
A Re-Evaluation of the Role of Crustal Contamination in the Formation of Magmatic Sulfides in the Bushveld Complex

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Introduction

In a recent paper, Li et al (2001a) have presented an empirically derived equation for the calculation of S solubilities of basaltic magmas. Based on this equation, they produced a sulphur solubility curve for such magmas (Fig. 1a). They interpreted their data as to support previous models whereby the sulfide-bearing reefs in the Bushveld Complex formed as a result of mixing of resident with replenishing magma, a model that has been used and accepted for many years by petrologists working on layered intrusions. Subsequently, Li et al. (2001b) pointed out that this interpretation is incorrect. Unlike S contents, S solubilities of mixtures cannot be compared to those of fractionating magmas. Hybridization of Bushveld parental magmas with resident magmas of variable composition cannot trigger sulfide supersaturation. This result requires that the mechanisms of formation of sulfides and associated PGE mineralization in the Bushveld Complex be reinvestigated.

Magmatic sulfides in the Bushveld Complex

The Bushveld Complex is a relatively sulfide-poor system. Ongoing systematic studies of the 7-9 km thick layered sequence (Maier and Barnes, 1999; unpublished data of Barnes and Maier) indicate that up to 99% of the rocks contain less than 500 ppm S. Higher sulfide contents are confined to a number of distinct settings: (i) Stratiform platiniferous sulfide-bearing "reefs", located mostly some 2 km above the base of the Complex, and generally less than 1.5 m in thickness. They include the Merensky and UG2 layers, the Pseudoreefs, Bastard Reef and the Boulder Bed. Sulfides occur generally in disseminated form, mostly not exceeding 3 vol%. Metal contents of the sulfides are generally high (several 100 ppm PGE, between 1.5 - 5.5 % Cu and 2.4 - 4 % Ni). A 6m sulphide-bearing reef-type occurrence has also been described within the orthopyroxenites of the Lower Zone in the northern limb of the Complex. Metal tenors are approximately 50 ppm Pt and Pd each, 3.5% Cu and 8% Ni. (ii) Sulfides near the base of the

intrusion, notably in the Platreef of the northern limb of the Complex where the intrusive rocks overlie dolomite, granite, Fe-formation and shale. The sulfides occur largely in disseminated form and less commonly as small, massive, pods and veins. The sulfides are somewhat less PGE-rich than those in the stratiform reefs (mostly 10-50 ppm PGE, see the section on the Platreef below), and have variable base metal contents (3-20% Cu, 5-15% Ni). (iii) Disseminated and semi-massive pipe-like transgressive sulfide enrichments in the Lower Zone of the far-western limb of the Complex (the Vlakkfontein Ni-pipes). Ni contents of the sulfides are higher than those of the reefs, at about 3.5-4%, and Cu contents are lower, at 1.5-2%. PGE contents may reach 80 ppm in semi-massive sulfides (C. van Zyl, pers. com.). (iv) Mostly metal-poor sulfides associated with several magnetite layers in the Upper Zone of the Complex, but unpublished data of Barnes and Maier indicate up to 5 vol% disseminated magmatic sulfides within a leuconorite some 40 m above the lowermost magnetite layer with up to 40 ppm PGE (Pd/Ir 36), 4.2% Cu and 1.2% Ni in the sulfide.

Contamination and sulfide segregation

Crustal contamination has been recognized as perhaps the most important ore forming mechanism in many large magmatic Ni-Cu-(PGE) sulfide deposits (e.g. Sudbury, Voisey's Bay, Noril'sk, Petchenga). If magma mixing is no longer an option to form the reef-type deposits of the Bushveld and other large layered intrusions, then it would seem reasonable to suppose that crustal contamination played a role in reef-type ore formation as well, in spite of the fact that wherever crustal contamination could be unambiguously linked to sulfide formation, sulfide contents are generally much higher than in reef-type deposits.

Three mechanisms of contamination to trigger sulfide supersaturation may be highlighted: (i) Addition of external Si, i.e. by assimilation of siliceous partial melts of the country rocks, thereby lowering the S solubility of the magma (e.g. Irvine, 1975); (ii) Addition of external S by means of

devolatilization, partial melting, or bulk assimilation of sulphidic country rock (e.g. Ripley and Alawi, 1988); (iii) An increase in O fugacity, resulting in a lowering of the FeO content and thus the S carrying capacity of the magma (e.g. Buchanan and Nolan, 1979). The latter mechanism may be particularly relevant where the magma intrudes and devolatilizes dolomite, such as in the Platreef or the Uitkomst Complex in the floor of the Bushveld.

Bushveld magmas and rocks have a distinct crustal signature, expressed by relative enrichment in highly incompatible trace elements, relative depletion in Ta, Nb, and Ti, and crustal Nd, Sr, Pb, Os, and O isotope signatures (e.g. Harmer and Sharpe, 1985; Schiffries and Rye, 1989; Kruger, 1994; McCandless et al., 1999; Schoenberg et al., 1999; Maier et al., 2000; Harris and Chaumba, 2001). In particular, there is a distinct increase in crustal component across a 300-400 m interval hosting the Merensky Reef and several other sulfide-enriched layers including the Pseudoreefs, the Boulder Bed and the Bastard Reef, particularly in terms of Sr (Kruger, 1994), and Nd isotopic signature (Maier et al., 2000). The incompatible trace element data are broadly consistent with this model. Thus, the data of Barnes and Maier (2002) show that the Merensky Reef has much higher REE/Ta and Cu/Se ratios and thus crustal component than the sills that are believed to represent the parental magmas to the Lower and Critical Zones (e.g. Sm/Ta 26 vs. 5; Cu/Se 500 vs. 214).

Most authors believe that the crustal signature was acquired by contamination during ascent through the Kaapvaal crust, rather than during melting of enriched sub-continental lithosphere. For example, Schiffries and Rye (1989) argued that there is no evidence for mantle sources enriched in ^{18}O in the Kaapvaal Craton. Estimates of the amount of contamination for the parental magmas to the Lower and Critical Zones range from about 5-20% (Schiffries and Rye, 1989; Schoenberg et al., 1999; Maier et al., 2000), and most authors argue that the contamination occurred in a lower staging chamber rather than in the Bushveld chamber itself, in view of the homogenous isotopic signatures of individual layers along some 400 km of strike (Sharpe, 1985; Schiffries and Rye, 1989; Lee and Butcher, 1990; McCandless and Ruiz, 1991; Harris and Chaumba, 2001; but see Kruger, 1992, and Rice, 1998 for an alternative view). If that were the case, it appears conceivable that crustal contamination in a staging chamber triggered sulfide supersaturation. However, in that case, the sulfide melt must have been entrained by the ascending magma (Lee and

Butcher, 1990). The available evidence from the composition of fine-grained, mafic sills in the floor of the Complex that are generally thought to represent the parental magmas to the Complex does not support this model. Some 20 samples of mafic sills have been analysed in the past for PGE (e.g. Davies and Tredoux, 1985). Their average Pt+Pd content is around 30 ppb, all samples are undepleted in noble metals relative to Cu and Ni, and S undersaturated. This suggests that the parental magmas to the bulk of the Lower and Lower Critical Zones have not equilibrated with sulfides in a staging chamber or during ascent, and that the segregation of the magmatic sulfides of the Complex occurred in the Bushveld chamber. Further, there is a progressive increase in Cu/Pd and Cu/Pt through individual cyclic units in the UCZ (Maier and Barnes, 1999; Barnes and Maier, 2002) that is best explained by in situ formation of the sulphides. For example, the PGE-rich Merensky reef sulfides are overlain, after about 50 cm, by metal-depleted sulfides. This pattern is best explained by segregation of the upper sulfides from the metal depleted Merensky Reef residual magma. It is much more difficult to argue that the upper sulfides were brought in by a distinct magma surge from depth.

The implication is that the crustal contamination of the Bushveld magma in the staging chamber did not trigger sulfide segregation, possibly due to a large degree of S undersaturation related to a S-poor mantle source and depressurization during ascent (e.g. Mavrogenes and O'Neill, 1999).

Summary

The formation of reef-type ores in the Bushveld Complex remains more enigmatic than ever. Mixing of resident and replenishing magmas can no longer be seen to be responsible for the formation of the sulfides. Many important magmatic Ni-Cu-(PGE) sulfide deposits elsewhere formed by assimilation of crustal material, and thus the role of crustal contamination in the formation of the Bushveld reef-type ores needs to be reinvestigated, particularly in view of the distinct crustal signature of Bushveld magmas and rocks. Crustal contamination may have occurred before emplacement, in a staging chamber or a magma conduit, or it may have occurred in the Bushveld chamber itself. Most authors favour contamination before emplacement, mainly in view of the apparent lateral consistency of isotopic signatures. However, sills in the floor of the Complex that are interpreted to represent the parental magmas are sulfide and PGE-poor, suggesting that contam-

ination at depth did not trigger sulfide segregation, possibly due to large degrees of S undersaturation of Bushveld magmas.

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