WHOLE-ROCK GEOCHEMISTRY IN THE ULTRAMAFIC AND LOWER BANDED SERIES OF THE STILLWATER COMPLEX, MONTANA, USA

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ABSTRACT

There have been a large number of papers on the Stillwater stratigraphy, petrology, and mineral chemistry; however, there are a limited number of modern, whole-rock analyses for the full suite of major and trace elements. This work presents results from lithophile-elements analyses performed on samples taken along a stratigraphic section of the Ultramafic and Lower Banded series in the Mountain View area of the Stillwater Complex, Montana.

In the Lower Banded series, plagioclase is the most common mineral present and plots of Al_2O_3 vs elements compatible with plagioclase (e.g., Na_2O, Ga, Sr, and Eu) show strong positive correlation. Ba and K_2O also show plagioclase control, although altered samples show K_2O enrichment. The rocks from the JM-reef and the OBI unit do not show a different trend. Plots of elements compatible with pyroxene (TiO_2, MnO, Cr, Sc, V, Y, HREE and Zn) also show positive correlations with MgO (up to 20 wt % MgO). In rocks with more than 20 wt % MgO, the mafic mineral present is olivine rather than pyroxene and most of these elements are incompatible or only slightly compatible with olivine and thus the concentrations of these elements fall or remain flat as MgO content increase above 20 wt %. The incompatible elements U, Th, Nb, Zr and Hf are present at very low levels, 0.1 to 1 time mantle values. The proposed liquid for the Lower Banded series is based on the group 2 dykes (very fine-grained gabbronorites) which contain approximately 10 times mantle incompatible lithophile elements. Thus the liquid fraction in the Lower Banded series represents <10% of the rocks. Despite the disruption of layering at the level of OBI and the reappearance of olivine, the lithophile-element compositions of the rocks in OBI are similar to rocks from other units. In particular, the reef is not enriched in incompatible elements and unlike the Merensky reef of the Bushveld Complex, but similar to the Great Dyke, there does not seem to be a change in magma linage across the reef.

In the Ultramafic series, in addition to olivine and pyroxene, chromite is an important mineral. Plots of Cr_2O_3 vs Al_2O_3, FeO, Co, Ga, V and Zn show that chromite is the main mineral controlling these elements. Compatible elements such as MnO and Ni show chromite, orthopyroxene, and olivine control. Incompatible element concentrations are very low, at 0.1 to 1 times mantle values, indicating a very low liquid fraction.

Mantle-normalized-trace-element plots show large negative Nb anomalies, $(U/Nb)_N$ and $(La/Nb)_N$ ~5 in both series. Aside from the Nb anomalies, the patterns are relatively flat in the Ultramafic series. In the Lower Banded series, the patterns are also relatively flat apart from their positive, Ba, Sr, and Eu anomalies, reflecting the presence of plagioclase.

The Lower Banded series rocks can be modelled by crystallization from the group 2 dykes. The Ultramafic series is more problematic in that the TiO_2 and Al_2O_3 content of the massive chromite indicates that the liquid that they crystallized from contained ~ 0.7 % TiO_2 and 13 wt % Al_2O_3. These concentrations are higher than those of the proposed parental magma of the Ultramafic series, the group 3 dykes.

GRAVITY SETTLING VS IN SITU CRYSTALLIZATION: AN ONGOING DEBATE

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ABSTRACT

As well as marking the 50th anniversary of the classic Wager and Brown volume celebrated in this workshop, 2018 also marks the 40th anniversary of another landmark publication in layered intrusion petrology, Campbell's (1978) critique of classical cumulus theory. This paper, which had its genesis in Campbell's PhD thesis work on the Jimberlana Dyke in Western Australia, raised a number of lines of evidence to argue that much of the crystallisation in layered intrusions happens as a result of in-situ nucleation and growth in boundary layers at the margins of the convecting magma, rather than by accumulation of crystals that nucleated elsewhere and sank to the floor of the chamber. This contribution considers some of the major points raised by Campbell (1978), some of which were actually first raised in the same year as the Wager and Brown volume (Campbell, 1968). I consider to what extent this work has held up, and how far subsequent research has helped resolve the controversy. Have we made significant progress in determining where and how crystals grow in magma chambers?

The arguments raised by Campbell (1978) and in subsequent papers (e.g. Campbell 1987) against crystal settling fall into three categories:

1. Hydraulics of gravity settling – evidence from inversely graded layers with plagioclase at the bottom; buoyancy of plagioclase in Fe-rich magmas;
2. Development of cumulus textures in rocks developed on steep side walls and overhanging upper margins of Jimberlana and other intrusions;
3. The presence of "clustering" of cumulus phases indicative of heterogeneous self nucleation, and inconsistent with free settling or gravity flow deposition of individual non-adhering crystals.

The first two observations are based on straightforward field observations and experimental evidence and are largely unchallenged. Formation of wall and roof cumulates clearly requires in-situ nucleation, unless some mechanism is possible whereby crystals suspended within convecting magma can become physically attached to the walls and roof. The synneusis hypothesis of Schwindinger et al. (1999) holds that suspended crystals in a basaltic magma can stick together following fortuitous impact, and this provides a possible if rather implausible way out of the problem; suspended crystals in convecting magma could become physically plastered onto the walls and roof. However, on microtextural evidence such as that from inverted pigeonite clusters noted by Campbell (1978), it is much more likely that crystal clusters in lavas and in cumulates form by heterogeneous self-nucleation, i.e. nucleation of grains on a substrate of other grains of the same mineral. This provides a more economical explanation for roof and sidewall cumulates.

The third observation, evidence of clustering, indicative of heterogeneous self-nucleation, is abundant in cumulate rocks. A recently recognised example is the common presence of linear arrays or chains of chromite grains preserved within plagioclase and pyroxene oikocrysts in chromitite seams. These features are present in the basal chromitite of the Merensky Reef, where they occur both in "normal" reef and in chromitite developed at steep side walls of potholes that can only have formed by in situ growth (Latypov et al., 2017; Latypov et al., 2015). Such textures are also evidence against kinetic sieving in gravity currents, a currently popular hypothesis for the development of the Merensky Reef and other delicately phase-layered units in the Bushveld Complex (Maier et al., 2013), which requires that crystals behave as individual non-interacting particles (Forien et al., 2015).