Crystallization of the Bushveld Complex and its bearing on melt percolation and metasomatism in the mantle

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Introduction

Large layered mafic intrusions, such as the Bushveld Complex, illustrate processes of melt percolation and metasomatism of a preexisting cumulate assemblage by that melt. Because these bodies are well exposed and accessible, they may provide insight into similar processes in the mantle. Layered intrusions preserve original textural and chemical properties and are generally not metamorphosed or disrupted by tectonism. Accordingly, we have made a detailed textural and geochemical study of a fifty-six meter long continuous drill core from the Upper Critical zone of the Bushveld Complex. The core was taken from the Atok mine in the northeast part of the Complex.

The Bushveld core

The core includes the Bastard and Merensky Reef units and penetrated to approximately 12 m below the Merensky reef. The core consists of a sequence of pyroxenites, norites and anorthosites and exhibits cyclical variations in texture and grain size as well as mode. The rocks in the lower nine meters of the core are dominated by norite but include two poorly-defined cycles in which pyroxene-rich assemblages are overlain by progressively more plagioclase-rich ones. The cumulus minerals are orthopyroxene (opx) and/or plagioclase (plag), except in two well-defined layers ~10–20 cm thick where clinopyroxene (cpx) is both abundant and cumulus. This sequence is overlain by the Merensky Reef and Bastard Reef units, the former being 16 m thick. These units consist of a basal pyroxenite overlain by norite, which is in turn overlain by anorthosite. The Merensky reef proper is embedded within the basal pyroxenite of the Merensky Reef unit. The Merensky and Bastard reefs are composed of granular (locally texturally equilibrated) pyroxenite with localized pegmatoidal patches and, in the case of the former, an extensive basal pegmatoid. The pegmatoids have coarser grain sizes (by factors of 2 to 10) than their host pyroxenites but are composed of the same major minerals (opx and plag). The Merensky reef contains base metal sulfides and is known, of course, for its high concentrations of the platinum group elements (PGEs); the Bastard reef is also mineralized but PGE-free. Evidence for percolation of melt through the Merensky and Bastard reefs and adjacent rocks comes from micro-textural and geochemical observations.

Micro-textures

The equilibrated pyroxenites of the Merensky and Bastard reefs as well as the anorthosites and norites above and below the pyroxenites show evidence of substantial densification (mostly in the solution creep field). Small residual melt geometries are pseudo-morphed by cotectic crystallizing phases and occur on cumulus phase triple junctions. These may represent a very small (< 1%) residual melt fraction. Opx grains in the pegmatoids have euhedral crystal faces and are enclosed in poikilitic plag. We interpret the latter to represent pseudomorphs of the interstitial melt geometry. The large opx grains show evidence of slip and glide (dislocation creep) deformation, indicating locally high grain scale stresses. This deformation may be related to the expansion of the matrix as melt collected beneath the relatively impermeable anorthositic reef hanging walls. A second generation of granular opx occurs in the pockets of 'melt' between the large opx grains. We speculate that the latter grew as the matrix expanded and then prevented subsequent collapse of the matrix (compaction). The hanging wall anorthosites show some textural and modal

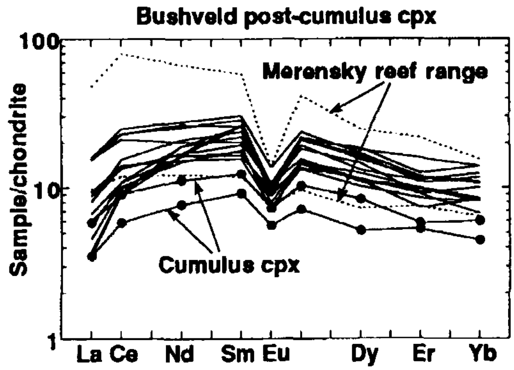

FIG. 1.

modifications in a zone ~ 1 m thick immediately above the Merensky and Bastard reefs, probably as a result of melt percolation through them.

Geochemistry

Pyroxene and plag in samples from the sequence were analyzed with IMS-3f ion microprobe following established procedures. A primary beam of O^- focused to a diameter of 40 μm was used. Secondary ion intensities were measured for ^{139}La, ^{140}Ce, ^{146}Nd, ^{147}Sm, ^{151}Eu, ^{163}Dy, ^{166}Er and ^{174}Yb, and molecular ion interferences were eliminated using an energy offset of 60 eV. Secondary ion intensities were normalized to ^{30}Si and referred to appropriate standards.

There are two anomalous geochemical characteristics in the sequence. The first is that Merensky reef pyroxenes contain high and variable amounts of the *REE*s (Fig. 1). In particular, the chondrite-normalized Ce contents (Ce_N) of cpx range from ~10 to 90, and Yb_N contents range from 4 to 17. The *REE* patterns are characterized by deep negative Eu anomalies, which are deeper for crystals having high *REE* contents and relatively shallow for those with low *REE* contents. This indicates that at least the former equilibrated with melts which themselves had equilibrated with substantial amounts of plagioclase. Opx exhibits similar features, although absolute *REE* concentrations are, as expected, much lower than those of coexisting cpx. The high concentrations of *REE*s are not accompanied by evolved major element compositions, and the cpx and opx diverge relatively little from their average respective compositions of $Wo_{43}En_{47}Fs_{10}$ and $Wo_3En_{76}Fs_{22}$ throughout the Merensky reef and its host pyroxenite. Pyroxenes characterized by high incompatible trace element but unevolved major element contents cannot be explained by closed-system crystallization from intercumulus melt. The divergence of major and incompatible trace elements concentrations is recognized, however, as a classic feature of metasomatism in geologic systems. In the Bushveld Complex, metasomatism involved reaction between a pre-existing cumulate assemblage and infiltrating melt. Pyroxenes in the Bastard reef are also relatively enriched in *REE*s. Therefore, the geochemical anomalies correspond to textural and modal discontinuities.

The second anomalous feature is that intercumulus pyroxene in the cumulate rocks above and below the Merensky reef are enriched in the *REE*s compared to cumulus cpx in the gabbronorite units below the reef (Fig. 1). The intercumulus cpx also exhibit deep Eu anomalies and are not evolved in terms of major elements. Absolute *REE* abundances in intercumulus cpx are greatest in the rocks immediately below the Merensky reef. These data are interpreted to indicate that the intercmulus minerals crystallized from melt that percolated through the cumulus assemblage. The melt was equilibrated with that assemblage in terms of the major (compatible) elements but not in terms of the incompatible trace elements.

Conclusion

The observations indicate that the Bushveld rocks record processes of melt percolation, extraction, and accumulation/segregation in specific horizons and of metasomatism of a pre-existing cumulate assemblage by infiltrating melt. The study of such rocks should eventually provide length and time scales for melt migration and rheological constraints for partially molten systems. Although the time and length scales of these processes in the mantle and layered intrusions are different, the creep mechanisms and grain sizes are comparable. Therefore, observations in layered intrusions are also relevant to the mantle.