Compaction in the Bushveld Complex and the Nature of the Lower Zone-Critical Zone Transition

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A fundamental question in modern studies of layered intrusions is how they fractionate. In the Bushveld Complex, processes of chemical and physical fractionation led to the concentration of important PGE deposits. Compaction in the mush zone of a crystallizing chamber is gaining favor as a model for fractionation, whereby evolved interstitial liquid expelled from the compacting crystal pile is returned to the magma chamber. The role of compaction in the chemical fractionation of igneous bodies, from thick lava flows and lava lakes to large intrusions, has been the subject of many studies recently, and although such a process is beginning to be accepted as a factor in some settings (e.g., Stillwater Complex, Holyoke Flows, Palisades Sill), its role is debated for others. In the Bushveld Complex, for example, some scientists argue that there was no significant crystal-liquid mush zone in which compaction could have occurred (e.g., Cawthorn, 1999). In this study, we present new quantitative textural data that show compaction could have been important during the crystallization of the Lower and Critical zones of the Bushveld Complex. Establishing that compaction was a factor in the evolution of the Bushveld Complex confirms the presence of a significant mush zone during its crystallization, from which PGE could have been harvested.

Introduction

Much attention has been paid to the mechanisms of formation of PGE-enriched sulfide deposits in the Bushveld Complex. Recently, the debate has focused on whether the PGE are concentrated by immiscible S-rich liquids that separate from mixed magmas, or whether an upwardly migrating volatile-rich fluid phase exsolved from late expelled melt fractions was the concentrating mechanism. The presence of volatile bearing phases in the stratiform deposits, as well as the Cl- rich nature of volatiles in those phases has been shown to substantiate the latter view (Boudreau et al., 1986). Here we address the mechanics of how such a phase could be expelled from the crystallizing mush zone of the intrusion via compaction.

Post-nucleation processes have been implicated for the development of small-scale features such as inch-scale layering in the Stillwater Complex (Boudreau and McBirney, 1997). In this study, we evaluate the degree to which similar processes can be implicated in large-scale, chamber-wide fractionation. We focus on two textural parameters: crystal size distributions and alignment factors.

Crystal Size Distributions

Crystal Size Distributions (CSDs) are a semi-log plot of population density against crystal size, and allow for a direct method of determining some of the crystallization kinetics in a system independent of experimental approaches or theoretical thermodynamic/kinetic techniques. For example, they have been used to provide information on crystal growth rate and residence time (Marsh, 1988), nucleation density and magmatic processes such as crystal accumulation and crystal removal (Cashman and Marsh, 1988) and aging (e.g, Waters and Boudreau, 1996). Timing of aging in an equilibrating crystal pile has also been established through studies of chadocryst populations whose growth was sequentially arrested by the enclosing oikocryst (Higgins, 1998). Thus, combining CSD data with other chemical and physical petrologic findings may enable the temporal evolution of igneous and metamorphic systems to be more fully appreciated (Marsh, 1988).

The basic precept of CSD analysis of igneous rocks is that easily measured parameters such as crystal size, crystal number and other crystal population characteristics can be related to rates of crystal nucleation and growth. Fundamentally, if growth rate is constant and nucleation rate increases exponentially with time a typical log-linear CSD plot is produced. Changes to the magmatic system are reflected in the shape of the CSD plot. For example, when melt is expelled from the system, there is a decrease in nucleation rate and a corresponding decrease in small size fractions (Marsh, 1998). Such overturned CSD plots can also be related to crystal aging or annealing wherein small size fractions are consumed at the expense of growth of larger crystals (e.g, Marsh, 1998).

Alignment Factors

The extent of alignment of tabular grains can be quantitatively determined based on the eigenvectors of the major axes of the grains of interest (Ben and Allard, 1989; Meurer and Boudreau, 1998). Combining AF data with parameters such as trace element distribution or modal changes with stratigraphic position can be useful in gaining insight into how foliation development is related to compaction and redistribution of late interstitial liquids. Furthermore, alignment factor (AF) has been compared to mineral aspect ratio to determine to what extent foliation is related to recrystallization under uniaxial compression (Meurer and Boudreau, 1998).

Compaction induced fractionation

Compaction has been cited as a mechanism for the fractionation of evolved liquids in several settings. For example, the depletion of lower parts of the Holyoke flood-basalt in Connecticut in incompatible trace elements has been shown to be due to compaction of that segment of the basalt flow such that late liquids enriched in the incompatible elements were expelled from the lower portion of the pile (Philpotts et al., 1996). In the Bushveld Complex, we expect that if the last fractions of interstitial liquid were squeezed out of a compacting pile then the compaction zone should be relatively depleted in incompatible elements.

Results

A suite of 40 accurately located and oriented samples were obtained from a ~ 130 m interval bracketing the stratigraphically significant transition between the Lower and Critical Zones in the Bushveld Complex. Textural data for these samples are summarized in figure 1.

AF decreases with stratigraphic height and foliation is best developed in the pyroxene-rich harzburgite of the Lower Zone (Figure 1). This result is expected: compaction in a mush zone is best developed in single-crystal systems. At the Lower Zone-Critical Zone transition, plagioclase content increases, thereby pinning pyroxene grain boundaries and decreasing the efficiency of compaction. Furthermore, there is a positive correlation between the quality of the foliation and mineral aspect ratio (Figure 2), a result consistent with compaction: selective grain resorption of unfavorably oriented grains and uneven crystal growth caused by uniaxial stress of compaction can result in grains with high aspect ratios.

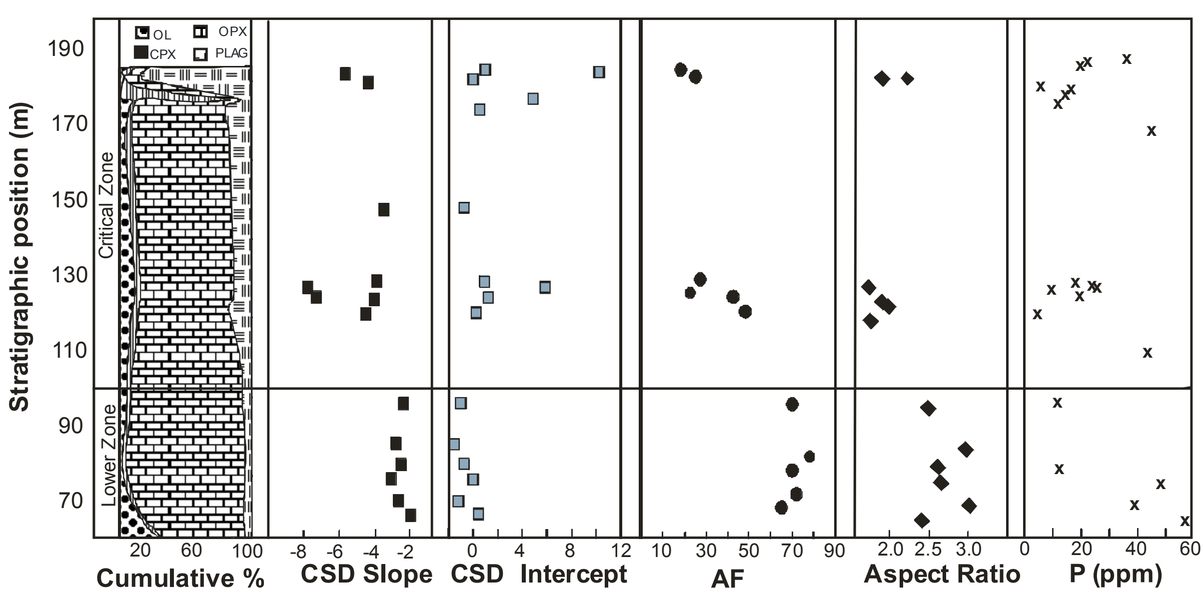

Figure 1. *Summary of textural and compositional data from the Lower and Critical Zones of the Bushveld Complex.*

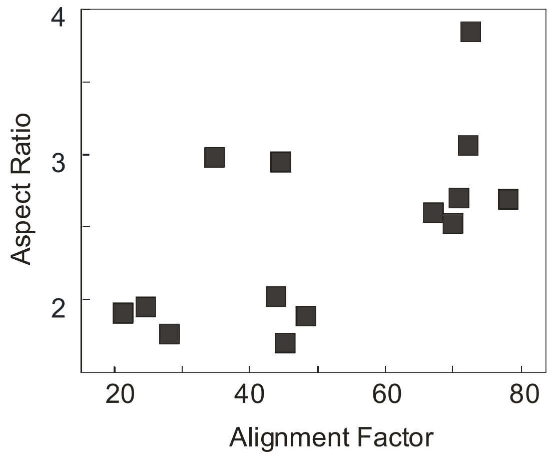

Figure 2. *Plot of mineral aspect ratio against the mineral alignment factor.*

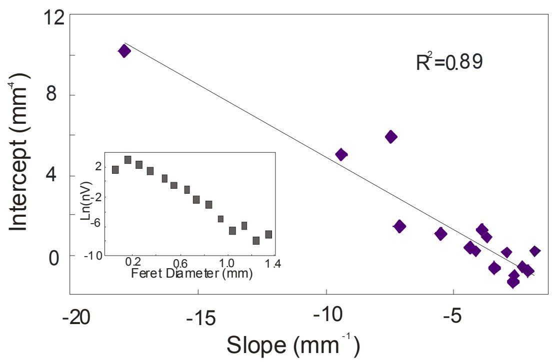

Figure 3. *Plot of intercept valueagainst the slope of the log-linear portions of CSD curves fro samples from the Lower and Critical Zone samples. Inset: typical CSD plot.*

Plots of population density versus crystal size show a log-linear trend overturned at smaller grain sizes, a result consistent with both crystal aging, wherein larger grains grow at the expense of small ones in the crystallizing pile, and melt migration, where nucleation is suppressed by the loss of late melt fractions (inset, Figure 3). CSD slope and intercept data vary with stratigraphy (Figure 1). Slopes in the Critical Zone are steeper, indicating less recrystallization and less of a compaction effect. In contrast, slopes in the Lower Zone are shallower, a result consistent with slower cooling and a greater compaction/recrystallization effect. CSD intercepts vary with stratigraphy in the same way: lower intercepts are associated with the shallower slopes of the Lower Zone and vice versa. Finally, a plot of CSD slope v. intercept (Figure 3) shows a linear array, indicating single system dynamics.

Bulk rock major (DCP-OES) and trace element (ICP-MS) data were obtained for our sample suite. The incompatible element P is used as a proxy for trapped liquid fraction because it is equally incompatible in all major phases present. Thus, it can be used to indicate the extent to which late melt has been expelled. These data cannot be simply explained by expulsion of late liquid fractions from a compacting crystal pile: There is not a negative correlation between amount of foliation developed and amount of incompatible trace element found in the bulk rock. In fact, incompatible trace elements such as P, U, Zr all are fairly consistent throughout the sampled section. This result, though unexpected, is consistent with compaction. We envisage a scenario wherein the upwardly migrating compaction zone was followed by an upwardly migrating solidification front such that a similar amount of late liquid was trapped throughout the sequence. Models of trapped liquid content based on Mg # shift (e.g., Meurer and Boudreau, 1998) could clarify whether this scenario is appropriate.

Textural data for the Lower Zone and Lower Critical Zone of the Bushveld Complex is consistent with compaction, and bulk rock geochemical data support this interpretation. CSD plots consistently show a loss of smaller size fractions, which may be explained by either later liquid expulsion or by crystal aging. Both of these processes would be expected of compaction is occurring in the slowly cooled mush zone.

The positive correlation between mineral aspect ratio and AF suggests that recrystallization (crystal aging) demonstrated by CSD plots occurred in a regime of uniaxial stress, as would be expected in a compacting crystal pile. Furthermore, systematic variation of alignment factor with stratigraphy is indicative of compaction: AF decreases suddenly at the Critical Zone boundary where modal plagioclase increases, pinning orthopyroxene grain boundaries and preventing further compaction.

Conclusions

Quantitative textural studies are gaining prominence as a means for understanding crystallization kinetics in igneous systems. Such studies have established a role for compaction in a range of crystallization settings, on a case-by-case basis. We expect to see a continuum amongst these settings such that the slowest cooled, largest magma chambers have the greatest compaction effect. Thus, demonstrating that compaction was a factor in the chemical evolution of the Bushveld Complex suggests that compaction in a crystal-liquid mush zone can be considered as a process that generally leads to fractionation in large igneous intrusions. In fact, we suppose that eventually a great deal of igneous differentiation in these bodies may be shown to be the result of post-nucleation processes in addition to traditional fractionation mechanisms.

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