Computer Simulations of Magma Chamber Evolution:

Testing an Alternative Model for the Development of Layered Mafic Intrusions and the Origin of Granite

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Abstract

The association of granite and basalt is observed in every large basaltic magma chamber. Large basaltic rock bodies (termed LMIs, for Layered Mafic Intrusions) provide unique insights into the evolution of the material that makes up over 75% of the Earth's crust. Yet, the details of LMI evolution remain obscure and controversial. For example, many studies of the well-exposed Skaergaard Intrusion in Greenland document a relatively simple, closed-system evolution in which a single vat of magma progressively crystallized from the outside in. However, the compositions of individual rock layers do not represent realistic magma compositions, and the average composition of the entire intrusion is significantly more mafic (i.e., poor in SiO_2) than the initial basaltic melt preserved on the chilled margins of the intrusion. Here, we test the viability of an alternative model that can explain this paradox. The new model invokes the sequential extraction of evolved felsic liquids from within a crystal mush zone located behind the advancing crystallization in the magma chamber. Our code is written using test-driven development with C++ to track three diagnostic chemical parameters (SiO_2, Mg/Fe, and Ca/Na) that change systematically with progressive crystallization of magma.

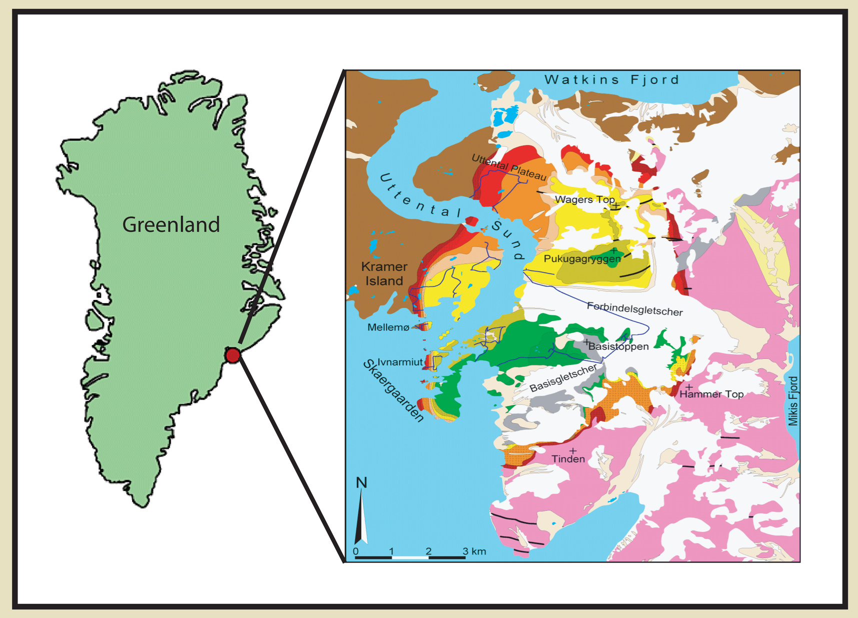
Layered Mafic Intrusions (LMIs): The Key to Understanding Magma Evolution

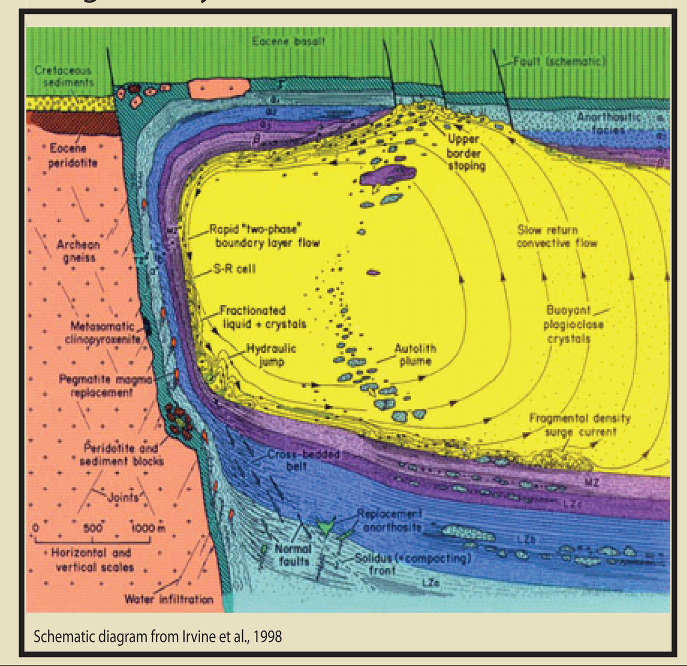
Igneous rocks formed from tholeiitic magma cover nearly 80% of the Earth's surface. They form by melting of the Earth's mantle and are found in Spreading Center and Hotspot tectonic environments. They also form flood basalts on the continental crust. Surprisingly, there is still much debate regarding the nature of basaltic magma evolution (e.g., Hunter & Sparks, 1987; McBirney & Naslund, 1990). Serious questions remain concerning the compositional liquid 'line-of-descent', including when and how granitic liquids are generated as a result of crystal fractionation. Large layered mafic intrusions (LMIs) are ideal for examining the crystallization behavior of basaltic magma. They often expose the crystalline products from the time of magma emplacement to the last drop of liquid. Here, we use a computer simulation to test a recent model for the generation of granite from basaltic liquids in LMIs. The model offers an exciting new explanation for a series of paradoxes observed in the evolution of igneous rocks, including the cause of the extreme Fe-enrichment observed in the classic Skaergaard and Bushveld LMIs, which have been used to define the 'Tholeiitic Trend' on AFM diagrams.

Chromite Layers in the Bushveld LMI

Skaegaard: The Classic LMI

The Skaergaard Intrusion has been the focus of considerable attention by petrologists since the 1940s, when it was recognized that it represented a completely exposed crystallization product of a single pulse of tholeiitic magma. The rocks exhibit striking textures and mineralogies that show crystallization occurred from 'outside in' with final crystallization occurring in the silica-rich 'sandwich horizon'. Numerous granite dikes, sill, and pods found within the stratigraphic sequence were dismissed as unrelated to the Skaergaard magmatic system.



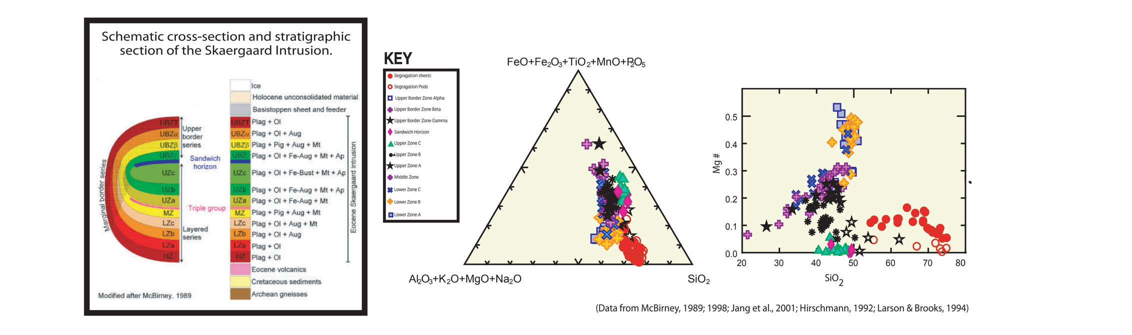


Schematic diagram from Irvine et al., 1998

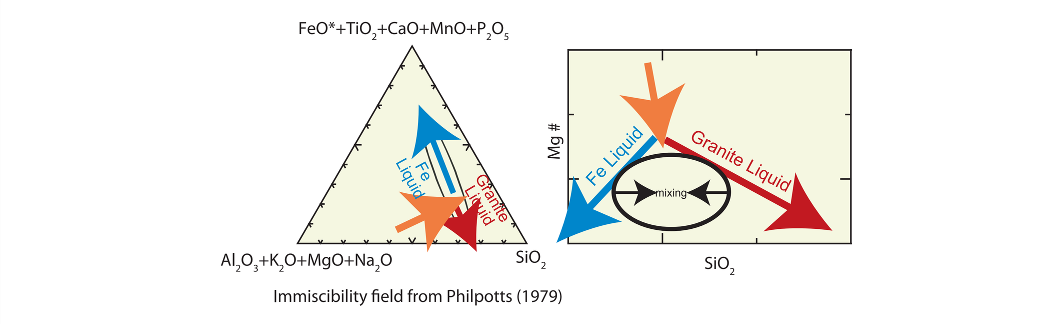
The Model

Here, we test a new model for the origin of granite that involves the sequential extraction of buoyant, felsic (i.e., rich in SiO_2) residual liquids generated within mafic magma chambers. It has long been recognized that removal of mafic minerals leads to more felsic residual melts. This is the fundamental precept behind 'Bowen's Reaction Series' taught in every introductory geology class. However, LMIs do not show the expected changes in composition from margin to core.

Geochemical Variations in the Skaergaard Intrusion



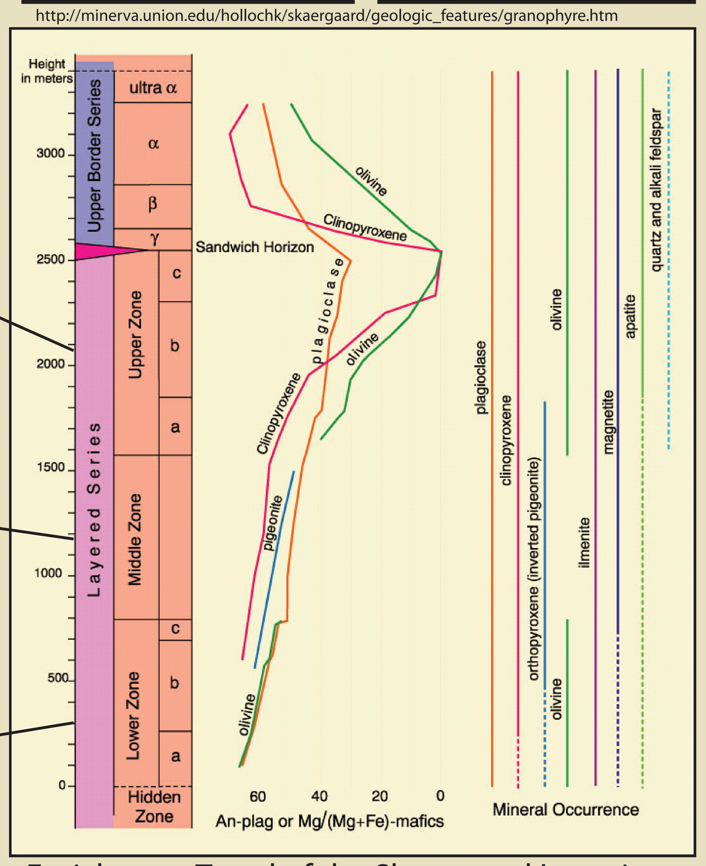
A Model for the Evolution of LMIs and the Origin of Granite



Granite bodies in the Skaergaard; Felsic Segregations?

http://minerva.union.edu/hollochk/skaergaard/geologic_features/granophyre.htm

Interstitial Magnetite; Fe-rich Sludge?



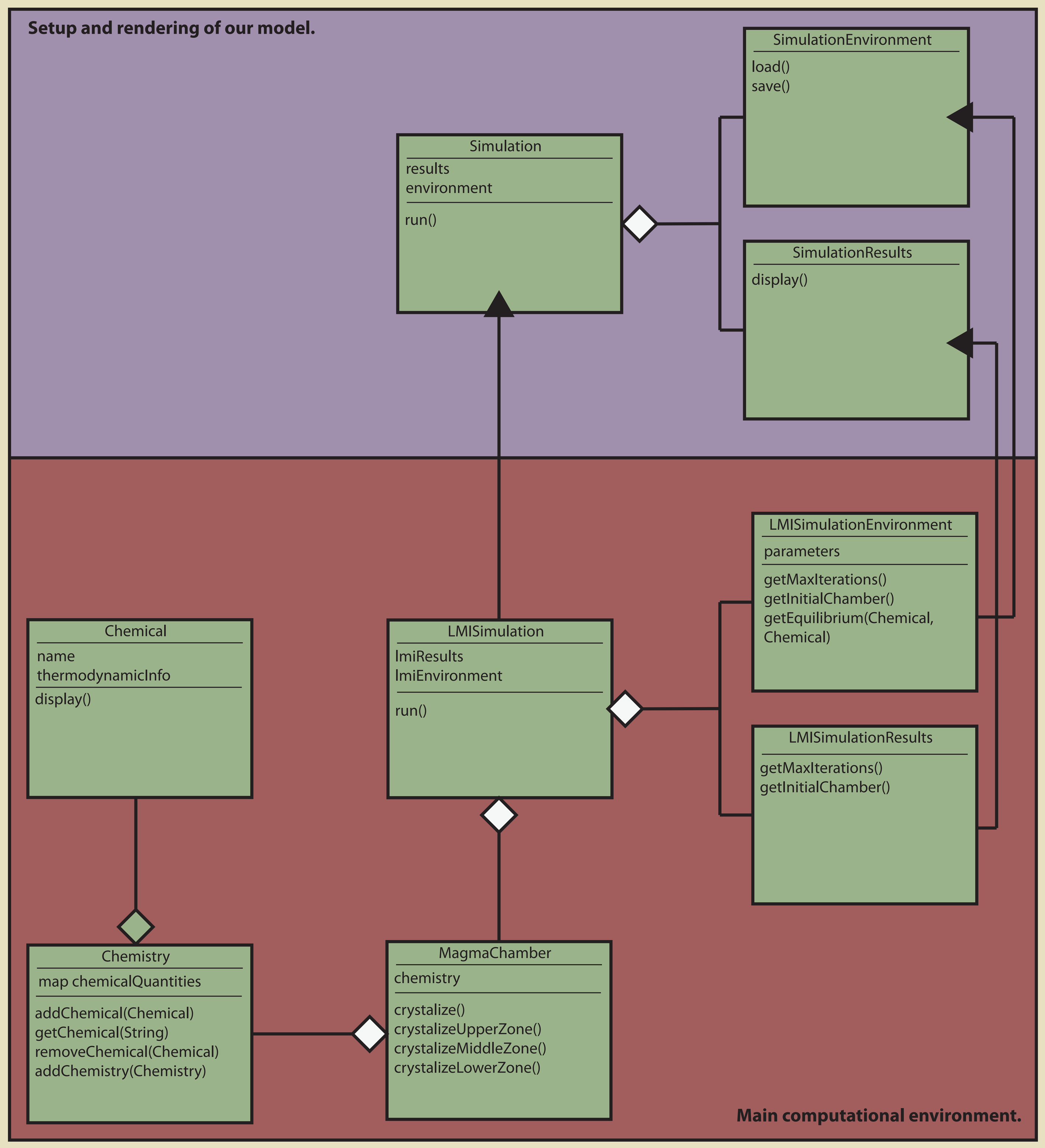
Enrichment Trend of the Skaergaard Intrusion (after Winter, 2008)

The new model invokes the removal of evolved felsic liquids from within a crystal mush zone located behind the advancing crystallization front in the magma chamber. The trapped residual liquid continues to crystallize and react with cumulate phases and becomes enriched in Si and Fe. The liquid line of descent enters an immiscibility field and separates into a dense Fe-, Ti-rich sludge and a buoyant Si-rich granitic liquid. The felsic liquid migrates up, first through the host crystal mush and subsequently through the overlying basaltic magma. Their evolved composition prevents them from mixing with overlying mafic liquid, and their enhanced buoyancy allows them to penetrate through the overlying roof and up into the overlying country rocks to eventually crystallize as granitic bodies or erupt as rhyolitic lavas. The model is bolstered by the observation that every major LMI is associated with voluminous granitic and rhyolitic magmatism of equivalent age.

http://minerva.union.edu/hollochk/skaergaard/geologic_features/granophyre.htm

The Code

We use C++ to model the geochemical evolution of the Skaergaard layered mafic intrusion. Simulation coding demands iterative tuning to capture the many fine details that describe magma chamber crystallization. An object-oriented design gives us a powerful organizational tool to compartmentalize the code into objects that behave like their natural counterparts. Thermodynamic parameters (such as mineral-melt partition coefficients for Fe & Mg and Ca & Na and their dependence on composition and temperature) are fed to the program through the SimulationEnvironment interface. This decouples the set-up and rendering of our model from the main computational environment.



Parameters for the simulation are contained within a SimulationEnvironment object. A Simulation object is passed a SimulationEnvironment and runs. The simulation creates a MagmaChamber with the initial chemistry specified in the SimulationEnvironment. The MagmaChamber is iteratively crystallized. Each iteration removes an aliquot of liquid from the MagmaChamber which crystallizes according to the parameters defined in the SimulationEnvironment. Crystalization creates three components: a felsic liquid, a mafic liquid, and crystal solids. The two liquid components can be configured to reenter the overlying magma chamber, sink to lower layers, or rise out of the chamber. The amount and destination of all three components are tracked in a SimulationResult object. The simulation continues until the magma chamber crystallizes completely. Finally, the SimulationResult is rendered and can be processed further before the program completes.

Results and Conclusions

We have designed and implemented a computer simulation that tracks the chemical composition of both minerals and liquids in an evolving basaltic magma chamber. Our model can test the viability of a new hypothesis for the evolution of LMIs. The hypothesis invokes liquid immiscibility in an evolved residual melt remaining within the boundary layer along the margins of the intrusion. Our model tracks the amount and the composition of 1) the host crystal framework; 2) the immiscible buoyant felsic liquid, and 3) the immiscible dense iron-rich liquid.

References

Hunter, R. H., & Sparks, R. S. J., 1987, The differentiation of the Skaergaard Intrusion, Contributions to Mineralogy and Petrology, V. 95, p. 451-461.

Irvine, T.N., Andersen, J.C.Ø., & Brooks, C.K. 1998, Included blocks (and blocks within blocks) in the Skaergaard Intrusion: Geological Relations and the Origins of Rhythmic Modally Graded Layers: *Geological Society of America Bulletin*, V. 110, 1398-1447.

McBirney, A. R., & Naslund, H. R., 1990, The differentiation of the Skaergaard Intrusion, Contributions to Mineralogy and Petrology, V. 104, p. 235-240.

Philpotts, A. R., 1979, Silicate liquid immiscibility in tholeiitic basalts: Journal of Petrology, v. 20, p. 99-118.

Acknowledgements

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