The Skaergaard Layered Intrusion, East Greenland:

The mechanisms of the formation of layering and the trend of differentiation revisited

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Abstract

The Skaergaard intrusion on the coast of east Greenland is a prime example of a layered intrusion that has often been referred to since its discovery in 1932 by Wager and Deer due to its excellent exposure and its undeniable trend of fractional crystallisation. The intrusion, however, has posed several puzzles to scientists around the world. For instance, unlike the majority of tholeiitic layered intrusions, this one shows a clear trend of iron enrichment as opposed to silica enrichment. Secondly, the origin of formation of the layering found in the intrusion has been subject to numerous debates. And thirdly, the evolution of the intrusion itself is still not clear mostly due to the fact that the intrusion has been subject to extensive late-stage mineral alteration processes most likely caused by the presence of fluids. Many processes that contributed to the formation of layering in the Skaergaard intrusion are discussed in this paper. It has been proposed that layering can be produced via mechanisms that operate during magma emplacement, mechanisms that operate in response to magma convection patterns, mechanisms that are the result of mechanical processes and others. In order to understand the structure of the intrusion in relation to the layering present, there is a general overview of the lithological divisions and corresponding mineral content included. The trend of iron enrichment has also been addressed and found to be related to oxygen fugacities in the intrusion. It is generally agreed that the main mechanism responsible for differentiation was most likely compaction, but convective fractionation was also important especially in the upper layers of the intrusion. It is also evident that it is unlikely that any single layer-forming mechanism can explain all or even most of the known occurrences of layering in the Skaergaard intrusion, but that more processes are responsible for different types of layering at different stages of crystallisation.

[1]Picture on title page taken from:
http://www.union.edu/PUBLIC/GEODEPT/hollocher/skaergaard/geologic_features/ls-mbs-contact.htm

1. Introduction

The Skaergaard layered intrusion is a gabbroic intrusion measured 11 km from north to south and 8 km east to west and is box-shaped (Nielsen, 2003). It is located near the eastern coast of Greenland. Its volume is determined to be about 280 ± 23 km^3 (Nielsen, 2003). Despite the presence of several other gabbroic and syenitic intrusions, the Skaergaard intrusion is the largest and best exposed. Originally discovered by Wager and Deer in 1932, the Skaergaard intrusion is found to be a prime example of igneous differentiation and further studies of igneous intrusions have since referred to it.

The intrusion is almost entirely characterised by layering. Although it may seem at first that the layering was simply caused by gravitational settling of crystals, many in depth studies have shown that the various processes responsible for different types of layering present count up to 25 and maybe more. It is clear from the Skaergaard intrusion that there is no single process responsible for its layering. These various types of layering can be divided into two groups; dynamic and non-dynamic layering. The former refers to processes associated with magmatic flow and the latter refers to processes resulting from e.g. compaction and variations in rates of nucleation and crystallisation.

There are three different series of layering present; the Layered Series that consists of magma that crystallised from the bottom upwards, the Marginal Border Series that refers to the crystallisation of magma from the edges of the magma chamber inwards, and the Upper Border Series that refers to the crystallisation of magma from the top of the intrusion downwards. It is therefore possible to find a rock containing 'cross-bedding' of layers from the Layered series and the Marginal Border Series. The area where the Layered Series meet the Upper Border Series is called the 'Sandwich Horizon.'

The appearance of layering is often caused by the ordering of minerals and orientation of the mineral crystals in the rocks. Because the intrusion does not have the same mineral content throughout, but clearly shows a crystallisation trend, the layering changes in appearance and nature. The intrusion contains many common minerals such as olivine, pyroxene, plagioclase, apatite and FeTi-oxides. The concentration of each mineral varies throughout the intrusion. Olivine for example is Fo 68 at the base but becomes pure fayalite at the Sandwich Horizon. This is another important characteristic of the Skaergaard intrusion, which is the pronounced trend of iron enrichment as opposed to silica enrichment common for tholeiitic magmas.

2. Geological setting and structure

The intrusion remains mafic throughout. This is because it is believed that there was only one pulse of magma that intruded the crust during the opening of the North Atlantic, 55 Ma ago (Schwarz et al., 1979; Hirschman et al., 1996) and there was little or no chemical exchange from the surrounding rocks. The Skaergaard intrusion is therefore believed to be a closed system, only subjected to fractional crystallisation, magma convection and hydrothermal processes. It is Eocene of age which makes it one of the most recent larger igneous intrusions in the world yet dwarfed by the big Precambrian layered intrusions like the Bushfeld complex. The thickness of the intrusion has been determined to be maximum 3.5 km from gravity modelling (Blank and Gettings, 1973) and intruded into 10 to 100 metres of Late Cretaceous to Paleocene arkoses and siltstones, into magmatic flood basalts from the early Eocene sometimes 3 to 4 km thick (Wager and Deer, 1938;

Nielsen 1978) and into 3 Ga Precambrian rocks which flank the walls for about two thirds of the intrusion.

The Skaergaard intrusion is itself intruded by later dykes and sills. The largest sill intruded the Upper Border Series and is called the Basistoppen sill, which probably originated from the largest intruding dyke called the Vandfaldsdalen macrodyke. Most of these sills and dykes are gabbroic and doleritic in nature, but there are also swarms of smaller granophyric intrusions present in the Upper Zone of the Layered Series and in the Upper Border Series. The Tinden sill is the largest of this composition that intruded only a few hundered metres below the roof.

The Skaergaard intrusion was tilted by about 20 degrees southward 250,000 years after it cooled down and crystallised (Schwarz et al., 1979). This is how most of the sequence of the intrusion became visible after almost the entire Eocene flood basalts unit had eroded away as well as a large section of the Skaergaard intrusion itself and most of the pluton roof. Only a small portion is still unexposed which is called the Hidden Zone located below the Lower Zone in the Layered Series. Below is shown a simplified cross-section of the intrusion. In appendix A, a full-colour geological map can be viewed.

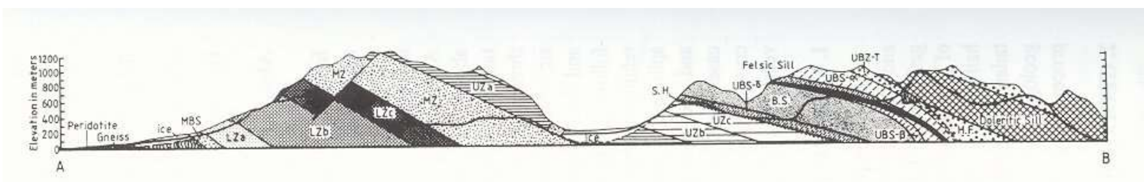

Figure 1: Simplified cross-section of the Skaergaard Intrusion with the geology included. Taken from: McBirney, 1996.

3. Overview of the lithological divisions and corresponding mineral content

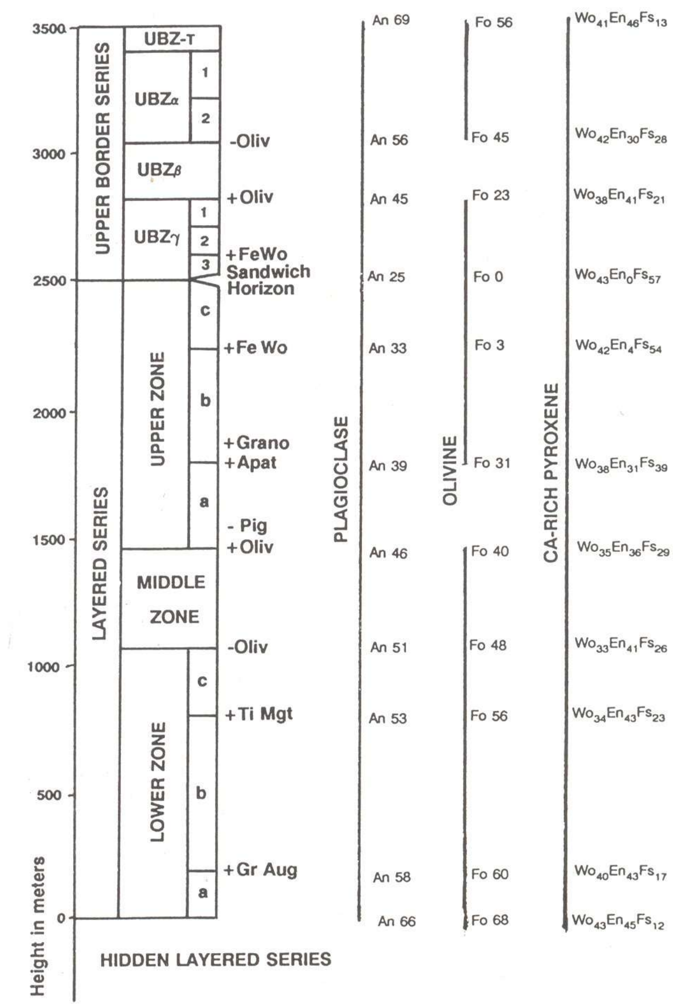

Figure 2: The units of the Layered Series are defined by the appearance or disappearance of primary phases. The Upper Border Series is divided into 3 main zones equivalent to the Lower, Middle, and Upper zones of the Layered Series. Further subdivisions are done also according to mineral changes in the rocks. Taken from: McBirney 1996.

The *Layered Series* is subdivided into three zones, the Lower Zone, the Middle Zone, and the Upper Zone. The former and the latter are again subdivided into three subzones. Olivine is the primary mineral in the Lower and Upper zone, but is only present in the middle zone in small concentrations formed as a by-product from chemical reactions between pyroxene and ilmenite / magmetite. The subzones of the Lower Zone are denoted as LZa, LZb, and LZc. LZb is distinguished from LZa by the distinctive poikilitic texture of pyroxene (augite) in LZb. In LZc Fe-Ti oxides (magmetite and ilmenite) first appear in abundant concentrations. Similarly, the Upper zone is divided up as UZa, UZb, and UZc. In UZa inverted pigeonite disappears as olivine reappears. At the base of UZb apatite becomes abundant. In the UZc an inverted form of ferrobustamite (formerly ferrowollastonite) is present. Interstitial granophyre is common in the upper part of the Upper Zone. The overall geochemical trend is that the rocks become somewhat more mafic upwards. Layering is prevalent in all units up to the lower part of the Upper Zone *b*.

The *Upper Border series* is divided into zones α, β, γ, which correspond to the Lower, Middle and Upper zones respectively in the Layered Series based on plagioclase compositions (Wager, 1960; Douglas, 1961). Naslund (1984a) later refined the sequence somewhat, but the overall divisions remain valid. For example the Upper Border Zone ultra-α is now called Upper Border Zone T, where T stands for tranquil. This refinement was made because a similar zone was found in the Maginal Border Series and defines the outline of the intrusion. It is a medium to fine grained rock containing primocrysts of olivine in a framework of plagioclase laths (McBirney, 1996). UBZα is, on the other hand, a coarse grained gabbro with abundant plagioclase and smaller amounts of olivine, ilmenite, magnetite, and apatite. Little pyroxene is present. UBZβ contains primocrysts of Ca-rich pyroxene but no olivine, whereas UBZγ does contain olivine. Quartz is rare throughout the series (McBirney, 1996). UBZα is divided into two subzones whereas UBZγ is divided into three subzones based on the mineralogical equivalence to the Layered Series subdivisions. On average the UBZ is more felsic and coarser grained than the Layered Series. Skeletal and dendritic crystals are common particularly among iron-oxides (Naslund, 1984b).

The *Marginal Border Series* was divided by Wager and Brown (1968) into two main units, an outer "Tranquil Division" and an inner "Banded division". The former was very little layering as opposed to the latter and it is now thought that the change is related in some way to the rates of cooling and *in situ* nucleation (McBirney, 1996). The Tranquil Division has two notable members which are the perpendicular feldspar and wavy pyroxene rocks (Wager and Deer, 1939). The former is characterised by elongated plagioclase crystals orientated normal to the contact. The latter contains lenticular dark clots of pyroxene 2 to 5 cm long and about a centimetre thick roughly orientated parallel to the contact. The Banded Division is subdivided into LZa*, LZb*, corresponding to the equivalent mineral composition found in the Layered Series. No rocks corresponding to UZc have been found. The rocks are, however, coarser and plenty of pegmatites are found of mafic and felsic compositions. It is thought that even though only about 5% of the MBS is exposed, it must have been as large as 15 to 20% of the original body (McBirney, 1996).

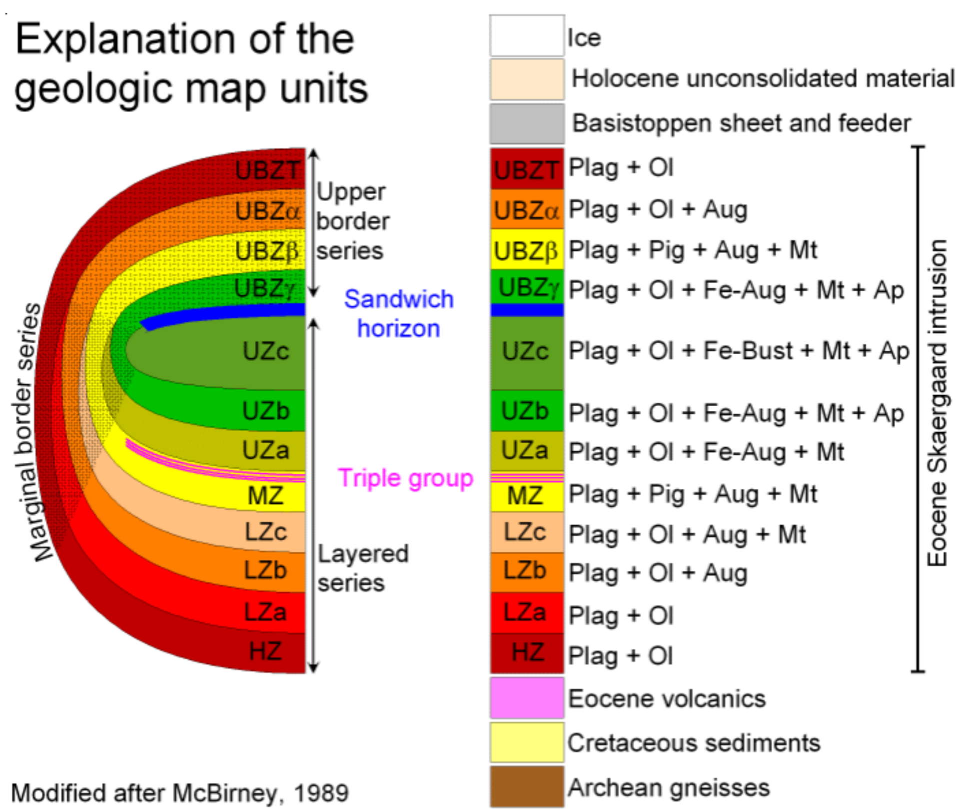

Figure 3: Geological map of the Skaergaard intrusion. Unit names within the Skaergaard intrusion largely follow that of McBirney (1989). Taken from: http://www.union.edu/PUBLIC/GEODEPT/hollocher/skaergaard/geologic_features/geologic_map.htm

4. Concept of layering in igneous intrusive bodies

The layering shown in intrusive bodies can vary greatly in scale. The spacing can be as much as several millimetres up to several metres. The appearance of certain type of layering can be due to several other factors such as the modal abundance of cumulus minerals, grain size, texture, or composition of minerals. *Cryptic layering* is referred to the type of layering where variations in mineral composition are not macroscopically evident. It may also be apparent that there is a clear variation in grain size and / or variation in mineral types, where coarse, dense minerals occur at the base and finer, less dense minerals occur toward the top of layers. This is called *graded layering*. The process behind this phenomenon is often thought to be gravity settling in a magma chamber. There is however a distinction between graded layering based on grain size sorting and density sorting. Which one applies to the Skaergaard intrusion will be discussed later on. Finally, there is *rhythmic layering*, which basically describes the variations of layering that are commonly repeated over and over again in a sequence.

5. Layering in the Skaergaard intrusion

The layering in the Skaergaard intrusion closely resembles the type of layering one would encounter in sedimentary rocks. There is even cross-bedding at the contact of the Layered Series and the Marginal Border Series. However, things are not what they seem and throughout the years it has always been realised that gravitational settling cannot account for the fact that low density minerals like plagioclase were crystallised on the floor whereas high density, iron enriched, minerals like olivine accumulated in layers under the roof. In this case one cannot rule out that magma convection took place, but another processes have can have been equally important.

The layering found in most parts of the intrusion has, in fact, been thought to relate to gravity settling in either a convecting or static magma chamber. However, as McBirney and Noyes (1979) correctly observed, this would not explain the abundant layering on the walls. They, for instance, reasoned that this type of layering was produced by nucleation and growth of minerals along the walls, roof, and floor in a static boundary layer in which the minerals were trapped in a Bingham liquid.

Layering can originate from a whole set of different, mutually exclusive, processes that can occur in a magma chamber. According to Naslund and McBirney (1996) layering can be produced via mechanisms that operate during magma emplacement, mechanisms that operate in response to magma convection patterns, mechanisms that are the result of mechanical processes and others. In all they listed 25 possible mechanisms which can occur independently from one another but it is generally assumed that two or more may have operated at one time to form various compositions of layering.

In 1996 McBirney proposed another view on how layering could have formed. He proposed that "the principle mechanism of crystal-liquid fractionation during formation of the Layered Series was compaction, but convective fractionation seems to have become important in the late stages of evolution."

However there are more processes at stake, for there are several different types of layering found not only in the Layered Series but also in the Marginal Border Series. The following section will deal with some of the processes that could have taken place in the Skaergaard intrusion.

6. Different types of mechanisms contributing to the formation of layering in the Skaergaard intrusion

In the Skaergaard Upper Border Series, where layering have been noted to be rich in skeletal magnetite, ilmenite, and hopper apatite crystals, it has been proposed that a mechanism of magma mixing is responsible for the formation of layering (Naslund, 1984b; Keith and Naslund, 1987). The theory assumes the formation of a hybrid magma that is oversaturated in one or more phases. Mixing along a saturation surface at specific temperature conditions and composition may cause supersaturation in one or more of these phases. Hence layering is formed.

Magma convection is also believed to contribute to the formation of layering in the Skaergaard intrusion. Because the intrusion is noticeably small, thick floor sequences formed at the same time as thin roof sequences formed. This attests to the efficiency of heat transfer from the floor to the roof. It has been proposed that there is a general tendency for the proportion of rocks crystallised under the roof to be an inverse function of the total thickness of intrusions (Naslund and McBirney, 1996). This, however, cannot be true if, during magma crystallisation, the crystal mush under the roof is unstable and sinks to the floor.

Another form of convection believed to have played an important role in the Skaergaard intrusion is intermittent convection other than continuous convection. Intermittent convection is the alternation of a convective period followed by a long period of stagnation and so forth. The Middle Zone of the Skaergaard intrusion is characterised by layering with alternating plagioclase-rich and pyroxene-rich layers with sharp upper and lower boundaries. The thickness of these boundaries varies from 0.6 to 6 metres and can be followed for more than 2 kilometres along strike with little change in thickness (Naslund et al. 1991). The layering is apparent from a distance because trace amounts of olivine in the pyroxene-rich layers give them a brown stain on weathered surfaces. However, up close the distinction between the two types of layering is hardly visible giving the false impression that the change is gradational. Naslund et al. proposed in 1991 that the pyroxene-rich layers formed during periods of convection and the plagioclase-rich layers formed during periods of stagnation. However, Naslund and Jang corrected this statement in 1994 by arguing just the opposite. This means that plagioclase-rich layers were formed during periods of convection. It was based on new data from plagioclase in the plagioclase-rich layers having a low K_2O content similar to the plagioclase in the Upper Border Series. And so it may mean that via convection the formation of plagioclase was similar throughout the intrusion. Next various mechanisms are described that are the result of mechanical processes that can also produce layering.

Gravity settling is the first important process. As mentioned before, gravity settling can occur via grain size and / or density sorting. In the Skaergaard intrusion graded layers are generally density sorted and show little or no size sorting. Grain size variations produced in layers by crystal settling follow Stokes' law, where the coarsest grain sizes of each phase should be concentrated at the base of a layer and become finer upwards. This is clearly not the case for the Skaergaard intrusion. In addition, crystal settling is generally most concurrent in very low viscous magmas with low yield strength.

Magma currents are thought to have pervaded the Skaergaard intrusion as well. Magma currents produce modally graded layering. Although modally graded layers are widespread, it is in the Layered Series where it is best developed whereas in the Upper Boundary Series it is least developed. The layers are density graded with the most dense minerals, olivine, ilmenite and magnetite concentrated at the base, pyroxene in the middle, and plagioclase at the top. The layers vary in thickness from a few centimetres up to tens of centimetres thick and exist laterally for more than a hundred metres. These layers have been related to crystal-rich density currents that broke away from the wall of the intrusion moving out across the floor, leaving behind a density sorted layer (Wager and Brown, 1968; Irvine, 1987; Conrad and Naslund, 1989). The passing current of crystal mush across the floor of the intrusion must have interacted with a stagnant zone of in situ crystallisation that was consequently stirred and sorted by the current (Conrad and Naslund, 1989). Studies have shown that laminar flow should result in grain size sorting whereas turbulent flow causes the largest grains of each mineral to accumulate where each mineral is most abundant. Conrad and Naslund have discovered in 1989 that a strong correlation between grain size sorting and mineral mode for the Skaergaard intrusion even though its modally graded layers do not show obvious size sorting.

In addition, the structures formed in magmatic flow have been revisited by McBirney and Nicolas (1996). These structures such as foliation, lineation, shear zones, folds, and current structures define parallel beds mainly around the western and northern margins. Their distribution suggests that the strongest component of flow was from the western side and that its strength decreased toward the east (McBirney and Nicolas, 1996). They conclude that shear flow trajectories point to mass movement toward the southeastern part of the floor and that flow must have been very weak or absent in the central parts of the Layered Series because of poor developed lineation as opposed to the margins of the LS.

Trough structures have been found in the Skaergaard intrusion near the top of the Upper Zone *a* that are believed to have been formed as a result of intermittent density currents that became 'canalised' during the later stages of crystallisation (Wager and Brown, 1968). They are composed of stacks of synformal layers, 10 to 50 metres wide and up to 100 metres high and 450 metres in length (Naslund and McBirney, 1996). Naslund and McBirney argue that their forms are deposition instead of erosional. If these structures were formed via density currents it is unclear why they are not filled up with a short vertical sequence. In addition, their compositions vary greatly from pure anorthosites to mafic rock containing olivines, pyroxenes and FeTi-oxides. Irvine (1987) proposed a model consisting of convection cells and other complex flow patterns that it may yet be possible, but Sonnenthal (1992), and Naslund and McBirney (1996) suggest that they are formed via compaction processes.

This leads us to the next mechanism contributing to the formation of layering in the Skaergaard intrusion which is compaction. The idea was first presented in 1936 by Coats who believed and demonstrated that crystals of differing sizes and densities tend to sort themselves in crude layers as they consolidate under the force of gravity. The crystals may deform themselves as they continue to compact by the overburden pressure as shown from textural evidence (McBirney and Hunter, 1995). But more importantly is the possibility and likeliness of pressure solution at the grain boundary contacts. Pressure solution will, however, only work with the presence of a liquid or fluid medium for effective transfer of mass out of the grain boundary contact into the pores. This process is driven by the concentrated stress at grain boundaries where dissolution takes place. The material is transported out of the grain boundary contact via diffusion and is precipitated in the pore spaces between the grains. This process can result in the development of layers. In addition, magma, expelled during compaction, which then moves through the crystal pile as waves or pulses, (Richter and McKenzie, 1984) can be another contributing factor.

Boudreau and McBirney (1997) described various structures and textures that are the result of compaction. They divided the evidence into geochemical and textural effects. For geochemical evidence, it is noted that the roof series has consistently larger concentrations of incompatible elements that the equivalent units on the floor. The depleted character of rocks on the floor is more logically attributed to a gravitational process, such as compaction (Boudreau and McBirney, 1997). They argue that density relations make convective fractionation less likely as a gravitational process at least during the early stages of crystallisation and during the later stages of crystallisation. For textural evidence Boudreau and McBirney (1997) and Higgins (1991) warned that planar fabrics, assumed to be a natural consequence of sedimentation and compaction, must be viewed with caution. This is because a number of other factors including interaction with exsolved liquids can contribute to the development of these fabrics (Meurer and Boudreau, 1997). Meurer and Boudreau (1997) described two distinct mechanisms that contribute to the development of foliation during compaction, one is mechanical rotation and the other is selective pressure solution and recrystallisation. Lineation in the Skaergaard intrusion is often weak or undetectable. Because lineation is formed as a consequence of magmatic flow, a component of simple shear is required. Thus foliation without lineation in the Skaergaard intrusion is more likely to reflect pure shear and compaction than the simple shear expected from magmatic flow (Boudreau and McBirney, 1997). Other textural evidence is the presence of bent laths of plagioclase and equilibrated grain boundaries. Compaction is thought to produce a regionally uniform upward percolation of liquid, a segregation that leads to the formation of planar layers. However, focused flow or non-uniform compaction may cause more irregular structures (Boudreau and McBirney, 1997).

The following processes are related to variations of intensive parameters. One of these mechanisms, that could produce layering in the Skaergaard intrusion, is nucleation rate fluctuations. Wager and Brown (1968) attributed the growth of crescumulate layers in the Marginal Border Series to delayed nucleation and rapid growth in stagnant magma before convection commenced. Maaløe (1978) suggested that both macro-rhythmic and modally graded rhythmic layering maybe the result of interplay between nucleation rates and growth rates in the magma chamber. The model starts with supersaturation developing until one phase nucleates. Growth of the phase occurs until supersaturation has adequately decreased but causing the nucleation rate of the phase also to decrease. Supersaturation hence increases again with fewer nuclei forming and with it the nucleation rate of other phases. Hort et al. (1993) have examined this phenomenon and concluded that layering due to oscillatory nucleation can occur only in intrusions with an adequate thickness and also depends on viscosity and crystal growth rate.

Brandeis et al. (1992) have showed that the rhythmic layering present can be developed in a static boundary layer by the interplay of crystal nucleation and the dissipation of the heat of crystallisation. The latent heat of crystallisation raises the temperature once nucleation occurs and prevents more nucleation to occur. Instead crystal growth will occur on the nuclei already present. As the crystals approach their final size determined by phase equilibria and temperature, growth slows down and the temperature begins to fall. At that stage the process starts over with the onset of new nuclei forming. Differences in nucleation and growth rates produce graded modal abundances across each layer. It has been calculated that layers of several centimetres thick can be produced via this process. These models by Maaløe (1978) and Brandeis et al.(1992) show that there are various methods of obtaining new nuclei and producing layering.

Fluctuations in oxygen fugacity are though to be another important mechanism that could have contributed to the formation of layering in the Skaergaard intrusion. The liquidus phases in equilibrium with a magma are controlled by temperature, composition, and oxygen fugacity. Oxygen fugacity variations in the magma of the Skaergaard intrusion could be caused by gas release through vents to the surface, loss of gasses by diffusion, temperature fluctuations, convection, or fractionation of oxide-rich phases. The alternation of magnetite rich and silicate rich layers in the intrusion may have formed as a result in variations in f_{O2} with the crystallising magma (Cameron, 1975; 1977). More will be discussed about this later on.

Finally, immiscibility plays another important role because mafic magmas that differentiate to extreme degrees of iron enrichment, like in the Skaergaard intrusion, may separate into two immiscible liquids (McBirney, 1975; Philpotts, 1967; Roedder, 1978). The one liquid is rich is silica, alumina, and alkalies, the other is rich in iron and other mafic cations. In the Upper Zone *c* and Upper Border Series γ of the Skaergaard intrusion, pods, sills, and layers of melanogranophyre appear to have formed as a result of liquid-liquid separation during the final stages of crystallisation of the intrusion (McBirney and Nakamura, 1974; McBirney, 1975; Naslund, 1984a). These same structures but of FeTi-oxides and apatite rich rocks associated with anorthosites and diorites at several other locations may also have formed via liquid immiscibility according to Philpotts (1967) and Kolker (1982).

There are also a number of late-stage processes that could have contributed to the formation of layering in the Skaergaard intrusion of which some are metasomatism, Ostwald ripening, and contact metamorphism. Metasomatism is believed to be very important. As Irvine (1980) suggested, a process of infiltration metasomatism acts in layered intrusions to re-equilibrate cumulus minerals with intercumulus liquids migrating upwards due to compaction. He also concluded that in some cases a vertical alignment of crystals is obtained. As can be observed from the Skaergaard intrusion, coarse-grained gabbroic pegmatite with plenty interstitial granophyre has replaced the leucocratic parts of some of the graded layers. Single 'bands' of pegmatite material have been observed to follow one graded layer for some distance and then abruptly cut across it continuing to follow another layer. Field relations suggest that these pegmatite 'layers' are the result of recrystallisation in response to fluid metasomatism (Naslund and McBirney, 1996). According to Sonnenthal (1992) and Larsen and Brooks (1994) another explanation is that these pegmatites are the result of upward migrating, water-rich, low-density, interstitial liquids in the final stages of crystallisation of the Skaergaard intrusion. In the Lower Zone *a* of the intrusion discontinuous layers and blocks of anorthosite and iron-rich pyroxenites are present that appear to have formed by metasomatic replacement of Lower Zone *a* gabbros (Naslund and McBirney, 1996). Naslund (1986) proposed that some of these layers are actually autoliths from the Upper Border Series but have been smeared out during partial remobilisation and melting after settling to the floor of the magma chamber. Other layers of this type are clearly the result of volume-for-volume replacement (McBirney, 1995). The autolith blocks present in the Lower Zone and Middle Zone must have detached from the roof of the intrusion as the magma was crystallising and convecting and were later converted to anorthosites and pyroxenites probably via metasomatism. Numerical simulations have been done by Sonnenthal and McBirney (1997) where the coupling crystallisation, melting, and heat and mass transfer for a multicomponent system have been carried out. These simulations show how the blocks reacted with the magmatic mush in which they were emplaced. Enhanced cooling and crystallisation of a compositionally stratified mush adjacent to these blocks resulted in pattens of melt compositions similar to those of layering around the blocks in the Skaergaard intrusion (Sonnenthal and McBirney, 1997). However, the exact process of how the composition of the blocks were altered remains unknown.

Ostwalt grain ripening can also lead to the formation of specific type of layering. Boudreau described in 1987 Ostwald ripening as: grains minimise the total surface free energy of the system by allowing larger grains to grow at the expense of many smaller ones. This is because larger grains tend to have less surface energy with respect to volume as opposed to small grains. A chemical potential resulting from unstable systems aids the transfer of components between grains. Near the east margin of the Skaergaard intrusion is located a dyke of rhyolitic composition. McBirney et al. (1990) believe that the presence of spherical, 25-30 cm in diameter, fine spaced layering, a couple of millimetres thick, has formed as a result of Ostwald ripening.

Lastly, there is good evidence that contact metamorphism can also be responsible for the formation of layering. The Basistoppen sill intruded into the Skaergaard intrusion shortly after the latter solidified, but before regional tilting (Wager and Brown, 1968). The sill cuts through the Upper Zone *c* and Upper Border Zone γ. The ferrodiorites in these zones have been partially remelted because of the intruding sill (Naslund, 1986). As a result of contact metamorphism the original unlayered ferrodiorites have been altered into alternating layers of andesine anorthosites and Fe-rich olivine pyroxenites.

The question remains, however, that even though all these processes describe the contribution to the formation of different types of layering, they do not fully explain how the Skaergaard intrusion followed an iron-enriched trend of crystallisation all the way up to the Sandwich Horizon. This phenomenon is discussed next.

7. Iron enrichment in the Skaergaard intrusion

It is generally known that the differentiation of the Skaergaard magma in the Layered Series, but also in the UBS and the MBS is accompanied with iron enrichment. The iron in plagioclase, for instance, can be used as a monitor for the differentiation of the Skaergaard intrusion (Tegner, 1997). Since Bowen set up the Bowen trend (1928), he proposed that the appearance of FeTi-oxides causes the termination of iron enrichment and the onset of silica enrichment during the differentiation of tholeiitic basalt. Tegner (1997) and others agree that this does not hold for the Skaergaard intrusion. McBirney (1996) showed that iron enrichment continues until the Sandwich Horizon and there is little silica enrichment. The reason why the Skaergaard intrusion deviates is because many authors believe that as the layered intrusion crystallised, it remained closed to oxygen exchange (Osborn, 1959; Presnall, 1966; Tegner, 1997).

Recently, however, there have been doubts about the timing of the onset of magnetite and ilmenite crystallisation (Jang et al., 2001). It is believed that this is a key factor in understanding the differentiation trend of the Skaergaard intrusion. Jang et al. (2001) pointed out that the Vanadium content of an evolving magma is generally controlled by the fractionation of the oxide minerals, particularly magnetite. Thus the onset of magnetite crystallisation should be marked by a sudden decrease in V content in the evolving magma and in all of the coexisting mafic phases too that are in equilibrium with the evolving magma. They discovered that the V content in the Skaergaard pyroxene does not decrease significantly until the upper part of the Middle Zone, meaning that the onset of extensive magnetite fractionation is much later than has previously been thought. Kennedy (1948) and Osborn (1959) demonstrated experimentally that the level of oxygen fugacity depends on the trend of differentiation of tholeiitic magma towards iron enrichment or silica enrichment. Higher oxygen fugacities mean early onset of magnetite crystallisation and reduced conditions allowing a magma to move towards silica enrichment. Since this is not the case, there must have been relatively low oxygen fugacities until the final 20% of crystallisation when conditions for the roof sequence became more oxidising but the floor series remained reduced. (Jang and Naslund, 2000). Jang and Naslund (2000) also concluded that this has to do with the ceasing of magma convection which resulted in an increase in fO_2 in UBS plagioclase. The presence of some magnetite in the Lower Zone and the lower part of the Middle Zone is attributed to the precipitation of trapped interstitial magma (Jang et al., 2001). Jang et al. (2001) conclude that the late onset of magnetite crystallisation in the Skaergaard intrusion resulted in a prolonged trend of iron enrichment in differentiation and inhibited the development of a silica-rich magma.

All of these processes, that probably operated at different stages of crystallisation, are important to the formation of layering. It is important to recognise that characteristics such as thickness and length, the nature of boundaries, any internal vertical or lateral variations and the relationship to nearby layers are essential to consider. Other factors such as modal proportions, grain size, mineral composition, whole rock composition, and textural patterns are equally important to notice as they reflect the mechanism responsible for their formation.

8. Differentiation mechanisms: summary

Most of the evolution of the Skaergaard magma can be explained as the result of processes operating within the zones of crystallisation at the roof, floor, and walls (McBirney, 1995). There is no conclusive evidence found of assimilation of country rocks, and must therefore have played only a minor role at most.

Diffusive exchange at the solidification front was originally considered the basic mechanism of cumulate processes (Hess, 1939; Wager, 1963). This does not seem the case for the Skaergaard intrusion according to McBirney (1995), due to no obvious difference seen in the behaviour of components of widely differing diffusivities.

Compaction, on the other hand, must have played a major role in the segregation of residual liquids from the floor forming rocks, because the Layered Series retained a much smaller proportion of late interstitial liquids than the corresponding rocks under the roof (McBirney, 1996). Also the geochemical and textural evidence proposed by Boudreau and McBirney (1997) concur with the suggestion of compaction processes that have taken place to produce layering.

Convective exchange must have been equally important. It was driven by differences between compositional densities of the main magma and interstitial liquids. The increasingly iron-rich liquids of the main stages of differentiation tended to migrate downwards whereas buoyant late-stage liquids, rich in incompatible elements, infiltrated upwards. The results were that at the floor iron enrichment took place and depletion of incompatible elements and vice versa for the roof. Magma convection seems to have been particularly effective at steep walls, where a dense boundary layer descended to pond on the floor.

9. Conclusion

Most information gathered from the Skaergaard intusion remains valid, including the descriptions of the basic geological features and units and the main trend of evolution of rocks. However, it is clear now that, as new data was collected, it would seem that the compositional and petrographic variations are more complex that thought before. For instance, there is clear evidence of late-stage metasomatic processes that have taken place, altering in places the bulk rock composition greatly, transforming mineral assemblages to yield rocks such as anorthosites and pyroxenites. What is known is that the magma in the Skaergaard intrusion never has come into contact with a new magma due to the undisputable evidence of iron enrichment. Yet, it is difficult to assume a simple mechanism of crystal-liquid fractionation based on crystal settling due to these late-stage effects. As has been described, a combination of processes must have operated, producing the layering we now see, through a long period of cooling and re-equilibration. As McBirney (1996) argues, the main mechanism responsible for differentiation was most likely compaction, but convective fractionation was also important especially in the upper layers of the intrusion.

10. References

Blank, H.R. & Gettings, M.E., 1973. Subsurface form and extend of the Skaergaard intrusion, East Greenland. *Trans. Am. Geophys. Un.* **54**, 507.

Boudreau, A.E., & McBirney, A.R., 1997. The Skaergaard Layered Series. Part III Non-dynamic Layering. *Journal of Petrology* **38**, 1003-1020.

Boudreau, A.E., 1987. Pattern formation during crystallisation and the formation of fine-scale layering. In: Parsons, I (ed.) *Origins of igneous layering*. Dordrecht: Reidel, 453-71.
Brandeis, G., 1992. Constraints on the formation of cyclic units in ultramafic zones of large basaltic chambers. *Contr. Miner. Petrol.* **112**, 312-28.

Cameron, E.N., 1975. Postcumulus and subsolidus equilibration of chromite and coexisting silicates in the eastern Bushveld Complex. *Geochim. Cosmochim. Acta.* **39,** 1021-33.

Cameron, E.N., 1977. Chromite in the central sector, eastern Bushveld Complex, South Africa, *Am. Miner.* **62**, 1082-96.

Coats, R.R., 1936. Primary banding in basic plutonic rocks. *J. Geol.* **44**, 407-419.
Conrad, M.E., & Naslund, H.R., 1989. Modally-graded rhythmic layering in the Skaergaard Intrusion. *J. Petrology* **30**, 251-69.

Douglas, J.A.V., 1961. Geologic investigations in East Greenland: Part VII. The basistoppen sheet, a differentiated basic intrusion into the upper part of the Skaergaard Complex, East Greenland. *Meddr. Gronland*. **164**, 1-66.

Hess, H.H., 1939. Extreme fractional crystallisation of a basaltic magma: The Stillwater igneous complex. *Trans. Am. Geophy. Un.* Pt. 3, 430-32.

Higgins, M.D., 1991. The origin of laminated and massive anorthosite, Sept Iles layered intrusion, Quebec, Canada. *Contr. Miner. Petrol.* **106**, 340-54.

Hirschmann, M.M., Renne, P.R., & McBirney A.R., 1997. 40Ar / 39Ar Dating of the Skaergaard Intrusion. *Earth and Planetary Science Letters* **146**, 645-658.

Hort, M., Marsh, B.D., & Spohn, T., 1993. Igneous layering through oscillatory nucleation and crystal settling in well-mixed magmas. *Contr. Miner. Petrol.* **114**, 425-40.

Irvine, T.N., 1980. Magmatic infiltration metasomatism, double-diffusive fractional crystallisation, and adcumulus growth in the Muscox intrusion and other layered intrusions. In: Hargraves, R.B. (ed.) *Physics of magmatic processes*. Princeton, NJ: Princeton University Press, 325-84.

Irvine, T.N., 1987. Layering and related structures in the Duke Island and Skaergaard Intrusions: similarities, differences, and origins. In: Parsons, I. (ed.) *Origins of Igneous Layering*. Dordrecht: Reidel, 185-245.

Jang, Y.D., & Naslund, H.R., 1994. Compositional variations within graded layers in the Skaergaard intrusion. *Geol. Soc. Am. Abst. With Prog.* **26,** no. 2, 25.

Jang, Y.D., & Naslund, H.R., 2001. Major and trace element composition of Skaergaard plagioclase; geochemical evidence for changes in magma dynamics during the final stage of crystallisation of the Skaergaard intrusion. *Contrib. Mineral. Petrol.* **140**, 441-457.

Jang, Y.D., Naslund, H.R., & McBirney, A.R., 2001. The differentiation trend of the Skaergaard intrusion and the timing of magnetite crystallisation: iron enrichment revisited. *Earth and Planetary Science Letters* **189**, 189-196.

Keith, D.W. & Naslund, H.R., 1987. Petrographic and chemical characteristics of a layered sequence in the Upper Border Zone of the Skaergaard Intrusion, East Greenland. *Geol. Soc. Am. Abst. With Prog.* **19,** 723.

Kennedy, G.C., 1948. Equilibrium between volatiles and iron oxides in igneous rocks. *Am. J. Sci.* **246**, 165-171.

Kolker, A., 1982. Mineralogy and geochemistry of Fe-Ti oxide and apatite (Nelsonite) deposits and evaluation of the liquid immiscibility hypothesis. *Econ. Geol*. **77**, 1146-58.

Larsen, R.B., & Brooks, C.K., 1994. Origin and evolution of gabbroic pegmatites in the Skaergaard intrusion, East Greenland. *J. Petrology* **35**, 1651-80.
Maaløe, S., 1978. The origin of rhythmic layering. *Miner. Mag.* **42**, 337-45.

McBirney, A.R. & Noyes, R.M., 1979. Crystallisation and layering of the Skaergaard intrusion. *Yrbk. Carnegie Inst. Wash.* **73**, 348-52.

McBirney, A.R., 1989, Geological map of the Skaergaard intrusion, east Greenland, 1:20,000: Department of Geology, University of Oregon, 1 sheet.

McBirney, A.R., & Hunter, R.H., 1995. The cumulate paradigm reconsidered. *J. Geol.* **103**, 114-22.

McBirney, A.R., & Nakamura, Y., 1974. Immiscibility in late-stage magmas of the Skaergaard intrusion. *Yrbk. Carniegie Inst. Wash.* **73**, 348-52.

McBirney, A.R., & Nicolas, A., 1996. The Skaergaard Layered Series. Part II. Magmatic flow and Dynamic Layering. *Journal of Petrology* **38**, 569-580.

McBirney, A.R., 1975. Differentiation of the Skaergaard intrusion. *Nature* **253**, 691-4.

McBirney, A.R., 1995. Mechanisms of differentiation in the Skaergaard layered intrusion. *J. Geol. Soc. London* **152**, 421-35.

McBirney, A.R., 1996. The Skaergaard intrusion. In: Cawthorn, R.G. (ed.) *Layered Intrusions*. *Elsevier Science B.V.*, 147-180.

McBirney, A.R., White C.M., & Boudreau, A.E., 1990. Spontaneous development of concentric layering in a solidified siliceous dyke, East Greenland. *Earth-Sci. Rev.* **29**, 321-30.

Naslund, H.R., & McBirney, A.R., 1996. Mechanisms of Formation of Igneous Layering. In: Cawthorn, R.G. (ed.) *Layered Intrusions*. *Elsevier Science B.V.*, 1-43.

Naslund, H.R., 1984a. Petrology of the Upper Border Series of the Skaergaard Intrusion. *J. Petrology* **24**, 185-212.

Naslund, H.R., 1984b. Supersaturation and crystal growth in the roof-zone of the Skaergaard magma chamber. *Contrib. Mineral. Petrol.* **86**, 89-93.

Naslund, H.R., 1986. Disequilibrium partial melting and rheomorphic layer formation in the contact aureole of the Basistoppen sill. *Contr. Miner. Petrol.* **93**, 359-67.

Naslund, H.R., Turner, P.A. & Keith, D.W., 1991. Crystallisation and Layer Formation in the Middle Zone of the Skaergaard Intrusion. *Bull. Geol. Soc. Denmark* **38**, 165-71.

Nielsen, T.F.D., 1978. The Tertiary dyke swarms of the Kangerdlugssuaq area, East Greenland. An example of magmatic development during continental break up. *Contrib. Mineral. Petrol.* **67**, 63-78.
Nielsen, T.F.D., 2003. The Shape and Volume of the Skaergaard Intrusion, Greenland: Implications for Mass Balance and Bulk Composition. *Journal of Petrology* **45**, 507-530.

Osborn, E.F., 1959. Role of oxygen pressure in the crystallisation and differentiation of basaltic magma. *Am. J. Sci.* **257**, 609-647.

Philpotts, A.R., 1967. Origin of certain iron-titanium oxide and apatite rocks. *Econ. Geol.* **62**, 303-15.

Presnall, D.C., 1966. The join forsterite-diopside-iron oxide and its bearing on the crystallisation of basaltic and ultramafic magmas. *Am. J. Sci.* **264**, 753-809.

Richter, R.M., & McKenzie, D.P., 1984. Dynamical models for melt segregation from a deformable matrix. *J. Geol.* **92**, 729-40.

Roedder, E., 1978. Silicate liquid immiscibility in magmas and in the system K_2O-FeO-Al_2O_3-SiO_2: an example of serendipity. *Geochim. Cosmochim. Acta.* **42**, 1597-617.

Schwarz, E.J., Coleman, L.C., & Cattroll, H.M., 1979. Paleomagnetic results from the Skaergaard intrusion, East Greenland. *Earth and Planetary Science Letters* **42**, 437-443.

Sonnenthal, E.L., & McBirney, A.R., 1997. The Skaergaard Layered Series. Part IV. Reaction-Transport Simulations of Foundered Blocks. *Journal of Petrology* **39**, 633-661.

Sonnenthal, E.L., 1992. Geochemistry of dendritic anorthosites and associated pegmatites in the Skaergaard Intrusion, East Greenland: evidence for metasomatism by a chlorine-rich fluid. *J. Volc. Geotherm. Res.* **52, 209-30.**

Tegner, C., 1997. Iron in plagioclase as a monitor of the differentiation of the Skaergaard intrusion. *Contrib. Mineral. Petrol.* **128**, 45-51.

Wager, L.R., & Brown, G.M., 1968. *Layered Igneous Rocks*, Edinburgh: Oliver & Boyd, 588.

Wager, L.R., & Deer, W.A., 1938. A dyke swarm and coastal flexure in East Greenland. *Geol. Mag.* **75**, 39-46.

Wager, L.R., & Deer, W.A., 1939. Geological investigations in East Greenland, Part III. The petrology of the Skaergaard intrusion, Kangerdlugssuaq, East Greenland. *Meddr. Gronland*. **105**, 352 pp.

Wager, L.R., 1960. The major element variation of the Layered Series of the Skaergaard Intrusion and a re-estimation of the average composition of the Hidden Layered Series and of the successive residual magmas. *J. Petrology* **1**, 364-98.

Wager, L.R., 1963. The mechanism of adcumulate growth in the Layered Series of the Skaergaard Intrusion. *Spec. Paper. Miner. Soc. Am.* **1**, 1-9.

Appendix A: Geological map of the Skaergaard intrusion and surrounding area

Figure 4: Geological map taken from: http://www.union.edu/PUBLIC/GEODEPT/hollocher/skaergaard/geologic_features/geologic_map.htm. Modified afterMcBirney (1989).