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Post-emplacement melt-flow as a feasible mechanism for reversed differentiation in tholeiitic sills

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This study provides a new explanation model for differentiation in sills, using a combination of geochemical data and field observations, numerical modeling and dimensional analysis. Geochemical data from a saucer-shaped dolerite sill intruded into the Karoo basin, South Africa reveal a process which causes reversed differentiation. The differentiation process is identified by D-shaped geochemical profiles. The notation is based on the vertical expression of whole-rock Mg-number (Mg# = 100*Mg/(Mg+Fe^{total})) with the most primitive composition (i.e. high Mg#) in its center, and progressively more evolved composition (i.e. low Mg#) towards the upper and lower margins.

Normal differentiation by fractional crystallization is known to produce C-shaped profiles (in terms of Mg# variations), as for example in the Skaergaard Intrusion. From a detailed field study of a saucer-shaped sill complex in the Karoo Basin, South Africa, we observe several different shapes (e.g. S, D and I) occurring within one sill. However, the C-shape is practically absent and hence fractional crystallization with double layer diffusion cannot be the main mechanism for differentiation in sheet intrusions. Several models have been proposed for the formation of D-shaped profiles, such as crystal settling and convection, multiple injections, flow differentiation, compositional convection, or Soret fractionation in combination with in situ crystallization. There is however no general agreement of one particular model, as they pose difficulties explaining all occurrences of D-shaped profiles.

Based on numerical modeling we introduce post-emplacement flow as a feasible mechanism to explain the D-shaped profiles. A melt-flow can cause magmatic differentiation in the sill by transporting incompatible and less compatible elements associated with the melt phase (e.g. Zr and Fe) in an advective process through a stationary crystal network. Crystal networks of considerable strength are known to form in the cooling stage of the sill when the crystal content exceeds $\sim$50%. The model is based on very few assumptions, and can hence be applied to all occurrences of D-shaped profiles. The model utilize the well established principle of differentiation by segregation of melt and crystals, but differ from classical view in terms of moving the melt rather than the crystals.

We show that a significant flow is feasible under natural occurring conditions. An underpressure of magnitude 10^8 Pa develops at the cooling margins, where melt will be sucked in by a porous flow. The forces of thermal stress associated with the phase change due to the cooling have previously been overlooked.

A porous melt-flow through a stationary crystal network from the hot central parts into the cooling margins will cause the latter to be enriched in the incompatible elements, while the center will be correspondingly depleted. We show that the amount of flow is primarily a function of viscosity of the melt and permeability of the crystal network, which in turn is a transient phenomenon dependent on a number of parameters.

Diagrams have been constructed to evaluate the feasibility of substantial melt extraction in terms of these poorly constrained parameters. Data from the Golden Valley Sill and many other natural occurrences of D-and I-shaped geochemical profiles show very good agreement with our final predictions of melt flow, and are thus well explained by the presented model. We have evaluated the potential flow in terms of vertical flow. In a full 3D setting of saucer-shaped sills, it is likely that flow occurs in other directions, e.g. lateral in accordance with the local driving forces.

To conclude, melt segregation from its equilibrium crystal network through post-emplacement flow represents an effective and feasible mechanism of differentiation which satisfactorily explains the geochemical data.