushveld and Stillwater Complexes) are famous for hosting giant platinum deposits – the world's major repositories of strategically important noble metals. These platinum deposits occur as thin, continuous layers of silicate or chromite rocks at the base of cyclic units and contain sulphides that are anomalously enriched in the platinum group elements (PGE; Os, Ir, Ru, Rh, Pt and Pd), thus are referred to as 'platinum reefs' (Naldrett 2004; Cawthorn et al. 2005; Mungall and Naldrett 2008; Mudd et al. 2018; Chistyakova et al. 2019b). Being an integral part of the cyclic units, the platinum reefs are also commonly attributed to replenishment of the evolving magma chambers by numerous pulses of ore-forming magmas derived from the deeper magma sources (Campbell et al. 1983; Naldrett et al. 2011; Latypov et al. 2015). From this, it would be logical to expect a large body of feeder dykes cross-cutting cumulate sequences beneath the platinum reefs associated with the bases of cyclic units in layered intrusions. The opposite is true, however – the dykes are notably absent. This paradox has been puzzling petrologists for many decades, although no concrete efforts have been ever undertaken towards its resolution. This study attempts to address this riddle of igneous petrology using, as a case study, the Bushveld Complex in South Africa – the largest host to platinum deposits, containing up to 80% of the globally exploited PGE (Cawthorn 2010).

Absence of feeder conduits for platinum reefs in the Bushveld Complex

The 2.05 billion-year-old Bushveld Complex in South Africa is the largest mafic-ultramafic layered intrusion in the Earth's crust. It occupies an area that most likely exceeds 100,000 km^2 and extends ~450 km east-west and ~350 km north-south (Naldrett et al. 2012; Cawthorn 2015; Finn et al. 2015; Latypov et al. 2022a). 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 about 7 to 9 km (Cawthorn 2015). The Bushveld Complex is a classic example of an open-system magma chamber (Kruger 2005). Its principal zones are attributed to major replenishment events, with numerous smaller episodes of magmatic recharges contributing to the formation of these zones. In this process, the magma chamber was incrementally increasing in size by inflation both vertically and laterally (Willemse 1959; Eales 2002; Kruger 2005). All major replenishing events are marked by regionally extensive magmatic disconformities, local erosive unconformities into previous strata, significant isotopic shifts, and notable changes in whole-rock and mineral compositions (Kruger 2005; Latypov et al. 2019; Chistyakova et al. 2021; Hasch and Latypov 2021). By far the largest body of such evidence comes from the Bushveld's famous platinum-rich reefs, such as the Merensky Reef (MR) (Latypov et al. 2015; Hunt et al. 2018; Chistyakova et al. 2019b, a) and UG2 chromitite (Mondal and Mathez 2007; Maier et al. 2013; Latypov et al. 2017b) as well as the less known platinum-poor reefs, such as the Pyroxenite Marker (PM; e.g., Cawthorn et al. 1991; Maier et al. 2001) and Main Magnetite Layer (MML; e.g., Kruger and Latypov 2020, 2021). As an example, the platinum-rich MR in the Critical Zone has been the subject of numerous studies over many decades and its formation through the multiple replenishment events is overwhelmingly supported by its transgressive relationships with footwall rocks (Viring and Cowell 1999; Viljoen 1999; Latypov et al. 2015, 2019; Hunt et al. 2018), sharp regressions in the crystallization sequence and marked changes in whole-rock compositions and isotopic ratios (Kruger and Marsh 1982, 1985; Kruger 1992) and its complex internal structure involving up to five compositionally distinct sublayers (Latypov et al. 2017c). This implies that many feeder channels must have been operating during the MR formation. Paradoxically, however, up to date no single feeder dyke has been found along its entire length of many hundreds of km despite extensive surface mapping and detailed underground observations by platinum mining as well as academic researchers for over a century. Similarly, no feeder dykes have been found associated with any other platinum-rich or platinum-poor reefs of the Bushveld Complex.

A potential explanation for absence of feeder conduits for platinum reefs in the Bushveld Complex

The first potential explanation is that feeder channels for the MR developed as traditional dykes that crosscut the underlying cumulate rocks but have not yet been found. This is because the feeders are relatively thin (perhaps, in the range of a few meters) and may therefore be overlooked. We find it, however, unlikely that the feeder conduits to the cyclic unit hosting the MR may have been overlooked because this unit is arguably one of the best-studied geological features in all layered intrusions (Campbell et al. 1983; Ballhaus and Sylvester 2000; Boudreau 2008; Cawthorn 2011; Naldrett et al. 2011; Maier et al. 2013; Latypov et al. 2015; Hutchinson et al. 2015; Latypov et al. 2017c). It should be noted that not only is the MR itself extensively studied, but also its footwall rocks are thoroughly traversed through exploration and resource definition drilling. This is because platinum mining typically involves traversing the MR down to a sufficient distance to access the underlying UG2 chromitite.

Furthermore, the occurrence of potholes and their mining (especially in the past) mean that the floor rocks adjacent to the stratigraphically normal MR are well-explored in mining areas.

A second explanation is that the feeder channels for the MR did not develop as traditional dykes crosscutting the underlying cumulate rocks, and instead the complex was mostly fed laterally through the basal flow emplacements. This idea is in line with recent seismic reflection- and field-based studies indicating that most basaltic magma travels sideways through the lithosphere as interconnected sill complexes rather than upwards as vertical dykes (Townsend et al. 2017; Magee et al. 2018). It has been shown that such sill complexes can transport magma laterally over distances as large as ~4100 km (Magee et al. 2016). Although the sill-like emplacement is not a perfect analogy for magma replenishment into the evolving chamber, one may speculate that the replenishing magma may have travelled as basal flows along the chamber floor. In other words, the feeders for the MR may occur in some highly localized places that are still unexposed, e.g., in the central part of the complex or along the Thabazimbi-Murchison Lineament (e.g., Cole et al. 2024), whereas most of the exposed rocks are formed from magmas that spread from these localized places laterally along the chamber floor. In addition, the available exposure of the Bushveld Complex merely represents the thin margins of a magmatic body with the shape of a soup dish (Kruger 2005). These two factors, that is, occurrence of the feeders in the unexposed places and the limited outcropping of the complex, may explain why feeder conduits for the MR have not yet been found. This explanation seems reasonable and can be accepted as a working hypothesis for the Bushveld Complex. However, it becomes much less appealing when one considers that the feeder channels are absent not only in the Bushveld Complex, but also in all other layered intrusions around the world. Therefore, if we embrace this interpretation for the Bushveld Complex, we must also acknowledge that the feeder channels in other layered intrusions were inadvertently concealed in the unexposed regions. This notion seems far-fetched.

As an alternative, we propose a third explanation, namely, that feeder conduits are indeed absent, rather than overlooked or unexposed. More specifically, we propose that the magma did ascend through the cumulate pile, but the feeder conduits failed to get preserved. A relevant question is what may have impeded the preservation of feeder channels in the cumulate pile of the Bushveld Complex? Two conditions must be fulfilled to avoid preservation of feeder conduits that deliver magma into the main reservoir of a magma chamber through the cumulate pile. The first is to prevent the chilling and crystallization of magma flowing through conduits against their sidewalls. If this fails, fossilization of the conduits in the form of crosscutting dykes is almost inevitable. Even if the original channels are closed, their crystalline material consisting of rocks formed along the sidewalls will still be preserved and easily identifiable in the field. The second is the complete closure of the feeder channels, so that all magma is removed from them. This is necessary even if no initial crystallization occurs against the sidewalls because the remaining magma in the channels will still crystallize upon cooling and form visible dykes crosscutting the cumulate pile.

Fulfilling the first condition is a relatively easy task. There is a fundamental difference between emplacement of magma into crustal country rocks versus cumulate piles of evolving basaltic chambers. In the former case, magma intrudes into the cold and rigid rocks. As a result, flowing magma is immediately chilled against cold sidewalls and then crystallizes from the margins inward from the flowing magma to form a mafic/ultramafic dyke. Because the chilling and crystallization of basaltic magma in such a situation is almost inevitable, the feeder channels are always fossilized into solid mafic/ultramafic rocks. Therefore, it is not surprising that dykes of such compositions are very common in crustal rocks of all tectonic regions around the world. In contrast, in the latter case, magma intrudes into a cumulate pile that is almost entirely solidified but may be still hot (Latypov et al. 2024). As a result, the cumulate pile can be dismembered by subvertical fractures (conduits), but the inflowing magma can hardly be chilled and crystallized against the hot sidewalls of the conduits. This is because flowing magma is expected to have a liquidus temperature (~1100-1200°C) that is close to that of the hot surrounding cumulates. In addition, magma can even be superheated relative to its liquidus temperature owing to its adiabatic rise from depth (Latypov et al. 2017c, 2022b, 2024). Thus, no solid rocks can be formed during magma flow to fossilize the feeder channel. Even if some initial magma chilling/rapid crystallization occurs, the subsequent flowing hot/superheated magma will completely remelt the initially solidified rocks (e.g., Huppert and Sparks 1989; Fabre et al. 1989; Latypov et al. 2007).

Fulfilling the second condition is much more difficult. We do not yet have any definitive solution to this problem and may only speculate on one potential mechanism that may result in closing the feeder channels. We suggest considering the possibility that magma may have propagated through the cumulate pile as isolated, melt-filled hydrofractures driven by the pressure differential along the subvertical fractures (Fig. 1). This mechanism of melt transport through crustal rocks has been pioneered by Weertman (1971) and has been subsequently developed in several other studies (Maaløe 1987; Sleep 1988; Bons 2001; Bons et al. 2001, 2012). What follows is a short summary on this mechanism from Kisters et al. (2009) and Bester and Kisters (2023) who

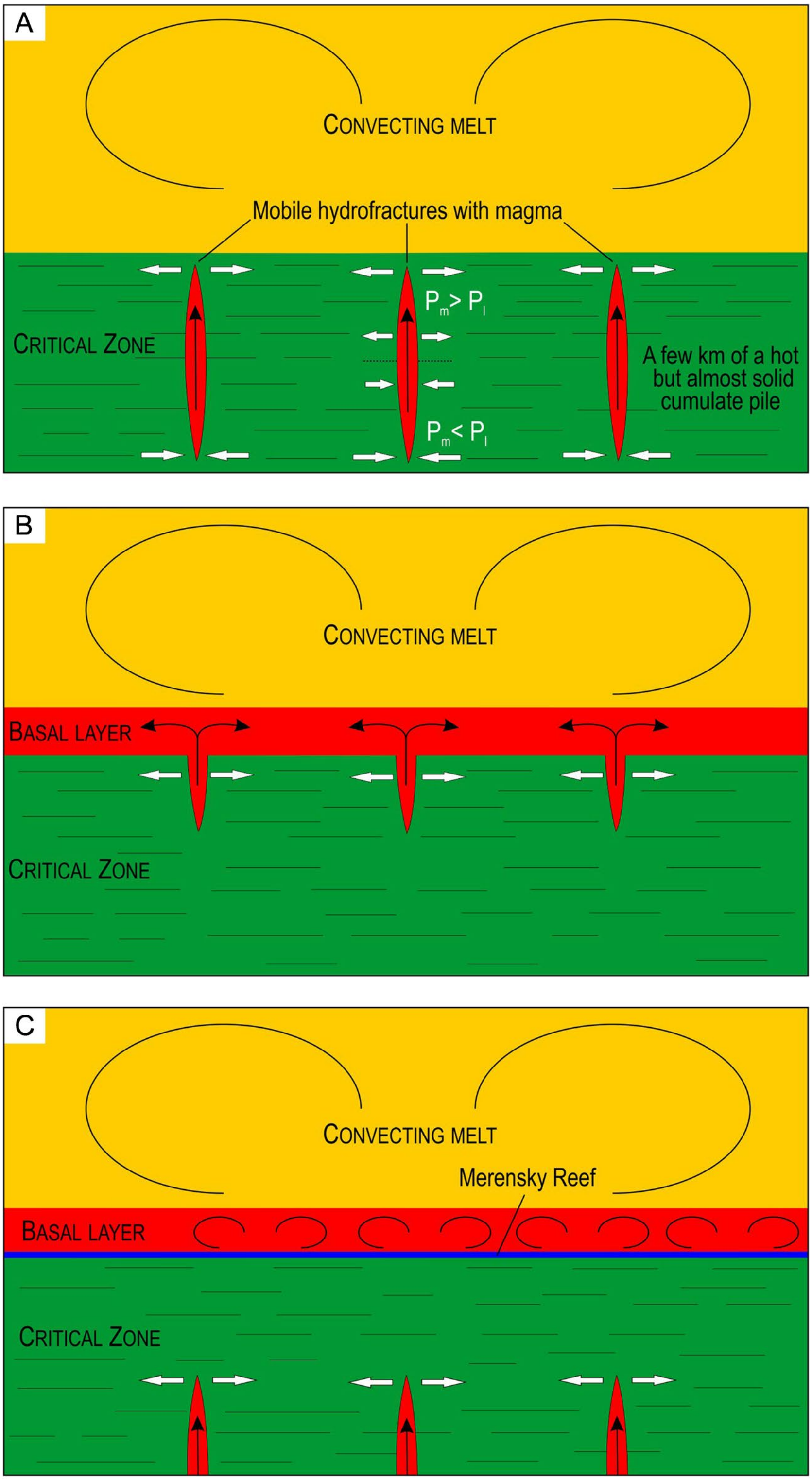

Fig. 1 A scenario that illustrates one potential explanation for absence of feeder channels for the Merensky Reef in the Bushveld Complex, South Africa. The channels are likely not preserved in the cumulate pile owing to two major reasons: (1) a flowing basaltic magma does not crystallize against channel sidewalls because the cumulate pile is too hot to cause its efficient cooling and crystallization and (2) the feeder channels are closed by the adjacent elastically deformable cumulate pile immediately after the cessation of the magma emplacement. The closure happens because the melt ascends with mobile hydrofractures that propagate at the upper tip where the melt pressure exceeds the lithostatic pressure at the tip of the hydrofracture ($P_m > P_l$) and simultaneously closes at the bottom end where the opposite is the case ($P_m < P_l$). The incoming melt thus moves through the cumulate pile within its containing fracture (**a**). The magma flowed into the main reservoir and spread across the chamber floor due to its higher density compared to the resident melt (**b**). Over time, the lower tips of the melt-filled fractures reached the crystal-liquid interface, and the fractures are closed and sealed by the surrounding deformable material (**c**). The Merensky Reef was formed from such a basal flow of magma (Latypov et al. 2015, 2017c). Importantly, this type of magma transfer through the cumulate pile into the evolving magma chamber does not leave any evidence of the original feeder conduits. The length and thickness of the mobile hydrofractures in the cumulate pile of layered intrusions remain to be defined

have recently applied it to interpret segregation, ascent and emplacement of magmas through mid-crustal rocks.

The movement of melt in hydrofractures is influenced by two factors: (a) the distribution of pressure within the fracture that is filled with melt, and (b) the differences in density and pressure between the fracture filled with melt and the surrounding rocks that contain melts. Figure 1a illustrates the pressure distribution in sub-vertical, melt-filled hydrofractures compared to the surrounding cumulate pile. The pressure (P) is determined by the density of the material (host rock and melt) and the change in depth (P=ρgh, where P is pressure in kPa, ρ is density of rock and/or melt in g/cm^3, g is acceleration due to gravity in m/s^2, and h is depth in m). The density of basaltic melt (~2.6 g/cm^3) is less than that of the LZ cumulate pile of dunitic/pyroxenitic composition (~3.0 g/cm^3). As a result, for any equal change in depth (h) along a sub-vertical hydrofracture, there will be a greater change in lithostatic pressure (P_l) in the cumulate pile compared to the pressure change in the melt-filled hydrofracture (P_m) (Fig. 1a) (Sleep 1988; Bons 2001; Bons et al. 2012). The melt pressure inside the hydrofracture is greater than the lithostatic pressure at the tip of the hydrofracture. The lithostatic pressure pushes the cumulate pile apart, causing the fracture to propagate upwards (Fig. 1a). At the lower end of the hydrofracture, the melt pressure is lower, and the lithostatic pressure causes it to close. However, if the fracture is long enough, the difference in pressure between the two tips will be significant enough to drive the process of the melt propagating upward independently. The fracture will thus propagate upwards at the upper tip while simultaneously closing at the lower tip. Instead of flowing *through* the fracture, the magma will move *with* the fracture (Bons 2001; Bons et al. 2001, 2012). Following Bester and Kisters (2023), we thus propose that magma underpressure at the lower end of the hydrofractures allows the surrounding cumulate pile to close off the hydrofractures so that the magma propagates as an isolated, buoyancy-driven, self-contained pockets that are independent of any driving pressure from an underlying magma source (e.g., Turcotte 1987; Sleep 1988; Bons et al. 2001; Brenner and Gudmundsson 2002; Rivalta et al. 2015).

One can envisage that magma parental to the MR has been propagating upwards with hydrofractures through the cumulate pile (Fig. 1a). Upon reaching the crystal-liquid interface (i.e., the temporary chamber floor) by their upper tips, the magma entered the main reservoir and spread across the chamber floor as a basal flow because of being denser than the resident melt (Fig. 1b). The MR (and other platinum reefs) is thought to have crystallized from such basal flows of a new magma (Latypov et al. 2015, 2017c, 2022b). With time, the lower tips of the melt-filled hydrofractures also reached the crystal-liquid interface and the fissures were closed by surrounding elastically deformable cumulate pile (Fig. 1c). Magma transport by such mobile hydrofractures thus leaves no trace of the former feeder conduits. There is one additional factor that may contribute to the closure of the feeder channels. Kavanagh et al. (2015) have recently shown that a transition from a vertical dyke to a horizontal sill is characterized by a significant magmatic pressure decrease of up to ~60%. This change is manifested by the rapid and dramatic contraction/closure of the feeder dyke at the moment when magma starts forming a sill (i.e., a basal flow in our case, Fig. 1b). Although not using our terminology, Kavanagh et al. (2015) have experimentally reproduced mobile hydrofractures that propagate upwards and rapidly close as soon as the liquid starts forming a sub-horizontal sill (see a movie at https://www.youtube.com/watch?v=RrLqINu-oXw&ab_channel=LiverpoolMAGMALab). The ascent of magma through the crustal rocks before its entry into the cumulate pile of the Bushveld Complex is beyond the scope of this study.

A key implication from the above discussion is that feeder channels have little chance to survive within a hot cumulate pile of evolving basaltic chambers. After their closure, most if not all evidence of the prior existence of the feeders will be obliterated by syn- and post-magmatic deformation/recrystallization of a cumulate pile. This is particularly true for the hottest uppermost portion of a cumulate pile that is in direct contact with the overlying resident melt in the chamber. It is conceivable, however, that the former magma transfer through conduits may still leave some compositional and/or textural traces in the cumulate rocks. The hot ascending magma is unlikely to be perfectly at equilibrium with a cooler pile of cumulus minerals and their associated interstitial melt. Some of the hot magma may migrate laterally into the interstitial melt-filled pore space of the host cumulates, causing melt-rock reactions such as partial melting of the cooler cumulate assemblage and modal metasomatism. The resulting rocks may resemble the mottled anorthosite and leuconorite that replace partially remelted/dissolved norite beneath the MR and UG2 orthopyroxenite/chromitite units (Mungall et al. 2016; Robb and Mungall 2020), or the extensively modified troctolites and anorthosites of the J-M Reef in the Stillwater Complex where they replace pre-existing gabbronoritic cumulates (Jenkins et al. 2021). The former pathways of the ascending magma may thus be recognized as the sub-vertically oriented rocks of broadly leucocratic composition. At issue here is the scale of the metasomatic aureole along the former pathways. In some studies, up to several meters of anorthosites below ultramafic units are attributed to the partial remelting of the norites by hot komatiitic magma (e.g., Mungall et al. 2016). Our field observations from the MR and UG2 units indicate that the thickness of a basal reaction rim consisting of mottled anorthosite is only about 5 to 10 cm and certainly less than 50 cm (Latypov et al. 2015, 2017c). The thickness of such metasomatically altered rocks may thus potentially range from several cm to meters. To our knowledge, such subvertical reaction-type rocks have not been reported from the complex. It should be noted, however, that these rocks have not been purposefully searched for thus far. Exploring these rocks may open an intriguing new line of future research in the Bushveld Complex.

The conclusion that conduit channels will tend to completely disappear after their closure may not be true for the lowermost portion of the cumulate pile that is in contact with cold country rocks. If this portion happens to be cold enough to induce crystallization of replenishing magmas, then some fossilized feeder channels may have a chance to get preserved there. If this would be the case, then the feeder dykes to the MR should be searched for close to the base of the Bushveld Complex. This idea about the chilling and rapid crystallization of the inflowing magma against the colder cumulates is consistent with field observations from the magnetite gabbro of the Upper Zone that form the transgressive depressions in the Northern gap of the western Bushveld Complex. The magma parental to these transgressive magnetite gabbro has been chilled against the colder cumulates of the Critical Zone, forming glassy and fine-grained textured rocks with plagioclase laths arranged in radial clusters (Chistyakova et al. 2021). It should be noted in this context that the high precision dating of zircons has recently indicated that the MR is ~3 Ma younger than the underlying UG2 Unit and overlying Bastard Unit (ca. 2057 Ma versus ca. 2060 Ma, respectively; Scoates et al. 2021). If the dating were true, then the host cumulate rocks to the postulated MR sill (Scoates et al. 2021) must have been already cold, and chilling and rapid crystallization of the magma parental to this sill would be inevitable just as this happened with the transgressive magnetite gabbro (Chistyakova et al. 2021). The total absence of chilled margins in the postulated MR sill indicates that absolute zircon ages are unlikely to represent the crystallization age of the rocks (from which zircons were extracted) and some alternative explanations for these ages are therefore required (Latypov et al. 2017a, 2024; Latypov and Chistyakova 2022).

Our above scenario may be extended to other layered intrusions in which no feeder conduits for cyclic units or other types of compositional reversals have been found. It should be emphasized that the proposed mechanism might not be a silver bullet for the conduit closure problem. It is not inconceivable that a better solution can be found in the future. All that we would like to stress at this stage is that the feeder conduits were likely physically closed to avoid their preservation as crosscutting dykes. This provides the simplest and straightforward explanation for the notable absence of such dykes from all layered intrusions. We hope that this study will arouse interest in this petrological problem and encourage our colleagues to come up with some alternative and perhaps better explanations for the absence of feeder conduits in layered intrusions.

Acknowledgements We started developing the ideas of this study almost ten years ago and are grateful to Tony Morse, Brian Robins, Lew Ashwal, Grant Cawthorn and Grant Bybee for lively discussion that helped us to better formulate the problem and its potential resolution. Paul Bons, Marline Elburg and Alexander Kisters are thanked for introducing us into the concept of mobile hydrofractures. Janine Kavanagh is thanked for providing a link to her experiment showing a mobile hydrofracture. More videos showing movement of magma in dykes are available at Youtube channel of the University of Liverpool, UK: https://www.youtube.com/channel/UCoqrW1B7ynDcKTTwhnUdhcQ. We would like to thank James Mungall and Steve Prevec for the careful review of our paper and a few critical comments that helped to improve the quality and clarity of the manuscript. The editorial handling of Eduardo Mansur and Bernd Lehmann is also gratefully acknowledged.

Funding Open access funding provided by University of the Witwatersrand. This work was supported in part by the National Research Foundation (NRF) of South Africa (Ref/Grant Number: SRUG2204193706-2023-04-19-CPRR) and the Bushveld Geology and Metallogeny (BUGEMET) Research Chair of the University of the Witwatersrand. Any opinion, finding, conclusion, or recommendation expressed in this contribution is that of the authors, and NRF and BUGEMET do not accept any liability in this regard.

Declarations

Conflict of interest The authors declare no competing interests.

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