Layered intrusions are important for a number of reasons. Primarily, they present a record of how mafic magmas crystallize and, as a consequence, change their compositions by the process of magmatic differentiation. However, it is increasingly recognized that deciphering the record preserved by layered intrusions is not as easy as once thought. The classic models envisioned that magma differentiation was the result of crystals settling out of the magma. Alternatively, it has been suggested that crystals precipitate ‘in situ’ on the floor and the walls of the magma chamber and that it is the evolved liquid that moves away from the crystals. Yet others have suggested that it is descending plumes of crystal-rich magma that accumulate at the floor of the magma chamber and then separate solid from liquid by compaction of the crystal pile. Layered intrusions also host important ore reserves of Ni, Cu, Cr, Ti, V, and then separate solid from liquid by compaction of the crystal pile. 

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My views on layered intrusions have been influenced by the study of the larger examples, such as the Bushveld Complex and the Stillwater Complex (Montana, USA). These intrusions had a long time to be modified as they slowly cooled and crystallized. I have taken as my initial hypothesis that magmas simply crystallize and fractionate along a cotectic, and that many of the more interesting features of layered intrusions, including in many cases the layering itself, are imparted later. The thick sections of rather homogeneous igneous rock that occur in intrusions from the Skaergaard Intrusion of Greenland to the Stillwater Complex are, perhaps, the purest expression of how unexciting most of the crystallization of these magmas can be. Interest begins to peak once heterogeneities appear, whether it be the trough bands developed in the Skaergaard gabbro or the reappearance of olivine in the Banded Series of the Stillwater Complex contains troctolites (rocks composed of olivine and plagioclase) that crosscut gabbros (composed of pyroxene and plagioclase). These relationships have been explained by the interaction of the gabbroic protolith with fluids that became silica-undersaturated as they rose through the crystal pile, i.e. rose into hotter rocks. What this implies is that a reactive agent (a melt or fluid) can migrate through the crystal pile at high temperature and leave little evidence of its passage until it becomes out of equilibrium with the host assemblage.

Another process, which I believe can modify the original magmatic crystalline assemblage is compositional zone-refining whereby liquids and vapor migrate through the crystal mush. This may lead, in some instances, to wholesale remelting or replacement of the original mineral assemblage (McBirney 1987). This is most evident when the process results in bodies that crosscut layering. For example, the Middle Banded Series of the Stillwater Complex contains troctolites (rocks composed of olivine and plagioclase) that crosscut gabbros (composed of pyroxene and plagioclase) (Fig. 1B). Not only is there a change in the mineralogy, but there is a textural change from a well-foliated mineral laminar in the gabbro—in which the tabular minerals are all lying in the same plane—to a massive texture of unaligned minerals in the troctolite. These relationships have been explained by the interaction of the gabbroic protolith with fluids that became silica-undersaturated as they rose through the crystal pile, i.e. rise into hotter rocks. What this implies is that a reactive agent (a melt or fluid) can migrate through the crystal pile at high temperature and leave little evidence of its passage until it becomes out of equilibrium with the host assemblage.
The problems described above become even more acute when the modification of an original magmatic assemblage and texture is more or less conformable with the original layering, and it becomes difficult to infer what was a primary feature of the crystallizing magma and what occurred at a later stage. An example of this is the transition between poikilitic (a texture describing an igneous rock in which large crystals contain inclusions of other minerals) and equigranular (a texture in which euhedral crystals are of equal size) harzburgite in a typical cyclic unit from the Ultramafic Series of the Stillwater Complex that can develop “finger structures” in which the poikilitic harzburgite forms thin pipe-like intrusions into the overlying granular harzburgite (Fig. 1C). This geometry is typical of structures that develop at reaction fronts (e.g. Kelemen et al. 1995; Boudreau 2016). Regardless of the actual cause, the finger structures and the possibility of one rock having formed by replacement of another suggests that the poikilitic harzburgite may not have initially crystallized as conventionally thought.

My work has convinced me that the use of “cumulus” terminology is one of the major impediments to understanding layered intrusions. This is because the terms, derived from the idea that the rock formed by “accumulated” minerals, has genetic/interpretive implications. Yet, these terms have been used for decades to describe the rocks. Although in many instances it may be true that some of the layered rocks formed as conventional cumulates, the examples noted above suggest this is not always the case. For example, the ultramafic rocks from the Stillwater can be texturally similar to mantle peridotites, but no one uses cumulus terminology to describe the latter. Other examples are those rocks interpreted to have formed by incongruent hydration melting—rocks more properly interpreted as “restites” (residual solid assemblages), not cumulates (e.g. Boudreau 1988, 1999)—and those rocks subject to metasomatic changes (e.g. Irvine 1980). Using a neutral descriptive terminology allows one to be open to other interpretations. It may be that nine times out of ten a conventional interpretation is correct, but why be prejudicial in the observational description of the rocks?

All of this, somewhat ironically, has led me to see that studies of large intrusions may not be the best way to understand how magmas crystallize. There is just too much overprinting and modification of the original mineralogy and texture. One of the avenues I find particularly promising is the integration of observations from small to large basaltic magma systems. For example, thick lava flows can show significant textural, lithological, and geochemical features that developed as the result of compaction (e.g. Philpotts et al. 1996). At the other extreme is the integration of observations from high-grade metamorphic rocks. For example, metamorphic banding can have many similarities with fine-scale mineral layering in layered intrusions, and both the igneous and metamorphic systems can show extensive evidence for isotopic disequilibrium. In regard to the latter, it is observed that grain-scale interaction of fluids based on isotope reequilibration is on the order of $10^3$–$10^5$ years for amphibolite–granulite facies metamorphic rocks (e.g. Graham et al. 1998). The longer times are approximately the timescales of crystallization of the larger intrusions, and exploration of similarities with high-grade metamorphic isotopic disequilibrium may yet bring insights into the igneous problem.

This brings me back to my original concern as a young geologist: “No more interesting questions to be explored in layered intrusions?” Nah! We are just getting started...

REFERENCES


