The Skaergaard intrusion (Fig. 1) is probably the most studied layered gabbro intrusion in the world (Wager & Deer 1939; Wager & Brown 1968; McBirney 1996; Nielsen 2004). The intrusion is c. 54.5 Ma old and was formed during the Palaeogene opening of the North Atlantic Ocean, intruding into the base of the East Greenland flood basalts. The intrusion is relatively small with a volume of c. 300 km³ (Nielsen 2004). Spectacular magmatic layering and systematic evolution in the compositions of liquidus phases and estimated melt compositions (e.g. Wager & Brown 1968) have made the intrusion the most studied example of the development of the ‘Fenner trend’ of iron enrichment in basaltic liquids (e.g. Thy et al. in press; Veksler in press).

The identification in the late 1980s of significant platinum-group elements (PGE) and gold (Au) occurrences in the intrusion (e.g. Bird et al. 1991; Nielsen et al. 2005) has led to continued investigation and exploration drilling. The Skaergaard intrusion is suggested to hold c. 33 million ounces (1000 tonnes) of PGE and c. 13 million ounces (400 tonnes) of Au (Nielsen et al. 2005). The mineralised zone is located in a c. 100 m thick zone of anomalous PGE and Au enrichment in the upper part of the Middle zone (Bird et al. 1991; Nielsen et al. 2005) of the Layered series. The mineralised zone consists of a succession of bowl-shaped, stratiform and very tightly controlled levels of palladium (Pd) enrichment referred to as Pd1 to Pd5 (Fig. 2; Nielsen et al. 2005). The bottom level, Pd5, is developed from margin to margin of the intrusion, whereas the overlying levels Pd4 to Pd1 are increasingly restricted in width, and the entire succession of Pd levels is only developed in the central part of the intrusion. The structure of the mineralised zone can be compared to a set of bowls with upward-decreasing diameters. Gold is always concentrated in the uppermost palladium levels or in a level above the top palladium level, irrespective of the number of developed Pd levels. More detailed descriptions are provided by Nielsen et al. (2005).

The exploration drill cores provide material and structural information from previously inaccessible parts of the intrusion (Nielsen et al. 2005). The 3-D image presented in Fig. 4 is based on drill-core information (petrographical, petrophysical, geochemical etc.) and surface information. It allows an unprecedented insight into the internal structure of the upper part of the intrusion and offers a possibility of refinement of volume estimates and quantitative modelling of the
zones and subzones of the intrusion. A constrained structural model will in turn allow evaluation and revision of crystallisation models for the basaltic liquid in the magma chamber.

3-D modelling of the intrusion and the mineralised zone

The initial aim of the 3-D modelling was a visualisation of the intrusion and the associated PGE and Au mineral occurrences. Geographical information system software was used for the compilation of the surface data used for the model. These data, together with subsurface data, were subsequently imported into modern 3-D mining and resource software (Gemcom GEMS®), which was used for the construction of the 3-D model of the intrusion and its mineralised zone.

The detailed topographical model needed for the modelling (Fig. 3) was constructed from satellite Aster data (resolution 30 × 30 m). Aster scenes and the 1:20 000 scale geological map of the intrusion and adjacent area were draped on the terrain model.

Forty-one cores with a total length of 23 425 m have been drilled since 1989. The deepest holes reached levels of c. 1200 m below the collars of the drill holes. The petrographic variation in all these cores is described in drill-hole logs in company reports in the archives of the Geological Survey of Denmark and Greenland. These logs were digitalised and compiled. The courses of the drill holes (taking azimuth and dip into account) were visualised in 3-D, and assays for PGE and Au displayed together with the petrographic information. All the information was subsequently assessed for each drill hole, and the delineation of specific lithologies and mineralised sections was interpolated manually by the geologist software operator from one drill hole to another and from drill holes to surface exposures of the mineralised zone. Triangulation surfaces were constructed mathematically by the GEMS software from the delineations and united into wire-frames that represent 3-D solids (geological bodies). The delineation and resulting solids were validated by the software. Dykes in the intrusion were also modelled as solids. Mapped-out fault planes were visualised as 3-D surfaces.

In intrusion-wide images the mineralised zone is a very narrow structure. The 3-D model is best seen ‘live’, and we have chosen, as examples, to show the initial results of the imaging of the mineralised zone in two vertical 2-D panels through the intrusion (Figs 4, 5). In Fig. 5 the mineralised zone is shown as the zone between the lower boundary of the lowermost Pd-levels (Pd5, cut-off at c. 1 gram per tonne Pd) and the top of the Au-rich part of the mineralised zone (Pd1/Au or Au + 1 levels, cut-off at c. 0.8 gram per tonne Au).
Results

The west–east section of Fig. 5A shows the mineralised zone to be bowl-shaped with a central depression of c. 400 m. The magnitude of the depression reflects that the 3-D model does not reach all the way to the margins of the intrusion. As expected, the imaging also shows that the vertical distance between the lower and upper boundaries of the mineralised zone increases towards the centre of the intrusion, in agreement with the structure of the mineralised zone proposed by Nielsen et al. (2005). The demonstrated bowl-shape of the mineralised zone, and thus the layered gabbros, corroborates the model suggesting concentric crystallisation of the gabbro on the floor, walls and below the roof of the intrusion (Nielsen 2004). The north–south section (Fig. 5B) shows the general 20° dip of the layered gabbros and the mineralised zone.

Application of 3-D modelling to the evolution of the Skaergaard intrusion

Nielsen (2004) developed a structural model for the intrusion solely on the basis of field observations and analogies. Compared to the classic and traditional accumulation models, the apparent concentric crystallisation in the 300 km³ magma chamber reduces the volumes of the most evolved zones and subzones in the intrusion and thus the proportions of the products of the crystallisation process.

Table 1. Compositions of liquids during the fractionation of the Skaergaard magma

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<tr>
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<th>Bulk SK-TPDN</th>
<th>L1 Mg</th>
<th>L2 Mg</th>
<th>L3 Mg</th>
<th>L4 Mg</th>
<th>L5 Mg</th>
<th>L6 Mg</th>
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</table>

Based on bulk liquid SK-TPDN in Nielsen (2004). The composition of the liquid as it evolves is calculated by subtraction of average compositions of correlated LS, MBS and UBS subzones (McBirney 1989) in the mass proportions in Nielsen (2004). The spread sheet with the calculations is available on request. The composition of the liquid of a specific zone refers to the composition of the liquid at the base of the indicated zone. Bulk composition is corrected so that the end-result matches the composition of average melanogranophyre (MG). Fe₂O₃/FeO has been set at 0.15. The abbreviations are explained in Fig. 4.
The LLD of the Skaergaard intrusion is of utmost scientific interest. Well-constrained deviations from the expected can be reflections of processes that have not been taken into account in the modelling of the fractionation process. The lack of balance in the SiO₂ distribution, as reflected in the account in the modelling of the fractionation process. The can be reflections of processes that have not been taken into scientific interest. Well-constrained deviations from the expected mass balances and geophysical models for the shape of the magma chamber can numeric models for the evolution of the Skaergaard intrusions be developed and the relative importance of all the suggested processes in the evolution of the melt evaluated.

All well-constrained internal boundaries and the details of the mineralised zone (bulk chemistry, lithologies and mineralogy) in the Skaergaard intrusion will be included in the 3-D model in the coming years. This will allow refinement of the 3-D distributions and volumes of different lithologies, including the mineralised zone, lead to more advanced mass-balance models for the Skaergaard intrusion, and provide more general constraints for modelling of the crystallisation and fractionation processes in basaltic magma chambers.

References