# *In situ* fractionation and inward migration of the solidification front in the Skaergaard intrusion, East Greenland

Troels F.D. Nielsen

For more than 80 years the Skaergaard intrusion, 68°N in southern East Greenland, has been a foremost natural laboratory for the study of the crystallisation and fractionation of basaltic magma. This process has been of prime importance in the evolution of the Earth and other stony planets. Models that have been developed and refined during numerous studies of this particular intrusion have been part of the foundation for petrogenetic modelling for decades. In later years, vast amounts of new data have been added, due to systematic sampling in the field and from analysis of exploration drill cores. Methods for the study on grain-size scale have advanced, and the quest for a well-supported genetic model for the PGE-Au mineralisation of the intrusion has intensified. The new data and insight question the applicability of conventional petrogenetic modelling, and as a consequence, increasing importance is placed on *in situ* crystallisation and fractionation in mush zones at the roof, walls and floor of the intrusion.

## The Skaergaard intrusion

The Skaergaard intrusion (Wager & Brown 1968) is a comparatively small but well-preserved and well-exposed layered gabbro intrusion (Fig. 1A). It is 56 Ma old (Wotzlaw *et al*. 2012) and was emplaced during the opening of the North Atlantic. It is 7 × 11 km in surface exposure, has a total structural height of *c*. 4 km, and, dependent on the chosen modelling paradigm, has a box-like (Nielsen 2004) or ellipsoid shape (Irvine *et al*. 1998, Svennevig & Guarnieri 2012) and a volume of *c*. 300 km$^3$. The intrusion crystallised concentrically inward from the margins (Fig. 1B) with the Layered Series (LS, LZ, MZ and UZ) in the bowl-shaped floor, the Marginal Border Series (MBS) on the walls, and Upper Border Series (UBS) below the roof. The UBS and LS meet at the Sandwich horizon (SH). All three series are subdivided on the basis of a parallel evolution in liquidus parageneses (Salmonsen & Tegner 2013 and references therein).

## New research initiatives

Petrogenetic modelling of the Skaergaard gabbros and the evolution of the melt in the intrusion have traditionally rested on the textural interpretation of the gabbros as rocks composed of liquidus crystals, continued growth of these

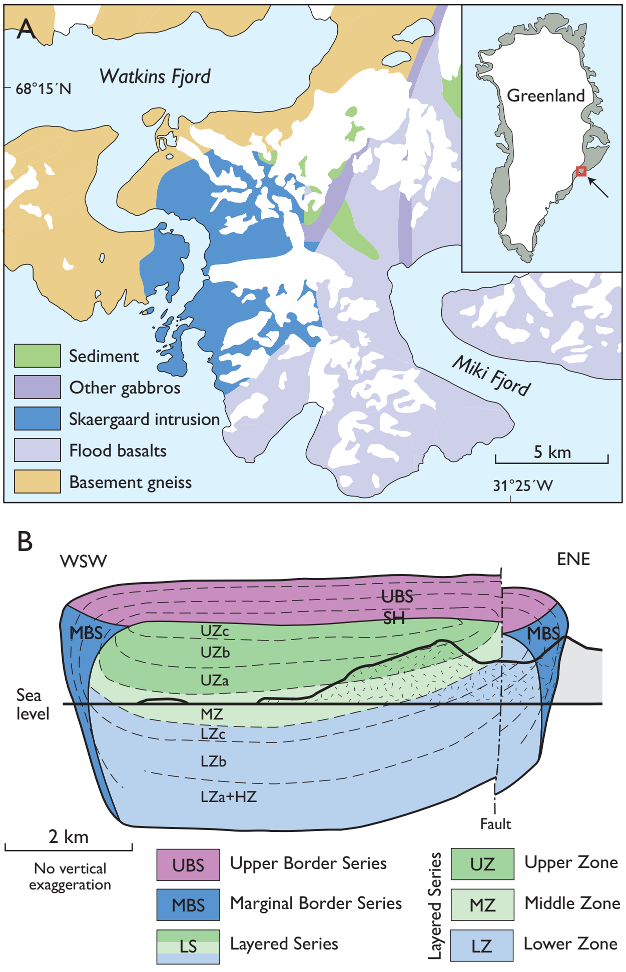

Fig. 1. **A**: Geological setting of the Skaergaard intrusion between basement gneisses, sediments, other gabbros and flood basalts. Location in Greenland in insert. **B**: Reconstructed cross-section (Nielsen *et al*. 2015). The Upper and Lower Zones of the Layered Series are subdivided on the basis of liquidus paragenesis (see text). Sea level and present topography are shown in black lines.

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crystals in equilibrium with the bulk liquid (adcumulus growth), and crystallisation of solids from trapped liquids. Sorting of crystals on the magma chamber floor has been likened to processes established for clastic sediments, including stratification of crystal mushes in matrix-supported mass flows. Despite challenges these models have remained robust, and most researchers are faithful to this classic cumulus paradigm and the modelling tools developed therefrom.

Research initiatives in the later decades of the 20th century (McBirney 1996 and references therein) provided much new information and were accompanied by investigations facilitated by the exploration of PGE-Au mineralisation in the intrusion (e.g. Bird *et al.* 1991). Notable outcomes of this research include the development of double diffusive convection models (McBirney & Noyes 1979), evaluation of the petrogenetic importance of immiscibility between Fe-rich and Si-rich silicate melts (Jakobsen *et al.* 2011 and references therein), as well as evidence for isotopic disequilibrium and tight age controls on the emplacement and solidification of the intrusion (see Wotzlaw *et al.* 2012, and references therein).

The studies of the Skaergaard intrusion surged in 2000 with access to assay data and up to 1200 m long drill cores. The data in the public domain allowed calibration of structural models for the interior of the intrusion (Nielsen 2004), erection of compaction models (Tegner *et al.* 2009; McKenzie 2011), and studies of the mineralisation (Nielsen *et al.* 2005, 2015; Andersen 2006; Rudashevsky *et al.* 2015 and references therein; Holwell *et al.* 2015; Keays & Tegner 2015). Petrographic studies focused, e.g. on compositional variations in plagioclase (Namur *et al.* 2014) and on clinopyroxene-filled dihedral angles between plagioclase crystals (e.g. Holness 2015 and references therein). Changes in dihedral angles give indications for, e.g. the arrival of new phases on the liquidus of the silicate melts and changes in permeability, and thus for the controls on the mobility of elements of economic interest.

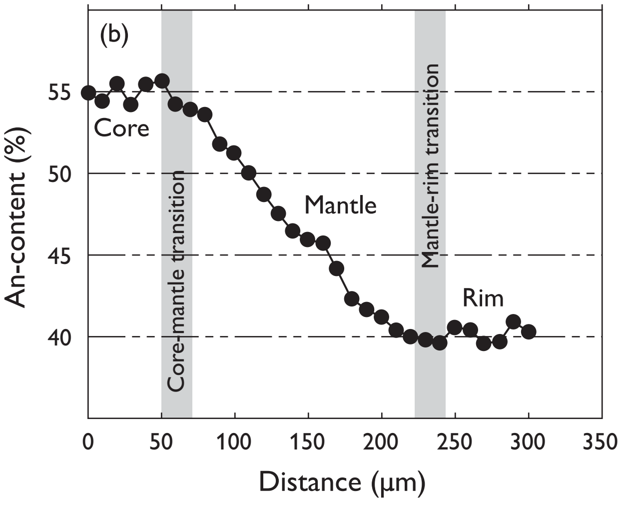

Fig. 2. Compositional variation in LZb plagioclase crystal with small core (liquidus) and broad mantle crystallised during *in situ* fractionation involving mush melt, and rim crystallised during buffered crystallisation (after Namur *et al.* 2014).

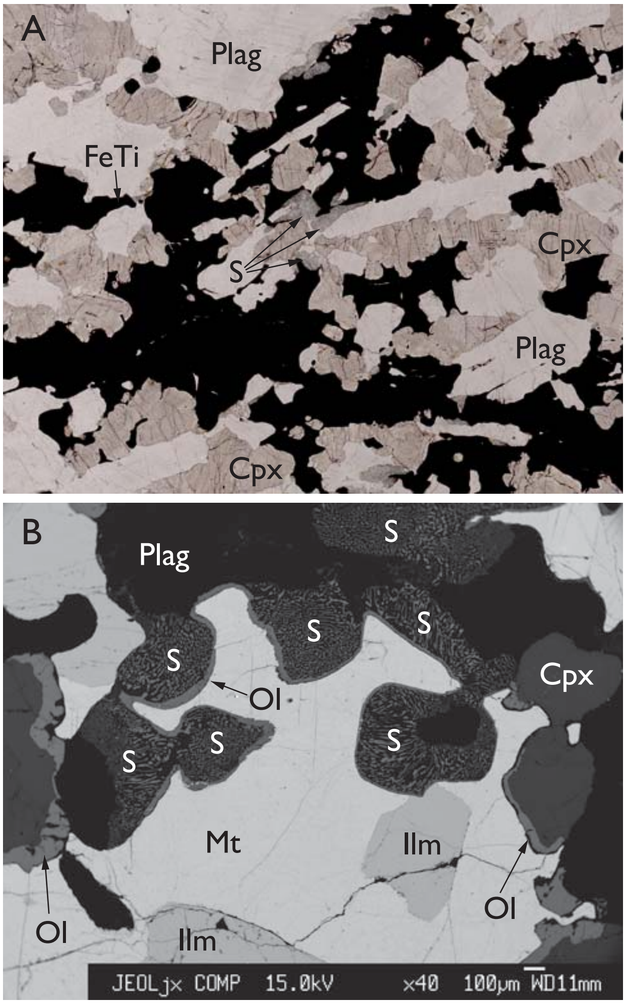

Fig. 3. **A**: Transmitted light image (*c.* 13 × 9 mm) showing interconnected magnetite and ilmenite that crystallised from interstitial mush melt. **B**: Electron microprobe backscatter image (see Nielsen *et al.* 2015). Symplectites (**S**) formed by reaction between plagioclase and reactive Fe-rich mush melt that crystallised most of the magnetite and ilmenite in the view. **Cpx**: clinopyroxene (with exsolutions in Fig. 3B). **FeTi**: Fe-Ti-oxides. **Ilm**: ilmenite. **Mt**: magnetite. **Plag**: plagioclase. **Ol**: olivine. **S**: symplectitic intergrowths. Scale at base of the image.

## The importance of *in situ* fractionation

Modelling based on the classic cumulate paradigm suggests that the proportion of trapped liquid decreased from 30–50 per cent to only a few per cent during the solidification of the intrusion (Tegner *et al.* 2009). This is, however, in conflict with reactions between liquidus minerals and Fe-rich silicate melts (Holness *et al.* 2011) and the occurrence of immiscible melt droplets throughout much of the floor cumulates (Jakobsen *et al.* 2011 and references therein). They are supposed to result from extended *in situ* crystallisation and fractionation (Langmuir 1989) in crystal mush, long residence time, and ineffective compaction. This is supported by the very common zonation in plagioclase (an example is shown in Fig. 2, Namur *et al.* 2014) and the distribution of magnetite crystallised from interstitial melt (Fig. 3A; Nielsen *et al.* 2015).

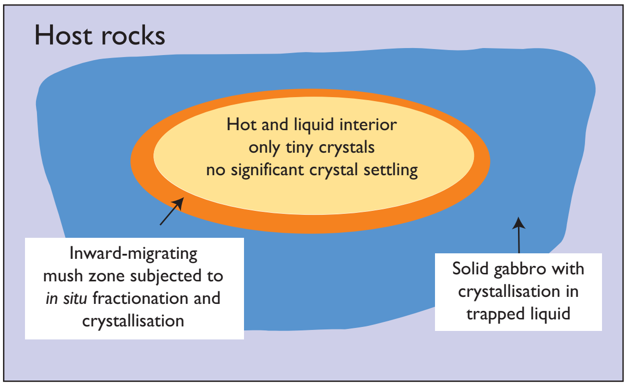

Fig. 4. Principles of the proposed model of inward migration of mush zone and liquidus front. The inward-migrating mush zone is shown in orange. The residual bulk liquid in the centre has only small and suspended crystals of liquidus phases. The remaining bulk melt is always at liquidus due to feedback from the mush zone (see Nielsen *et al.* 2015 for details of model).

## Toward a new solidification model

A magma chamber will always be hot in the middle and crystallisation will always occur in the crystal mush between solidified gabbro and the remaining melt, unless the system is affected by vigorous convection. In the Skaergaard intrusion this seems unlikely due to the concentric solidification (Nielsen 2004). All gabbro samples have recorded a temperature interval on the line of liquid descent and all have witnessed the inward migration of the crystallisation front, fronts with new phases on the liquidus of the mush liquid, and the solidification front. The mushy layer is a sub-chamber of crystal mush migrating inwards, and the samples we collect reflect only processes within the mush itself and the bulk composition of the liquid that was processed in the mush (Fig. 4).

Any sample of the gabbros is composed of minerals left behind by the inward-migrating mush layer. In broad terms, the composition of the floor gabbro is equal to bulk liquid minus what rose out of the floor, e.g., low density melt, and that of the roof gabbro is equal to what remained under the roof, e.g. low density minerals and melt (Salmonsen & Tegner 2013; Nielsen *et al.* 2015). Roof and floor series are complementary, and neither series represents the evolution of the bulk magma, but their weighted average does. The modelling of the evolution of layered intrusions is commonly only based on exposed floor cumulates, and the common neglect of complementary successions in the lost roof of the intrusions may therefore lead to erroneous petrogenetic conclusions.

Undoubtedly, future research in the Skaergaard intrusion and its mineralisation will focus on very detailed petrography, mineralogy, *in situ* mineral chemistry and isotope geochemistry, and on unravelling of the complexities of the solidification processes.  Petrogenetic modelling on the basis of bulk rock chemistry without detailed petrographic information is prone to lead to significant oversimplification and unwarranted confirmation of the chosen models.

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**Author's address**

*Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark*; E-mail: *tfn@geus.dk*