NEW INSIGHTS INTO ORIGIN OF PLATINUM DEPOSITS IN LAYERED INTRUSIONS FROM THE UNDERCUTTING MERENSKY REEF OF THE BUSHVELD COMPLEX

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Abstract

Models proposed to explain Merensky-type reefs in layered intrusions fall into two major groups: (a) orthomagmatic ones, which consider platinum-group element (PGE) mineralization as an integral part of magma crystallization processes in the chamber; and (b) hydromagmatic ones, which attribute PGE mineralization to volatile-rich fluids exsolved from cooling cumulate piles (e.g. Mungall & Naldrett, 2008; Cawthorn, 2011; Godel, 2015). Most recent studies on stratiform PGE Reefs appear to favour an orthomagmatic approach and interpret them as the result of accumulation of highly PGE-enriched immiscible sulphide liquids on the temporary floor of the host magma chamber. Here we specifically focus on the orthomagmatic models, which can be subdivided into two major categories invoking either (1) gravity-induced settling of crystals from the overlying magma onto the chamber floor, with subsequent sorting of minerals during late-stage slumping of the cumulate pile or (2) *in situ* crystallization of all minerals, including chromite and sulphides, directly on the chamber floor, accompanied by re-deposition of the minerals in association with convection in the magma chamber. The resolution of this dilemma has an important implication for our understanding of processes of crystallization and differentiation of magma as well as formation of economically viable magmatic mineral deposits.

A unique feature pertinent to this issue is the undercutting Merensky Reef (MR) of the Bushveld Complex, South Africa, which is commonly associated with potholes, roughly circular depressions in which footwall rocks are removed by magmatic erosion (Fig. 1). The undercutting MR forms sill-like apophyses of medium- to coarse-grained harzburgite and orthopyroxenite enriched in sulphide and chromite, which extend laterally from pothole margins into

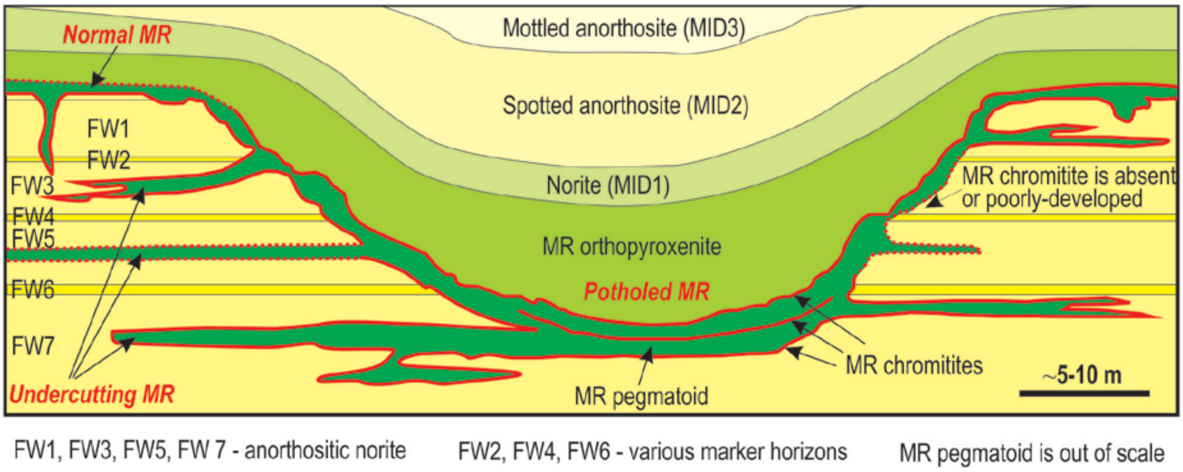

Fig. 1. A sketch of a typical MR pothole at the Impala Platinum Mine, Western Bushveld (modified from Golenya, 2007) illustrating the transgressive relationship of the normal and potholed MR to its footwall. Note that the potholed MR along the edge of the pothole is accompanied by undercutting MR bodies that are sill-like sulphide- and chromite-mineralized protrusions extending laterally from pothole margins into footwall rocks. Morphology of undercutting MR is depicted based on our personal observations from the Pilanesberg Platinum Mine and those of Ballhaus (1988) from the Rustenburg Platinum Mine. FW – footwalls; MID – middling.

They vary in thickness from 5 cm to 1-2 m and can be traced away from pothole margins for distances from a few centimeters to dozens of meters (in one case up to 300 m). Locally there may be several (six or more) apophyses of undercutting MR that are vertically stacked within the footwall cumulates in the vicinity of a single pothole. The most telling field, textural and geochemical features of the undercutting MR are as follows: (a) there is no evidence of deformation of igneous layering or rotation of xenoliths associated with these reefs; (b) thin reaction-type selvages of almost pure anorthosite after host leuconorite or mottled anorthosite are commonly developed along both margins of undercutting MR; (c) undercutting MR are mineralogically zoned; thin seams of massive chromitite are commonly developed along both margins and pass inwards into rocks with decreasing amounts of disseminated chromite (Fig. 2); sulphides can be most abundant at the base, along both margins or in the centre of the apophyses; (d) undercutting MR are also compositionally zoned, with rocks displaying either an increase or decrease in whole-rock MgO content from the margins inwards; (e) undercutting MR are highly enriched in PGE, which are mostly controlled by sulphides and chromite, with the grade and tenor being comparable to those of the normal MR.

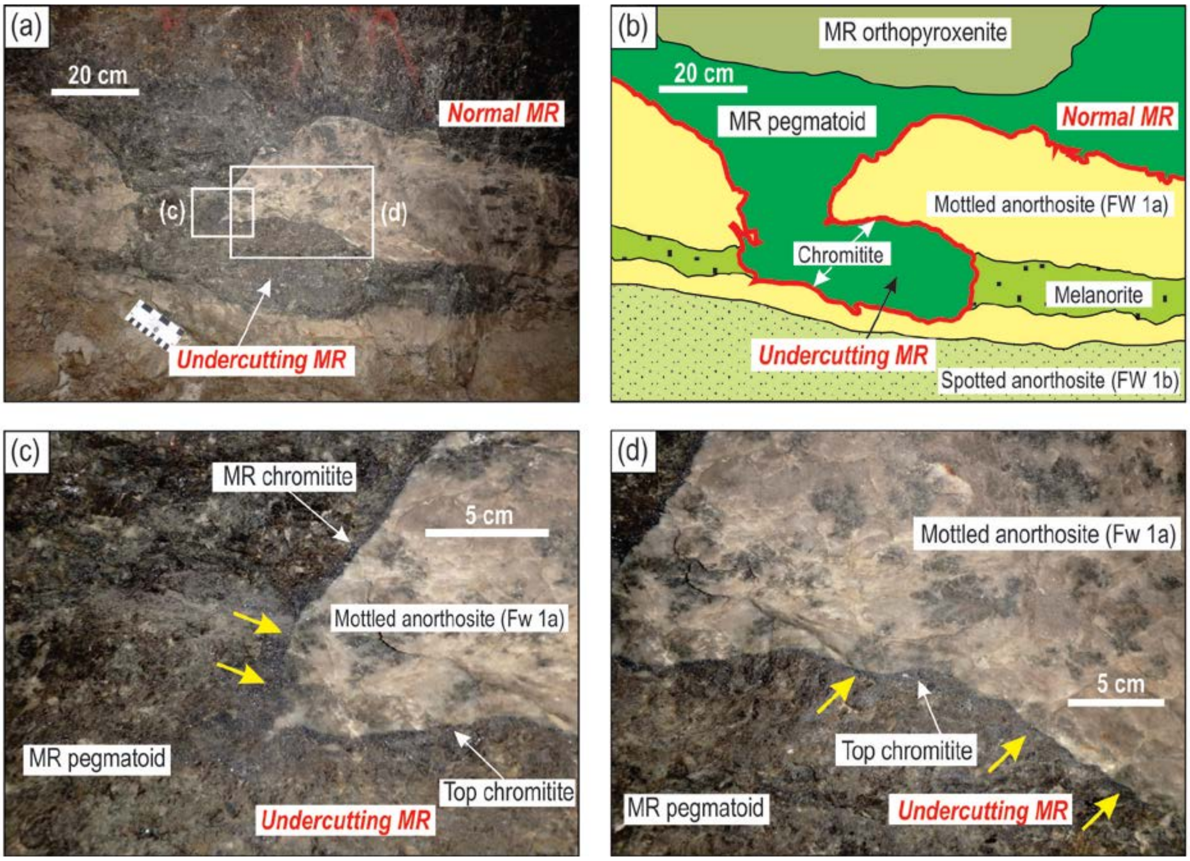

Fig. 2. Photo (a) and sketch (b) of undercutting MR that is rimmed by chromitite seams. Note the lack of deformation of layering in footwall rocks by undercutting MR. Close-up photos showing details of undercutting MR (c-d) rimmed by chromitite seams. Note that the chromitite seams appear to cut across single pyroxene oikocrysts in host mottled anorthosites (yellow arrows). 22mE 9B RSE, Shaft 3 of the Karee mine, Lonmin Platinum, Western Bushveld Complex.

A key inference is that the development of the undercutting MR within footwall rocks, in some cases many metres below a temporary chamber floor, completely eliminates their origin by gravitational settling from the overlying magma. *In situ* crystallization appears to be the only possible mechanism through which these zoned reefs could be produced. The undercutting MR is interpreted to develop along particularly amenable horizons at pothole margins through thermal/chemical erosion of the footwall rocks by superheated magma, followed by *in situ* crystallization within the resulting cavities. This indicates that scavenging of PGE by sulphides and chromite must have been taken place essentially *in situ*; that is, directly on magma–cumulate interfaces and that this process must have been remarkably efficient to concentrate PGE to an economically viable extent (10-60 ppm in grade). This process appears to have been just as efficient in the undercutting environment as in normal "open" MR, based on the observed similarity in the PGE tenors of the sulphides in both settings. This appears to only be possible if convective magma flow has acted as a conveyor that delivered a large amount of fresh, PGE-undepleted magma towards the crystal-liquid interface. Formation of PGE-rich cumulates in such sill-like bodies is possible because the rate of mass transfer by convection (km/year to km/day) is typically several orders of magnitude higher than the rate of crystallization (0.5-1.0 cm/year). This means that magma in the apophyses could exchange with the main body of magma in the chamber rapidly, compared to the rate of crystallization in the undercutting bodies. It follows that *in situ* crystallization was the dominant mechanism for the formation of not only undercutting MR, but also of the more common normal and potholed MR, which occur along flat and inclined portions of the chamber floor, respectively. The same inference may be valid for platinum deposits in other layered intrusions that do not display convincing field evidence for *in situ* crystallization due to a lack of potholes and their associated sill-like protrusions into footwall rocks.

To conclude, the new field, textural and geochemical observations on undercutting MR reinforce our idea (Latypov et al., 2015; 2017) that the formation of PGE deposits in layered intrusions does not require long-range gravitational settling of chromite and sulphide droplets from overlying magma, as implied in most current models. The gravity settling mechanism does not appear to be crucial for the origin of either PGE deposits or the host layered intrusions. The highly mineralized undercutting MR bodies in the Bushveld Complex are remarkable evidence for the attainment of high PGE concentrations in stratiform PGE deposits of layered intrusions through *in situ* crystallization directly on crystal-liquid interfaces.

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