# Physical and Chemical Processes in the Bjerkreim-Sokndal Magma Chamber

**Federico Chiodoni**

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# Contents

# Preface

This dissertation entitled “Physical and chemical processes in the Bjerkreim-Sokndal magma chamber” has been submitted by Federico Chiodoni in partial fulfilment of the requirements for the degree of philosophiae doctor (PhD) at the Department of Earth Science, University of Bergen (UiB), Norway. The dissertation is the result of a research project “Physical and chemical processes in a large magma chamber: The Bjerkreim-Sokndal Intrusion” funded by the Norwegian Research Council (NFR) for the period 2005-2007. The work was carried out at the Department of Earth Science at the University of Bergen and included a total of 18 weeks of geological mapping and sample collection in the county of Rogaland, SW Norway, during the summer months of 2005, 2006 and 2007.

I thank Prof. Brian Robins (University of Bergen) for his close supervision during the course of this study and Richard Wilson (University of Århus, Denmark) for stimulating discussions and reviewing manuscripts. Ole Tumyr and Øyvind Skår are thanked for their technical assistance during data acquisition in the laboratories at the Department of Earth Science at the University of Bergen and the Geological Survey of Norway (NGU), Trondheim.

# Statement of authorship

Professor Brian Robins was responsible for the initial project outline and for eliciting sufficient financial support from the Norwegian Research Council to cover salaries and the cost of the field and laboratory work.

The geological mapping of the Sokndal area was principally carried out by the candidate. Professor Brian Robins mapped a subsidiary part of the Sokndal area and assisted during the collection of samples for analysis.

The candidate had the sole responsibility for compiling the new version of the geological map of the Sokndal lobe at a scale of 1:10.000, as well as constructing all of the figures presented in Chapters 1-3. The candidate was also responsible for the collection and interpretation of most of the analytical data. Loredana Pompilio contributed some of the whole-rock analytical data used in Chapter 3.

As first author of the papers comprising Chapters 1-3, the candidate wrote the manuscripts and compiled the accompanying tables of analytical data. The factual descriptions and interpretations were extensively discussed and agreed with co-author professor Brian Robins, who read and corrected the English language and otherwise contributed to the formulation of the final versions of the manuscripts. The manuscripts were reviewed by co-supervisor Dr. J. Richard Wilson at the University of Århus, Denmark, and have been revised in accord with his recommendations.

The discussion forming Chapter 4 was written by professor Brian Robins, but the criticisms and alternative views presented in the paper are the result of joint discussions of the original publication and the interpretation of a more extensive set of analytical data available to the authors.

Acknowledgments of the contributions of others are, as usual, included at the end of the individual papers.

# Introduction

Magma chambers are large pockets of molten rock that are emplaced, cool slowly, crystallise and differentiate within the crust of the Earth, commonly beneath central volcanoes. Physical and chemical processes that take place in magma chambers are of fundamental importance for magma differentiation, mixing and contamination as well as for the nature and products of contemporaneous volcanic activity. They can also lead to the concentration of elements such as Cr, Fe, Ti, V, Pt, Pd, Au, P and Al into economic deposits. There is exploitation or test mining of large deposits of these important elements within or adjacent to fossil magma chambers at several places in Norway, Finland, Greenland (and many other locations in the world), and active exploration at others.

One approach to the identification of processes in magma chambers is the study of layered intrusions, i.e. solidified magma chambers now exposed at the surface of the Earth. Minerals that crystallise in magma chambers coat cooling surfaces, such as the roof and walls, but mainly they accumulate successively on the floor, resulting in layered series. Layered series are records of temporal and/or spatial variations in the composition and temperature of the magma occupying the chamber. They can subsequently be compacted, recrystallised and react to varying degrees with percolating melts and other fluids as solidification continues to completion, forming rocks known as cumulates. The individual mineral species in cumulates generally preserve evidence of the composition, temperature, oxygen fugacity and isotopic ratios of the magmas from which they crystallised. Thus liquidus minerals in cumulates that formed successively on the floor of chambers contain a more or less continuous record of variations in melt composition, temperature etc. that took place during the evolution of the magma chamber.

Cooling and crystallisation of low-viscosity magma may lead to various forms of magma circulation in chambers, such as thermal, compositional and two-phase convection and possibly even double-diffusive convection. The progressive cooling of magma chambers is commonly interrupted by periodic replenishment and the incursions of fresh magma may interact and mix in various ways with the resident melts, depending principally on viscosity and density differences and the momentum of the inflowing melts. Melting of rocks, forming the walls and roof of chambers, or occurring as included blocks (xenoliths), can result in a significant degree of contamination of the resident magmas. Repeated replenishment and/or melting of the roof or buoyant xenoliths may conceivably result in the development of a persistent compositional stratification within the magma occupying a chamber.

The study of layered series in solidified magma chambers can therefore contribute to an identification and evaluation of the processes and events that have taken place during their evolution, and complement the data that can be obtained from volcanic sequences that erupted from individual magma chambers. Such studies have contributed to an appreciation of the complex nature of the interactions that may occur in magma chambers between different physical and chemical processes.

The thesis consists of an introductory chapter and four papers, either published (chapter 4) or manuscripts prepared for publication (chapters 1-3). Chapters 1 and 2 are complementary accounts addressing different aspects of the geology and petrology of the southern, Sokndal part of the Bjerkreim-Sokndal Layered Intrusion and therefore contain some introductory repetition. Chapter 4 is a discussion concerning the interpretation of whole-rock analyses of Bjerkreim cumulates and the mechanism of magmatic differentiation that also is dealt with in chapter 3. Retaining the manuscript format, references are included at the end of each chapter, together with accompanying figures, figure captions and tables of supporting data, rather than collecting them together in a single appendix. An overview of the background and aims of the study and a summary of the main findings and their significance for the evolution of the Bjerkreim-Sokndal magma chamber are included in this introductory chapter.

## Background for the research

The project aims to cast further light on the evolution of a specific large magma chamber as revealed by the Layered Series (LS) of the Proterozoic Bjerkreim-Sokndal Intrusion (BKSK), part of the Rogaland Anorthosite Province, SW Norway (Fig. 1). This igneous province consists of four large anorthosite plutons: the Egersund-Ogna, Håland, Helleren and Åna-Sira massifs and a number of smaller intrusions (Michot and Michot, 1969; Duchesne et al. 1985). The intrusions were emplaced into Sveconorwegian (Grenvillian) granulite facies gneisses as late- to post-orogenic plutons. Field evidence shows that the BKSK is younger than the anorthosite massifs (Michot & Michot 1969). A recent U–Pb zircon study by Schärer et al.

(1996) indicates that the anorthosite plutons were emplaced in a 10 Ma period between 920 and 930 Ma.

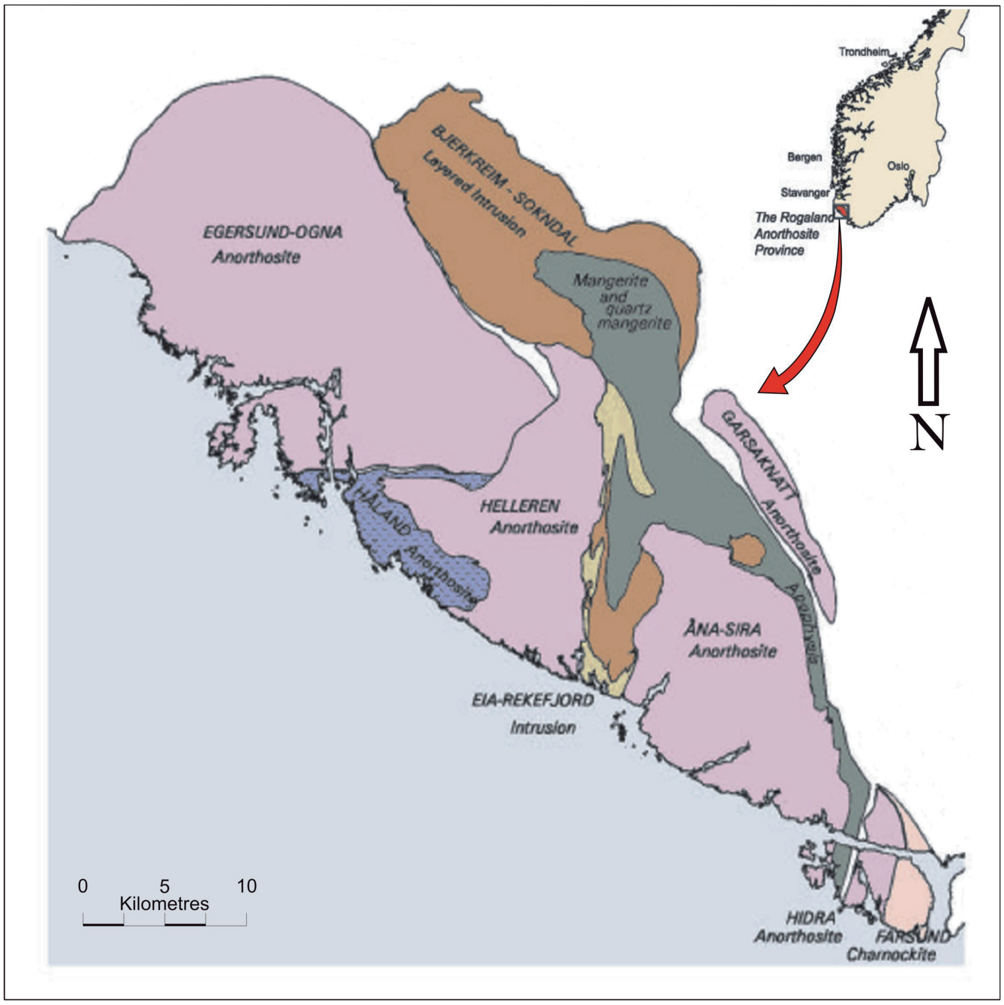

**Fig. 1.** *Highly simplified map of the Rogaland Anorthosite Province, SW Norway, showing the main igneous intrusions (after Marker et al. 2003).*

The BKSK consists of three lobes: the Bjerkreim lobe in the north-west, and the smaller Sokndal and Mydland lobes to the south and south-east respectively. It extends for 40 Km in the N-S direction and 15 Km in the E-W direction and occupies an area of about 230 km$^2$. The present form of the intrusion is that of a doubly plunging syncline that branches in the south around the Åna-Sira Anorthosite (Paludan et al. 1994, Bolle et al. 2002). The BKSK is the largest Norwegian layered intrusion and contains a thick Layered Series (LS) of rather unusual composition. Based on field and petrographic observations the intrusion may be divided into two parts: An anorthositic to gabbronoritic LS which outcrops in the northern part of the intrusion and in the two southern lobes, and a generally more massive mangeritic, quartz-mangeritic and charnockitic upper part that occupies the core of the syncline (Nielsen et al. 1996, Duchesne & Wilmart 1997, Wilson et al. 1996, Wilson & Overgaard 2005). These are separated by a thin Transition Zone (Duchesne et al. 1987). The roof of the intrusion has been entirely removed by erosion. The Layered Series is divided into 6 megacyclic units (MCU 0-IV) characterised by repetitions of sequences of rocks with similar cumulus assemblages referred to as zones a-f. The megacyclic units have different stratigraphic thicknesses, lateral persistence and development of modal layering. Plagioclase, orthopyroxene and ilmenite are the main cumulus minerals in MCU IA, IB and II and in the lower parts of MCU III and IV. Cumulus olivine is present in thin, laterally persistent intervals just above the base of MCU III and IV; more Fe-rich olivine is present in the Transition Zone. Cumulus titanomagnetite, Ca-rich pyroxene and apatite appear in the upper parts of MCU III and IV (Wilson et al. 1996).

The Bjerkreim-Sokndal Intrusion has been studied intensively over recent years (see e.g. Wilson et al. 1996, Robins et al. 1997, Robins & Wilson 2001, Jensen et al. 2003). The northern and largest part of the intrusion, the Bjerkreim lobe, has been carefully mapped at the scale of 1:5,000 and extensively sampled by professors Brian Robins and J. Richard Wilson and their masters and Ph.D. students (Marker et al. 2003). Despite the volume of this earlier work, several important aspects of the geology of the BKSK and the magma chamber evolution were unresolved prior to the current work.

One such aspect concerns the nature of the Layered Series in the southern, Sokndal lobe (see Fig. 2) of the intrusion which had previously only been the subject of reconnaissance-type studies (Michot, 1960, 1965, 1969; Schott, 1984; Nielsen, 1992; Schiellerup, 2001). The distribution of the cumulates in this lobe had not been mapped in the same detail as in the Bjerkreim lobe, and phase contacts could not be drawn on a geological map with any confidence.

The studies carried out earlier suggested that the main features of the cumulates present in the Sokndal lobe were similar to those of the uppermost subdivision of the Layered Series in the Bjerkreim lobe (i.e. Megacyclic Unit IV) but it was not known whether the series was continuous or uninterrupted, or whether any older cumulates are represented in the Sokndal lobe. Nielsen (1992) had previously collected a very limited number of samples and identified the local existence of troctolite in the southern part of the lobe that is similar to cumulates near the base of MCU III and IV in the Bjerkreim lobe but with anomalously high amounts of apatite. Schiellerup (2001) also investigated a small number of samples from the Layered Series in the Sokndal lobe. Duchesne et al. (1987) analysed 25 samples collected through the thin Transition Zone in the eastern part of the Sokndal lobe in order to constrain late-stage differentiation mechanisms in the BKSK. Nevertheless an inadequate number of samples had been collected and analysed and the cryptic variation in the Sokndal Layered Series was very poorly documented. These issues are addressed in chapters 1 and 2, which focus on the Layered Series in the Sokndal lobe of the BKSK and its relationship with the Bjerkreim lobe.

Chapter 1 presents the results of detailed mapping and sampling carried out in the southernmost part of the Sokndal lobe, the western limb and the southern half of the eastern limb that supplant earlier, reconnaissance work in this area. Phase contacts in the cumulates have been mapped at a scale of 1:5000 by careful determination of cumulus mineral parageneses in the field, supplemented where appropriate by petrographic analysis of thin sections. Very inhomogeneous sills of jotunite, mangerite and quartz mangerite, the Eia-Rekefjord intrusion of Michot (1960) (Fig. 2), in the western flank of the Sokndal lobe, and the related Haugåsen jotunite-quartz mangerite intrusion emplaced into magnetite norite in the eastern flank and sheets of quartz mangerite were also mapped. The results of this detailed investigation gives a more complete picture of the mode of magma emplacement, its subsequent crystallisation and later deformation of the LS in the Sokndal Lobe, as well as the relations with the surrounding igneous bodies.

The cryptic layering in the Sokndal lobe (Fig. 3) is described in chapter 2 based on electron microprobe (EMP) analysis of the silicate minerals in several suites of hand specimens collected through different parts of the Layered Series. Altogether more than 2500 EMP point analyses were carried out on 118 samples from 5 traverses (at Rossland, Torvvegen, Kjelland, Øvre Lauvås and Heståsen). Cumulus ilmenite was also analysed by laser ablation inductively-coupled plasma mass spectroscopy (LA-ICPMS) in the suite of samples collected near Rossland. Samples collected along a westward prolongation of the Rossland traverse also document the existence of cryptic layering in one of the younger Eia-Rekefjord sheets.

This account is the first comprehensive documentation of the cryptic variation in the Sokndal lobe of the BKSK and together with the companion publication (Chapter 1), it is a contribution to the construction of a comprehensive model for the evolution of the Bjerkreim-Sokndal magma chamber. In particular, it is demonstrated that the major replenishment event

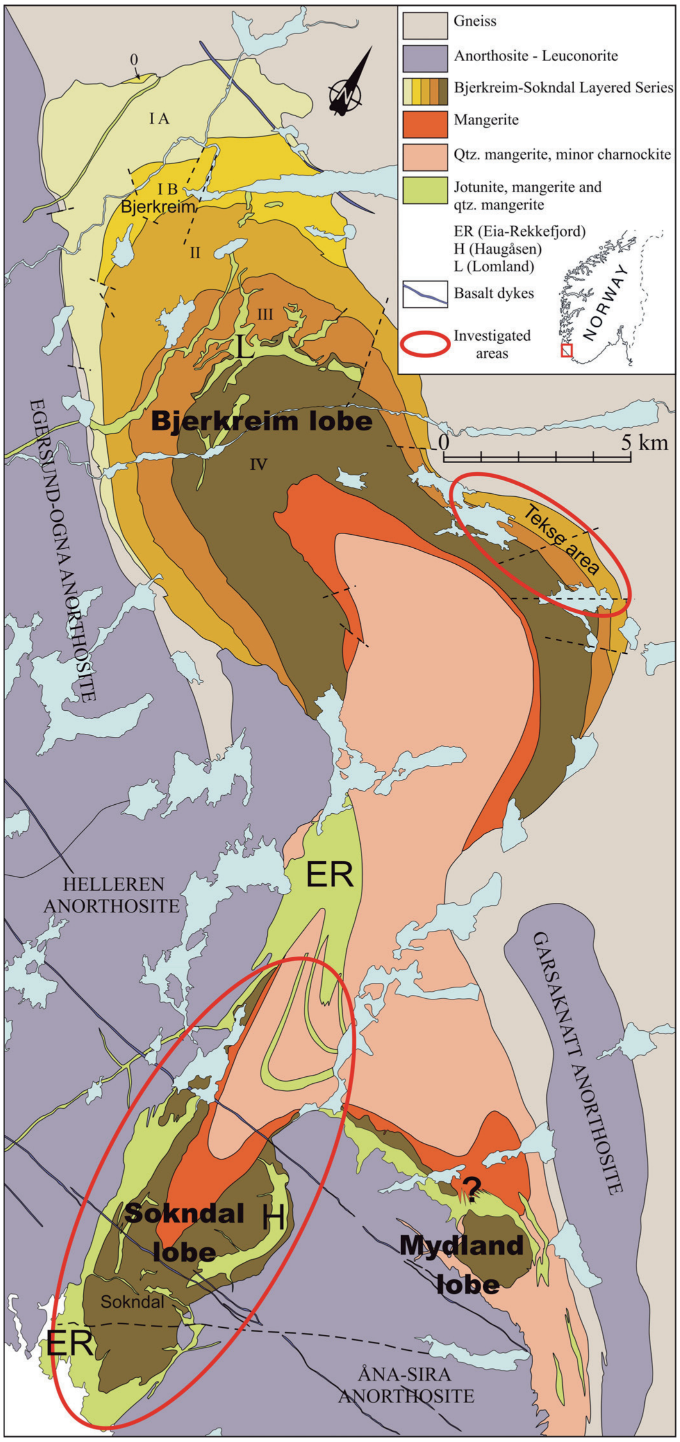

***Fig. 2.*** *Simplified geological map of the Bjerkreim-Sokndal Intrusion and its surroundings, based on the Norwegian Geological Survey map of the Rogaland Anorthosite Province (Marker et al. 2003). The subdivisions in the Bjerkreim lobe of the intrusion and the roman numerals refer to Megacyclic Units I-IV.*

responsible for the formation of the Sokndal lobe was followed by uninterrupted cooling and fractional crystallisation of a diopside-poor, jotunitic parental magma that eventually led to the formation of mangeritic cumulates. The stratified magma column in the Bjerkreim lobe was elevated during replenishment and it flooded the newly-formed floor of the Sokndal lobe with progressively more primitive magma. The thicker LS in the Sokndal Lobe is assumed to be a consequence of protracted subsidence of the floor the lobe during crystallisation of the stratified magma. The subsequent gravitational collapse into underlying anorthosite led to the deformation of the dense noritic rocks into a deep syncline. The amount of subsidence increased towards the central part of the BKSK, resulting in the northward plunge of the syncline in the Sokndal lobe. The abundant of apatite in the lowermost part of the LS is due to the cool floor of older anorthosite which contributed to initially high cooling rates of the magma in the Sokndal lobe that led to trapping of abundant intercumulus melt. In chapters 1 and 2 it is shown for the first time that the Eia Rekkefjord jotunite and other minor intrusions of jotunitic to mangeritic composition were emplaced as sills and sheets, both before and after the deformation of the Sokndal Layered Series into a syncline.

Another unresolved aspect of the evolution of the Bjerkreim-Sokndal magma chamber concerns the origin of certain ilmenite-rich sequences in the Bjerkreim lobe. Typically, cumulates in the Layered Series contain rather limited amounts of ilmenite, as to be expected during the cotectic crystallisation of ilmenite and plagioclase or ilmenite, plagioclase and orthopyroxene. Mafic layers and sequences are normally restricted to regressive zones at the bases of Megacyclic Units III and IV in the Bjerkreim lobe that are believed to be related to mixing of compositionally-different, but ilmenite-saturated magmas during magma-chamber recharge (Nielsen and Wilson, 1991; Jensen et al., 1993; Nielsen et al., 1996). In particular, the regressive base of MCU III is characterized by a sulphide-enriched orthopyroxenite, unique in the intrusion, or ilmenite melanorite, that represent the initial response to a replenishment event and have been explained by crystallisation of a hybrid magma residing within the orthopyroxene phase volume (Jensen et al. 2003). Replenishment culminated in the crystallisation of troctolite (plagioclase-olivine-ilmenite-magnetite cumulate) on the deeper, central parts of the chamber floor while the crystallisation of lower-temperature norite (plagioclase-hypersthene-ilmenite cumulate) continued on the marginal, elevated portions. However, in a restricted area along the north eastern flank of the Bjerkreim lobe (Tekse area of Fig. 2) of the intrusion, melanocratic, ilmenite-rich noritic cumulates form thin, strongly modally-layered sequences just above the base of MCU III. Here, they overlie rather massive coarse-grained leuconorite or leucotroctolite that rest on a sulphide-enriched layer of ilmenite-rich melanorite or ilmenite orthopyroxenite that marks the base of MCU III. The stratigraphic study of the MCU II/III boundary by Jensen et al. (2003) focused on the origin of the basal sulphide-enriched orthopyroxenite and melanorite and neither included data on the composition of ilmenite nor discussed specifically the origin of the modal enrichment in ilmenite. Unlike ilmenite-rich minor intrusions and ore bodies elsewhere in the Rogaland Anorthosite Province, that generally are plagioclase-ilmenite or noritic cumulates (Duchesne 1999, 1972, Schiellerup et al. 2003, Charlier et al. 2006), these particular ilmenite-rich cumulates in the Bjerkreim-Sokndal Layered Intrusion are also enriched in orthopyroxene and seem to form a genetically distinct type of oxide occurrence.

Chapter 3 presents the results of a very detailed investigation of the stratigraphy of the cumulates forming the basal portion of MCU III on the north-eastern flank of the Bjerkreim lobe (Fig. 3). A new set of closely-spaced samples supplement the earlier data which were presented by Jensen et al. (2003). The samples were collected along three sections and silicate mineral compositions, whole-rock major- and trace-element compositions as well as the composition of the ilmenite itself, were acquired to clarify the relationship between the relative enrichment in ilmenite and orthopyroxene in some of the cumulates and mixing of magmas during replenishment of the magma chamber. The cryptic variation revealed by these data suggests that the ilmenite-rich noritic cumulates crystallised after the termination of replenishment of the magma-chamber by hot, more primitive magma. The enrichment of the cumulates in ilmenite is inferred to be a consequence of differential sorting during vigorous convection, plagioclase crystals being carried away and deposited elsewhere. The ilmenite-rich cumulates are therefore only indirectly related to magma-chamber replenishment and magma hybridisation.

The published discussion paper forming chapter 4 is a by-product of the work reported in chapter 3 and argues against the notion that mafic minerals in the Bjerkreim cumulates occur in constant proportions, as claimed by Duchesne & Charlier (2005), and rejects their inferences of in situ crystallisation and a lack of mineral sorting.

## Processes in the Bjerkreim-Sokndal Magma chamber

A summary tying together the different aspects of the evolution of the Bjerkreim-Sokndal magma chamber dealt with in chapters 1-4, can take a number of possible directions, involving aspects of magma emplacement and mixing, the physical processes occurring

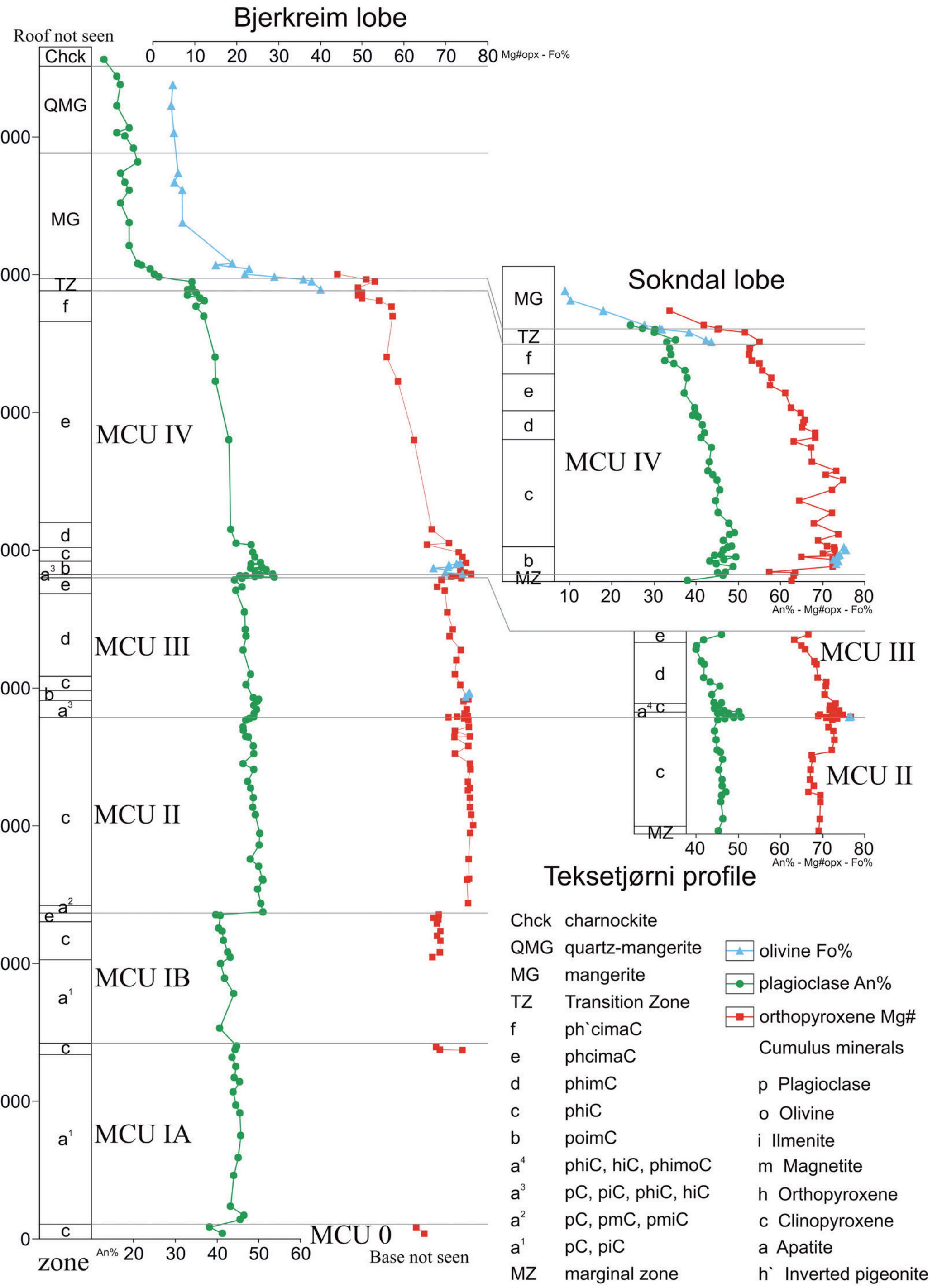

***Fig. 3.*** *Cryptic layering in the axial region of the Bjerkreim LS compared with the Layered Series in the Sokndal Lobe and in MCU II and III in the Tekse area. The compositional data used in the composite profile through the Bjerkreim LS are taken from Nesbø (1988)(MCU0 and IA), Cetin (1990)(MCU IB), Smedal (1990)(MCU II), Sandal (1990)(MCU II), Jensen et al. (2003)(MCU II-III), Jensen et al. (1993), Nielsen et al. (1996)(MCU IV), Wilson and Overgaard (2005) (TZ, MG, QMZ and charnockite). The compositional variations in the Sokndal LS are compiled from parts of the sampled profiles avoiding sections characterised by basal reversals (see chapter 2 for more details). The total and relative stratigraphic thicknesses do not correspond to any single section through the Sokndal LS. Cryptic variations in the Tekse area are from the Teksetjørni profile (see chapter 3 for more details).*

during the magmatic differentiation as well as post cumulus processes. It is apparent that what distinguish the different studies reported in Chapters 1-4, beside the different location of the areas studied is the different stratigraphic levels investigated.

A natural approach to summarise the results of the present study of the evolution of the BKSK is therefore to consider the effect of repeated influxes of new magma into the expanding magma chamber. The description continues with a consideration of the fluid dynamics of magma emplacement, magma hybridisation, magma stratification and interaction between cumulus minerals and intercumulus melt. A final section is reserved for post-cumulus deformation which is considered as a final important process in the evolution of the BKSK. These processes are specifically dealt with in chapters 1-4, and are compared here to processes that took place in other intrusions.

### ***Initial emplacement and subsequent replenishment and expansion of the magma chamber***

Generally, layered intrusions are interpreted as the result of fractional crystallisation of magma during solidification. This could involve two possible and very different scenarios. One is a closed-system magma chamber with fractionation of a single influx of magma without any later magma recharge such as the Skaergaard Intrusion (Wager & Brown 1968, Stewart and De Paolo 1990, McBirney 1995). On the other hand magma chambers can behave as open systems characterised by repeated episodes of replenishment, such as the Rum (Emeleus et al. 1996) and Muskox Intrusions (Irvine 1980).

After the pioneering studies of Michot (1960 and 1965) and subsequent work by Duchesne (1972), Nielsen et al. (1996), Wilson et al. (1996), the Layered Series in the BKSK was divided into 6 megacyclic unit (MCU 0 to IV) which repeats characteristic sequences of cumulates. The megacyclic units can be further subdivided into zones a-f, based on assemblages of cumulus minerals (Fig. 4). The repetition of a sequence of zones within each MCU is the result of brief episodes of replenishment followed by prolonged periods of fractional crystallisation. Each episode of replenishment was accompanied by expansion of the magma chamber, hybridisation of inflowing and resident magmas and simultaneous fractional crystallisation. These processes were also accompanied by continuous crustal contamination of the magma by country rocks (Tegner et al. 2005) and, at a late stage, by the interaction of accumulated crystals with trapped intercumulus melt (Charlier et al. 2005). Barling et al. (2000) on the base of isotopic variations divided part of the layered series into a replenishment interval, interpreted to be the result of mixing between the resident and newly injected magma, and a post-replenishment interval characterised by simple, progressive fractional crystallisation and assimilation of the country rocks.

In accord with various types of evidence Wilson et al. (1996) inferred that the Layered Series as "*crystallised in a continuously fractionating, periodically replenished magma chamber. Replenishment events were few in number and widely spaced in time. In the lowermost units the cumulates represented are predominantly high-temperature varieties and the proportion of more-evolved cumulates generally increases in the upper units. This pattern suggests that the bulk composition of the magma occupying the chamber became progressively more evolved with time.*"

The distribution and contact relationships suggest that, during the early stage of evolution of the BKSK, cumulates forming MCU 0-IB crystallised at the base of a wedge-shaped chamber. The horizontal and vertical extension of the magma chamber was limited by the displacement along a steep-normal fault located along the present north-eastern margin of the Bjerkreim lobe. The rather evolved composition of cumulus plagioclase ($An_{46\text{-}36}$) and orthopyroxene ($Mg\#opx_{70\text{-}68}$) of MCU IA and IB (Figs. 3-4) suggests that they may have crystallised from a magma, represented by the jotunite marginal chills, that was more differentiated than during the crystallisation of later MCUs. Fractional crystallisation of the parental magma of MCU1A led to the formation of a thick sequence of plagioclase-rich cumulates (pC and piC) and it was interrupted by a new episode of magma influx after the crystallisation of a thin sequence of ilmenite leuconorite (phiC) (Fig. 4). Conversely the sequence of cumulates comprising MCU IB reflects more protracted fractional crystallisation so that titanomagnetite and Ca-rich pyroxene were liquidus phases in addition to plagioclase, orthopyroxene and ilmenite prior to renewed replenishment. Surprisingly the cryptic variation in the compositions of the cumulus minerals is slight, despite the large change in the modal composition (Figs. 3-4).

Crystallisation of MCU IB was terminated by the emplacement of a large volume of jotunitic magma from which MCU II was formed. The influx of new magma led to elevation of the roof and the edge of the chamber migrated >6 km to the southeast. Cooling and fractional crystallisation of the jotunitic magma led to formation of a basal plagioclase-rich ($An_{52}$), magnetite-bearing, high-temperature zone (pimC), locally containing cumulus magnesian olivine, followed upward by a 1300m thick sequence of monotonous ilmenite leuconorite (phiC). Fractional crystallisation was interrupted by a new input of jotunitic magma before the resident magma re-attained saturation in magnetite, Ca-rich pyroxene or apatite. Compositionally the most evolved plagioclase and orthopyroxene at the top of the MCU II are ~$An_{45}$ and $En_{71}$ respectively (Fig. 4). The rather limited cryptic variation in MCU II suggests that crystallisation was interrupted at a fairly early stage of magmatic differentiation and presumably only a limited portion of the injected magma crystallised.

The replenishment event that terminated the fractionation of the parental magma of MCU II result in a more restricted lateral expansion of the magma chamber of 1600-3000m southwards (Fig. 2). The cryptic regression across the MCU II-III boundary is rather small due to the limited degree of crystallisation of the large volume of magma emplaced at the base of the MCU II. A meter-thick layer of sulphide-bearing orthopyroxenite or melanorite, enclosed within ilmenite leuconorite, marks the base of MCU III (see chapter 3). Leuconorite above the sulphide-bearing orthopyroxenite is 100-200m thick in the axial part of the intrusion but it thins toward the margins, indicating that the contemporary floor of the magma chamber had the shape of a shallow saucer (chapter 3). The latter is overlain by leucotroctolite (poimC), which represents the highest temperature cumulate in the whole intrusion ($An_{51}$ and $Fo_{80}$). During subsequent magma cooling and fractionation, cumulus olivine was replaced by orthopyroxene and at the same time magnetite stopped crystallisation. As temperatures decreased further, first magnetite and later Ca-rich pyroxene and apatite appear as cumulus minerals in the lower-temperature cumulus assemblage of zone IIIe ($An_{44}$, $Mg\#opx_{70}$, $Mg\#cpx_{71}$), before the final replenishment took place. It is particularly noticeable that the magma that crystallised at the upper part of MCU III had reached about the same degree of evolution as at the top of the MCU IB only after crystallisation of a >2000m thick sequence of layered rocks.

The last episode of magma influx was associated with very significant enlargement of the chamber to the south (Fig. 2). This phase of chamber expansion resulted in the development of the Sokndal and Mydland lobes of the BKSK, where only the equivalents of cumulates belonging to MCU IV in the Bjerkreim lobe are represented (chapters 1-2). The transition from MCU III to MCU IV is marked by marked compositional reversals from lower to higher temperature compositions in plagioclase (from $An_{44}$ to $An_{54}$) and orthopyroxene (from $Mg\#opx_{70}$ to $Mg\#opx_{77}$) and by the appearance of cumulus Mg-rich olivine ($Fo_{76}$). MCU IV contains the same sequence of cumulus assemblages as MCU III, followed upward by an uninterrupted cryptic variation through the TZ into the overlying mangerite and quartz-mangerite, due to progressive differentiation of the residual magma (chapter 2). Plagioclase varies in composition from $An_{54}$ to $An_{30}$ (antiperthite) in the TZ, while mesoperthite occurs in the overlying mangerite and quartz mangerite. Orthopyroxene varies within $Mg\#opx_{75-45}$ and is inverted pigeonite from the base of zone f. As in the underlying MCU III, olivine is present in the lowest part of the LS ($Fo_{76}$-$Fo_{67}$), but is not present in zones c-f. Cumulus olivine reappears in the TZ and becomes rapidly enriched in iron upwards into the quartz mangerite ($Fo_{40-5}$). Ca-rich pyroxene emulates the same pattern as in MCU III; it varies from $Mg\#cpx_{74}$ at the base of zone e to $Mg\#cpx_{15}$ in the quartz mangerite.

The description above highlights two important features of the Layered Series in the BKSK. The first is the more evolved composition and the different order of crystallisation of the lower MCUs, outcropping in the northern part of the Bjerkreim lobe. The repetition in MCU III and MCU IV of the sequence leucotroctolite/leuconorite (zone a/b), ilmenite leuconorite (zone c), magnetite-ilmenite leuconorite (zone d), apatite-bearing gabbronorite (zones e and f) is just partially reproduced in MCU IA and IB (Fig. 4). These differences can be explained in terms of crystallisation of the lower MCUs from a lower-temperature and more differentiated parental magma (Robins et al., 2008). On the other hand, the increasing proportion of more-evolved cumulates in the upper MCUs suggests that the bulk composition of the magma occupying the chamber became progressively more evolved with time.

The second feature is the volumetric relationship between the magma that occupied the magma chamber and new magma emplaced during episodes of replenishment. Geometrical relationships and the phase layering suggest that the volume of magma emplaced during the initiation of MCU IB was smaller than the volume of magma remaining after the crystallisation of MCU IA. The uppermost zone IBe wedged out against the temporary floor of the magma chamber when it was composed of zone c cumulates belonging to MCU IA. The limited extent of the MCU IA and IB compared to whole intrusion and the appearance of evolved cumulus assemblages, indicating advanced fractional crystallisation of the resident magma, suggests that the volume of magma occupying the chamber was much smaller than the volume of jotunitic magma emplaced on initiation of MCU II.

Conversely there is quite clear evidence that the volume of jotunite magma emplaced at the base of the MCU III and IV was smaller than the concurrent volume of resident magma. Due to the topography of the floor of the magma chamber the thickness of MCU III varies from 1100m at the axis of the intrusion to ~800m in the western limb and it thins more over the bulge in the floor at Teksevatnet to ~250m before it thickens again to ~550m further south. Nevertheless, according to Jensen et al (2003) and the results presented in chapter 3, the fractionation of the hybrid magma that resulted from mixing between the resident and the jotunitic magma injected at the base of the MCU III initiated the crystallisation of the sulphide-bearing horizon and terminated before the magnetite became a liquidus mineral. This means that in the axial region of the Bjerkreim lobe only a 300m thick sequence of cumulates crystallised from the hybrid melt, while the remaining 800m-thick sequence of cumulates crystallised from the resident magma before the last event of chamber refilling took place.

Similarly the hybrid melt that was generated during the last episode of magma chamber recharge crystallised just a fraction of the total amount of cumulates comprising MCU IV. According to Jensen et al. (1993) the hybrid magma crystallised a sequence of cumulates 350 to 500m thick on the inwardly sloping floor of the chamber. This thickness roughly corresponds to the sum of the thicknesses of zones IVa, b, c and d. In accord with this assumption, the ubiquitous decrease in the hematite content of the ilmenite, after the entrance of cumulus magnetite in zone IVd (Meyer et al., 2003) clearly indicates that fractional crystallisation was accompanied by a continuous decrease in the oxygen fugacity of the melt, consistent with a closed system (chapters 2-3).

This evidence, combined with the inference that the volume of resident magma left after the fractionation of the lowermost MCUs IA and IB was quite limited, suggest that the resident magma that occupied the magma chamber during the last two episodes of replenishment was mainly composed of melt remaining after the crystallisation of MCU II. If so, the voluminous batch of jotunitic magma that interrupted the fractionation of MCU IB, crystallised first the magnetite-bearing leuconorite and the thick sequence of ilmenite leuconorite in MCU II, the magnetite norite and gabbronorite in the MCU III and the gabbronorite in MCU IV. Uninterrupted fractional crystallisation of the differentiated magma led eventually to the formation of the overlying mangerite and quartz mangerite (Fig. 3). During the crystallisation of the quartz mangerite the BKSK was intruded by evolved melt (of jotunitic affinity) crystallising two-pyroxene quartz mangerite (Duchesne &Wilmart, 1997, Wilson & Overgaard, 2005).

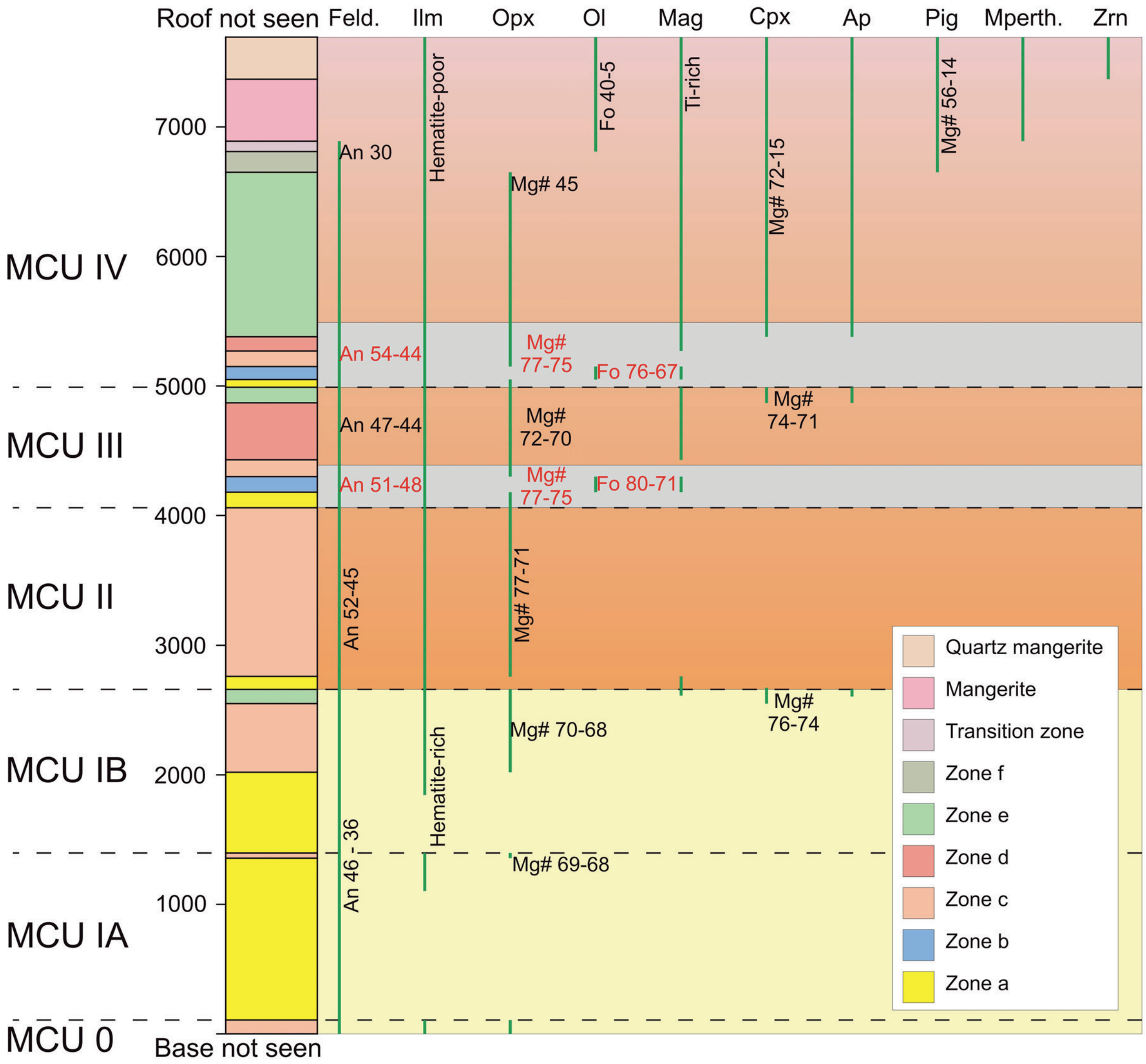

**Fig. 4.** *Revised version of the general stratigraphy, minerals and cryptic layering of the BKSK (after Wilson et al. 1996). The Layered Series consists of leuconorite and anorthosite (zones labelled a), troctolite (b), ilmenite norite (c), magnetite-ilmenite norite (d), apatite gabbronorite (e) and apatite gabbronorite with inverted pigeonite (f) organised into repeated sequences of Megacyclic Units IA-IV. The thickness of the zones in the upper part of the Layered Series as well as the cryptic layering takes account of the new data obtained during the present study. The field containing the cryptic layering has been divided in three sections. The lower yellow part represent cumulates that crystallised from a more evolved magma than later cumulates. The gray stripes at the base of the MCU III and IV mark cumulates that crystallised from new magma (Jensen et al. 2003; Jensen et al., 1993; Nielsen et al., 1996). The graded orange part marks cumulates that crystallised from the magma emplaced at the base of MCU II, together with a contribution from assimilated crustal material (Nielsen et al., 1996; Barling et al., 2000).*

The progressive differentiation and cooling of the magma was accompanied by simultaneous assimilation of the country rocks, either in situ or as xenoliths. The remarkable antithetic relation between the cryptic variations as defined by the composition of cumulus minerals

(An%, Mg# in pyroxenes) and initial $Sr^{87/86}$ ratio shows that the resident magma progressively assimilated country rocks or incorporated large amounts of anatectic melts (Nielsen et al., 1996). $Sr^{87/86}$ generally increases with stratigraphic height in the Bjerkreim Layered Series from 0.705 in MCU II to 0.7081 in the uppermost part of MCU IV (Nielsen et al. 1996). Contamination was probably related to the interaction between the magma occupying the chamber and xenoliths of quartzo-feldspathic gneiss. It is unlikely that the plagioclase-saturated BKSK magmas could have assimilated anorthosite or dry mafic gneisses. According to Tegner et al. (2005) the Sr-isotopic variation in the uppermost MCU IV and mangerite is consistent with a ratio between the rate of assimilation and fractional crystallisation of ~0.2. The data presently available gives no evidence that the quartz-mangerite and the charnockite crystallised from an anatectic roof melt since the $Sr^{87/86}$ of the country gneisses is generally higher (Versteeve 1975). However, a significant fraction of the resident magma during fractionation of the MCU IV and the overlying granitoids stems from assimilation of country rocks (Tegner et al. 2005) and there is a laterally continuous horizon with abundant xenoliths (Michot 1960) near the mangerite – quartz-mangerite boundary.

### *Fluid dynamics of magma emplacement*

Recently the fluid dynamics of magma emplacement, mixing and convection have been extensively studied and simulated in tank experiments (Turner 1973; Huppert & Sparks 1980; Turner & Campbell 1986; Campbell & Turner 1989; Campbell 1996). The means of magma emplacement can vary between two extremes. Repeated inputs of batches of magma may be separated by relatively short periods of cooling and fractional crystallisation. As a result the difference in composition and temperature between the new and resident magma is relatively small even though it may result in conspicuous modal variations, as in Intrusion 4 in the Honningsvåg Intrusive Suite (Lundgaard et al. 2002) and the Rum Eastern layered Series (Dunham & Wadsworth 1978). On the other hand if fractional crystallisation of the resident magma is interrupted infrequently by magma influx, the composition and temperature of resident and new magma can be very different, as in the Main Zone of the Bushveld Complex (Cawthorn et. al. 1991).

The physical properties of the resident magma can also influence the fluid dynamics of magma emplacement. After protracted fractional crystallisation, an increase in viscosity (Si-enrichment) or a change in density of the resident magma can influence the dynamics of magma emplacement. Besides the differences in density and viscosity the fluid dynamics of magma emplacement depend on the momentum of the injected magma. This determines the degree of magma mixing. Magmas can pond on the floor of a chamber or be injected into the chamber by as fountains or plumes. Magma chambers become also become compositionally stratified as a consequence of magma recharge.

Ponding typically occurs when the chamber is filled by a dense primitive magma, with little momentum. Mixing with the overlying lighter and cooler magma is limited as a consequence of the slow influx. A diffusive boundary separates the two magmas and turbulent convection can take place in the lower layer of hot primitive magma as a result of rapid cooling both into the floor and the overlying cooler magma.

If a dense hot magma is forcefully injected into the chamber it can form a turbulent fountain that results in extensive mixing with the resident magma (Sørensen & Wilson 1995; Nielsen & Wilson 1991). When the negative buoyancy overcomes the initial momentum, the new magma will fall back to the base of the magma chamber and flow laterally, away from the source, displacing the pre-existent host magma. This basal flow is composed of hybrid magma formed by the entrainment of the resident magma into the turbulent fountain. As filling continues the hybrid layer can thicken and the fountain will start to entrain the hybrid melt. Eventually the hybrid layer can grow above the top of the fountain and mixing with the host magma is prevented. As a result the degree of mixing in the hybrid layer is controlled by the height of rise of the fountain, which tends to increase with time. The hybrid layer can develop an internal stratification with cooler and compositionally lighter magma overlying hotter and denser magma. Because the destabilising distribution of heat and because the different rates of thermal and compositional diffusion the hybrid layer may break up into a number of double diffusive convective layers.

The opposite case is represented by a plume of light melt injected in a chamber containing magma of comparable viscosity (Sparks et al., 1980). The new input will mix vigorously with the resident magma and the hybrid magma will rise to the top the magma chamber. With continuing inflow of new magma, a stratified layer will build up at the top of the chamber and this will be bounded by a front that moves downwards. As the hybrid layer grows an increasing proportion of the injected light melt will reach the top of the hybrid layer, displacing the previously accumulated hybrid downwards. If the input of new magma is also hotter than the resident magma the chamber will become thermally stratified with hotter hybrid overlying cooler magma. In the case where the resident magma is appropriately stratified in terms of density and temperature, the lighter injected magma will rise through the column of stratified magma and the resultant hybrid can spread out at a level of neutral buoyancy.

During the evolution of the Bjerkreim-Sokndal Intrusion, very different types of magma emplacement and mixing occurred during the influxes that initiated MCU II, III and IV. At a particular stage in the crystallisation of MCU IB the density of the residual magma passed through a maximum when titanomagnetite became a cumulus mineral and thereafter decreased. Therefore, it is postulated that replenishment that initiated the formation of MCU II involved jotunite magma that was both denser and hotter than the resident magma, and hence flowed beneath it. Magma inflow was slow and mixing between the two melts was limited. The elevated evolved magma formed a separate, lower-density layer some distance above the floor of the magma chamber and since it was being heated from below it persisted while the underlying magma increased in density during the fractional crystallisation of the ilmenite leuconorites of MCU II.

Conversely, as suggested by Robins et al. (1997) and Vander Auwera & Longhi (1994) the magma residing on the floor of the chamber after crystallisation of the MCU II cumulates was inferred to be slightly more differentiated but denser than the hot jotunitic magma emplaced at the initiation of MCU III. For this reason they envisaged that the new magma entered the compositionally-stratified chamber as a turbulent plume (Turner & Campbell 1986). Variable degrees of mixing of the inflowing magma in the plume with the resident, differentiated, iron-enriched magma created a range of hybrids which rose to their level of neutral buoyancy and spread out laterally throughout the magma chamber. The thickening layer of hybrid melt sank of toward the magma chamber floor as resident magma was continuously entrained into the plume and possibly by concomitant crystallisation of the resident magma on the temporary floor of the magma chamber, as well as by uplift of the overlying less dense resident magma. Therefore as replenishment proceeded the rate of entrainment of resident magma decreased leading to an increased proportion of new magma in the hybrids generated by mixing. Eventually the hybrid layer reached the floor of the magma chamber so that mixing occurred only within the hybrid layer itself. Moreover it was envisaged that plume gained sufficient momentum during its uprise that it could form a fountain in the overlying buoyant resident magma and mix with it. The resultant buoyant and compositionally-different hybrid magma collected along the top of the hybrid layer. Hence, more primitive magma was added to the central part of the hybrid and it eventually reached the plagioclase-olivine cotectic. The hybrid magma started to crystallise on the colder floor of the magma chamber when the denser resident magma was entirely sucked into the plume. Later on, the resident lighter magma that was displaced upward returned to the temporary floor of the magma chamber and it started to crystallise ilmenite norite and, shortly after, magnetite norite (Chapter 3).

Fractional crystallisation of the resident magma during the formation of MCU III was prolonged enough to attain saturation in magnetite and later Ca-rich pyroxene and apatite. This suggests that the magma density decreased continuously during the crystallisation of MCU III. Based on this consideration Nielsen & Wilson (1991) inferred that the last input of jotunitic magma had a greater density than the residual magma in the chamber. Jensen et al (1993) and Nielsen et al. (1996) inferred on the basis of the cryptic and isotopic variations that the new magma was emplaced as a turbulent fountain. During the initial stage of magma influx, the inflowing magma mixed with residual magma and formed a hybrid which ponded on the deepest part of the floor of the chamber. Meanwhile, the overlying column of resident magma was displaced upwards along the sloping floor of the magma chamber as the primitive magma was injected. The replenishment event resulted in the last expansion of the Bjerkreim magma chamber (chapters 1-2). The stratified resident magma, together with the basal, denser hybrid flowed laterally and upwards from the north into a new, trough-shaped southern extension of the magma chamber to form the Sokndal and Mydland lobes.

### *Hybridisation*

Regressive layered sequences along the bases of MCU II, III and IV beneath the most-primitive cumulates (magnetite-bearing ilmenite leuconorite in MCU II and leucotroctolite in the MCUs III and IV) indicate that replenishment was not an instantaneous process but took place over a particular period of time. These regressive sequences are inferred to have crystallised from hybrid magma formed as a consequence of mixing during replenishment between the newly injected primitive magma and the evolved resident magma.

Mixing during the emplacement of the parental magma of MCU II is considered to have been rather limited. However, a 2 m thick sequence of ilmenite norite found between the low temperature gabbronorite at the top of MCU IB and the higher temperature leuconorite of zone IIa suggests that some mixing did take place between the inflowing and the resident magma (Robins et al., 2008).

The regressive sequence at the base of MCU III is thicker and more persistent along strike. Jensen et al. (2003) inferred that the sulphide-enriched ilmenite orthopyroxenite or melanorite that marks the base of MCU III was related to the initiation of replenishment and the consequent mixing between the inflowing jotunitic magma and more evolved resident magmas. This is succeeded by a general regression in mineral compositions that culminates in the zone IIIb troctolite cumulates on the deeper portions of the floor of the magma chamber. The stratigraphic relations are consistent with prolonged magma-chamber recharge associated with progressive mixing of the inflowing jotunitic magma and the resident, stratified magma whose basal portion was denser than the replenishing magma. As previously described the hybrid layer was stratified term of composition and temperature as a consequence of variable degrees of mixing during magma injection. Following the interpretation given in the chapter 3, leucotroctolite crystallised from the less hybridised central part of the compositionally-stratified hybrid magma on deeper parts of the floor of the magma chamber while sulphide-bearing ilmenite-rich melanorite and, later on, leuconorite crystallised on higher portions of the floor near the top of the gneissic ridge from the upper part of the hybrid layer.

The final major episode of replenishment is characterised by a prolong history of mixing with the hybrid magma pooling along the temporary floor of the magma. Nielsen & Wilson (1991) suggests that the influx of jotunitic magma was associated with the elevation of the contaminated and compositionally-zoned resident magma (chapters 1-2) as well as hybridisation of the inflowing and resident magmas in a turbulent fountain (Jensen et al. 1993, Barling et al. 2000). The modal regression from apatite gabbronorite (phcmiaC) to ilmenite leuconorite phiC/piC terminate with the crystallisation of the high temperature plagioclase-olivine cumulates of zone IVb. This is accompanied by a reverse cryptic variation in mineral compositions and a systematic upward decrease in initial $Sr^{87/86}$ ratio from 0.7061 to 0.7048, demonstrating that the cumulates crystallised from hybrid magmas with an increasing proportion of the inflowing, more primitive jotunite. Hybridisation was envisaged as taking place in a turbulent fountain with the efficiency of hybridisation decreasing with time.

### *Magma stratification*

The stratigraphic organisation of cumulates in the Bjerkreim lobe of the BKSK suggest that the layered series in the BKSK crystallised from a thermally and compositionally stratified magma. Stratification is inferred to be the result of the repeated inputs of jotunitic magma into the magma chamber as summarised above, as well as assimilation of varying amounts of buoyant xenoliths, wall-rocks and mixing between the resident magma and anatectic melts generated at the roof of the magma chamber (Campbell & Turner 1987).

In the lowermost MCUs IA and IB cumulate zones thin to the southwest, indicating that the stratified magma crystallised on a sloping floor dipping inward toward the steep northeast margin of the chamber. The wedge-shaped magma chamber seems to have persisted until the major influx of magma marked by the base of MCU II took place.  This was associated with a lateral enlargement of the chamber and consequently cumulates at the base of MCU III overstep from the uppermost cumulates of MCU IB onto a newly-formed basal contact above country rocks (Robins et al., 2008). Subsequently, the floor of the magma chamber had a saucer-like shape with inward-sloping crystallization fronts. The liquid layers were, of course, horizontal. As a result, cumulates belonging to zone IIc are thicker in the axial region of the intrusion but thin progressively into the western limb of the intrusion before wedging out against the floor of the intrusion. The floor of the magma chamber was not even and a very pronounced reduction in thickness takes place from the axial region towards Teksevatnet in the eastern limb where there was a marked ridge. Further south, on the opposite side of the ridge, MCU II increases in thickness before it wedge out against marginal zone rocks in contact with the floor of the intrusion. The cumulates of MCU II lack cumulus titanomagnetite and contain a lower amount of FeO than the inferred parental magma (Robins et al., 1997). For this reason it was envisaged that the resident magma differentiated towards increasing iron and density (at least in the lower portion of the magma chamber) during fractional crystallisation.

Less pronounced lateral variations in thickness suggest that the topography on the magma chamber floor had become more subdued during the crystallisation MCU III. Zone IIIa leuconorite and zone IIIb leucotroctolite, however, are thicker in the axial trough and they thin to the southwest. Zone IIIa is discontinuously present above the gneissic ridge while higher-temperature leucotroctolite is absent for a distance of more than 6000 m along strike, from a point north of Teksevatnet to the deeper part of the shallower eastern flank (chapter 3).

During fractional crystallisation of the upper part of MCU III horizontal liquid layers were crystallising magnetite norite of zone d in the central, lowest part of the floor of the chamber, while apatite gabbronorite of zone e was crystallising on higher parts of the floor. Based on the angle of the discordance between the zone d/e boundary and the base of MCU IV, Nielsen & Wilson (1991) suggest that the floor of the BKSK magma chamber during crystallization of zone IIIe sloped inwards at about 8-10°.

Before the magma parental to zone IIId was completely consumed by fractional crystallisation the emplacement of denser magma at the base of MCU IV displaced the stratified column of resident magma upwards. Fountaining of hotter and denser magma, into the less-evolved lowest levels of the resident magma, created a hybrid that ponded in the deeper portions of the saucer-shaped floor of the magma chamber. The hybrid magma crystallised the leuconorite of zone IVa quite rapidly. The thickness of zone IVa decreases away from the axis of the magma chamber and it seems likely that this unit evened out the topography of the magma-chamber floor. This led to the formation of an almost horizontal floor by the time zone IVb started to crystallize. By the time replenishment ceased, the new magma had spread out across the entire floor. The constant thickness of zone IVb along strike, from the flanks of the intrusion to its centre, implies accumulation on a floor which was very close to horizontal. The rather constant thickness of zone IVc indicates also that the magma-chamber floor remained essentially horizontal during its crystallization.

A major enlargement of the Bjerkreim chamber took place in response to the magma influx that initiated MCU IV. The first magma to come into contact with the floor at the leading edge of the expanding magma chamber was the more evolved and buoyant magma at the top of the stratified magma column. As the stratified magma column was elevated and the newly formed floor was gradually flooded by more primitive magma (chapter 2). The stratified resident magma, together with the basal, denser hybrid flowed laterally and upwards from the north into a new, trough-shaped southern extension of the magma chamber. The onlap of successive zones, characterised by the same cumulus assemblages as in the MCU IV in the Bjerkreim lobe, from the axial onto the more distal parts of the floor of the Sokndal Lobe supports the hypothesis that the magma was compositionally zoned upon emplacement (chapter 1). The absence of cumulates equivalent to zone IVa in the Sokndal lobe implies that the chamber expansion occurred after the crystallisation of the latter cumulates in the deeper part of the Bjerkreim chamber. The dense magma parental to zone b started to crystallise in the lowermost portion of the Sokndal lobe while at the same time zones c, d and e-f crystallised higher up along the inwardly sloping floor in both flanks of the chamber.

Excluding the basal regressive intervals, at the base of the MCU III and IV, the degree of magma differentiation increased upwards through the column of magma. The stratigraphic relationships suggest that the magma was stably stratified in term of density and temperature across the floor of the chamber during fractional crystallisation and large-scale magma convection involving transport of crystals, nucleated near the roof, to the floor of the magma chamber can be excluded (Wager & Brown, 1968; Irvine et al., 1998; Maaløe, 1976). However, the presence of cross-lamination, erosional unconformities and trough layers as described in chapter 3, suggest that compositional convection driven by density differences arising from crystallisation along inclined surfaces (McBirney et al. 1985, Higgins, 2005; Turner, 1973) was an active process during magma crystallisation. It is envisaged that the magma was discontinuously stratified, and consisted of horizontal, independantly-convecting and internally homogeneous liquid layers separated by relatively-sharp, diffusive interfaces.

Episodes of intense magma convection seem to follow periods of magma influx. In chapter 3 convection is envisaged as being particularly vigorous close to the margins of the chamber due to an inwardly sloping floor and relatively high cooling rates. Experimentally the same scenario was reproduced by Turner (1973) using stratified aqueous solutions in a tank with a sloping boundary. The result of the experiment showed that due to the rapid cooling the liquid in the shallower portion of the floor became denser than the liquid in the deeper part. Consequently the denser fluid flows down the floor toward the bottom of the tank. It is proposed that formation of strongly modally layered ilmenite-rich sequences was the result of differential accumulation (chapter 4) of the heavier mafic minerals due to enhanced convection in a wedge-shaped termination of a magma layer against a thin sequence of cumulates on a sloping magma chamber floor. At the same time less-dense plagioclase was carried out toward the central region of the magma chamber.

### *Trapped intercumulus liquid*

As demonstrated by Barnes (1986) the observed compositions of cumulus minerals can deviate from their original liquidus compositions as they re-equilibrate with trapped intercumulus melt. The result of the re-equilibration is a change towards more evolved (lower-temperature) compositions, termed trapped liquid shift. These changes are comparable to those of fractional crystallisation and therefore indicate that trapped liquid shift can be an important process in mafic intrusions. Barnes showed that a shift of 10 mole% in Mg# numbers of olivine and orthopyroxene can be achieved by crystallisation of 30% of trapped intercumulus liquid. The fundamental assumption of Barnes's model is that the intercumulus liquid is trapped and crystallises in equilibrium with the cumulus minerals formed by fractional crystallisation. The amplitude of the trapped liquid shift depends on mineral mode and the amount and composition of the trapped liquid. Hence, the higher the initial porosity and the lower the mode of the mineral in question, the larger will be the trapped liquid shift.

Crystallisation of intercumulus liquid produces postcumulus overgrowths on the original cumulus crystals. Diffusion of Mg and Fe is typically relatively fast in olivine and orthopyroxene whereas on the time scales of cooling of large mafic intrusions the slower migration of Ca-Al and Na-Si in plagioclase leads to compositionally zoned plagioclase grains (Morse, 1984).

In magma chambers the amount of melt trapped in cumulates is related in a general way to the rate of cooling and crystallisation. Extremely slow cooling and crystallisation permits extensive diffusive exchange between floor cumulates and overlying magma and extreme adcumulates consisting of minerals with uniform, liquidus compositions can result. Stronger cooling and more rapid crystal accumulation favour the retention of melt between the accumulating crystals and limits the degree of chemical interchange between the pore melt and the overlying magma reservoir. It is to be expected that large differences in the composition of originally uniform cumulus minerals can arise from the marginal more rapidly cooled parts to the inner slowly cooled parts of a magma chamber (Charlier et al. 2007).

Evidence of trapped liquid shift is presented in chapters 1-2. The anomalously high amount of trapped liquid in parts of the Sokndal lobe is ascribed to rapid heat loss through a thin, sequence of cumulates residing on a cool floor of older anorthosite. Similarly in chapter 3 elevated amounts of intercumulus melt are inferred to be present in cumulates at the base of the MCU III in the north eastern flank of the Bjerkreim lobe due to the vicinity of the colder gneissic floor. In both cases elevated cooling and more rapid crystal accumulation that prevailed in these locations close to the margins of the intrusion were assumed to be responsible for the abundant trapped melt and consequent re-equilibration of the cumulus minerals.

Several factors can reduce the amount of intercumulus melt trapped in cumulates, such as compaction (Sparks et al. 1985; Shirley 1986) and compositional convection (Tait et al. 1984; Tait & Jaupart 1992), as well as exchange with the main magma reservoir by diffusion (Morse, 1986; Campbell,1987). None of these processes seem to have affected the initial amount of intercumulus liquid in the investigated portions of the Bjerkreim-Sokndal intrusion. In some mafic cumulates the amount of trapped melt is inferred to have been reduced by the presence of small ilmenite crystals occupying the spaces between larger pyroxenes and plagioclases. This textural effect has hitherto not been generally considered in layered intrusions and differences between adjacent mafic and felsic cumulates commonly have been ascribed to variations in degree of compaction.

## Post cumulus deformation

Modal layering is the most prominent planar structure in the BKSK. It is generally assumed that, at the time of crystallisation, the modal layering was sub-horizontal and dipped inwards at angles of 2 to 6º into a broad saucer-shaped magma chamber (Nielsen & Wilson, 1991). The present disposition of modal layering in the BKSK is in a deep syncline that branches in the south around a dome cored by the Åna-Sira anorthosite into two smaller synclines forming the Sokndal and Mydland lobes to the south and south-east respectively (Figs. 1 & 2). Deformation of the layered series into the deep, doubly plunging syncline is the result of postmagmatic gravitational collapse into underlying and less-dense anorthosite and gneisses (Paludan et al., 1994) in connection with the final stage of diapiric emplacement of the adjacent anorthosite plutons (Bolle et al., 2000; 2002).

The gravitational deformation is recorded in the rocks by linear and planar fabrics defined by the orientation of recrystallised aggregates of mafic minerals such as olivine, pyroxenes and Fe-Ti oxides, which are assumed to be proportional to the amount of strain which the rocks have suffered. Based on the observed planar and linear fabrics it is envisaged that the emplacement and crystallization of successive magma pulses took place in a magma chamber that was simultaneously deforming by subsidence of its floor (Bolle et al., 2000). Based on the variations in thickness of MCU IV, Nielsen & Wilson (1991) suggested that that the floor sank faster in the axial region than in the flanks. Deformation of the BKSK was not the result of simple, inverted diapirism centred on a point but was more similar to an elongated trough that was sinking faster in a central area, beneath the quartz mangerite (Paludan et al., 1994). The increasing amount of deformation from the southern margin toward the mangerite observed in the Sokndal lobe (chapter 1) is in accord with the convergent flow towards a central zone of subsidence characterised by steep lineations, as postulated by Bolle et al. (2002).

The thicker sequence of layered rocks in the Sokndal lobe compared to the equivalents in the Bjerkreim lobe is inferred to be the result of sinking of the magma-chamber floor during crystallisation of the stratified magma due to gravity-induced deformation combined with displacements along a normal fault.

The gravitational deformation of the BKSK was protracted in time. The Eia-Rekkefjord “intrusion” (Duchesne et al., 1974, Wiebe 1984), a younger composite sheet emplaced mainly along the base of the Sokndal lobe, has been affected by this deformation (chapter 1). Primary layering and a tectonic foliation in the ER are both folded around the syncline defined by the modal layering within the BKSK. It is envisaged that the Eia-Rekkefjord intrusion originally consisted of a number of sub-horizontal differentiated sills and it acquired its present foliation during the gravitational sinking of the Bjerkreim-Sokndal intrusion. However, a younger generation of jotunitic to quartz mangerite minor intrusions has been recognised that cut across the synclinal hinge of the Sokndal lobe and hence postdates the deformation.

## Conclusions

Physical and chemical processes inferred from investigations in the shallower north eastern flank of the Bjerkreim lobe and in the southern Sokndal lobe have been summarised and discussed in relation to processes previously recognised in central and western parts of the larger Bjerkreim lobe of the Bjerkreim-Sokndal Layered Intrusion, South West Norway. It is concluded that:

- As consequence of periodic magma replenishment, assimilation of xenoliths, as well as mixing between the resident magma and anatectic melts the magma within the chamber became thermally and compositionally stratified. The stratigraphic relations just above the base of MCU III in the Bjerkreim lobe of the BKSK appear to be consistent with prolonged magma-chamber recharge associated with progressive mixing of the inflowing jotunitic magma and the resident, stratified magma whose basal portion was denser than the replenishing magma. Mixing between the injected buoyant plume and the resident magmas created layers of compositionally-different hybrids characterised by different proportions of the two melts and consequently different densities and temperatures. The distribution and crystallisation of these liquid layers was controlled by the morphology of the temporary floor of the magma chamber, the lower layers being absent above elevated portions.

- The density of the resident magma is postulated to have been reduced by prolonged fractional crystallisation of magnetite during the formation of MCU III and therefore the influx of magma that initiated MCU IV formed a turbulent fountain as it entered the magma chamber. It is inferred that during the last major replenishment of the Bjerkreim chamber, the stratified resident magma was displaced upwards and laterally, into a new trough-shaped southern extension that eventually formed the Sokndal lobe. The Marginal Zone in the Sokndal lobe crystallised during intitial magma emplacement. The leuconoritic cumulates of zone IVa crystallised only in the central deeper part of the saucer-shape chamber in the Bjerkreim lobe in response to mixing between resident differentiated magma and inflowing, denser and more primitive magma. Leucotroctolite of zone b were the first cumulates to crystallise in the Sokndal lobe after the influx of new magma had ended. The onlap of successive cumulate zones from the axial onto the more distal parts of the floor in the Sokndal Lobe of the intrusion is important evidence that the magma was compositionally stratified upon emplacement.

- Penetrative convection is excluded on the basis of the consistent evidence of magma stratification. However, it is inferred that independently-convecting and internally homogeneous liquid layers separated by relatively sharp, diffusive interfaces existed as indicated by the presence of cross-lamination, erosional unconformities and trough layers. Convection driven by density differences arising from cooling and crystallisation along inclined surfaces is envisaged to have been an important process during magma crystallisation.

- The anomalous appearance of apatite in high-temperature cumulates in the Sokndal lobe and in the Tekse area is inferred to be a consequence of high proportions of trapped melt in the cumulates. Rapid cooling and crystal accumulation in these marginal portions of the BKSK magma chamber due to the vicinity of cooler country rocks, anorthosite in the Sokndal lobe and gneisses in the Tekse area, led to enhanced trapping of melt in the crystallising cumulates. The amount of intercumulus melt in some cumulates was dependent on the texture; small ilmenite crystals could occupy spaces between the larger silicate crystals and hence reduce the initial pore volume. Preservation of olivine only in Fe-Ti oxide rich layers in zone b cumulates in the Sokndal lobe is inferred to be one consequence of reduced initial porosity in the cumulates due to an elevated modal proportion of small crystals of oxides. As a result, the amount of trapped liquid was considerably lower than in the associated plagioclase-rich cumulates that lost all of their original olivine by peritectic reaction. In the Sokndal lobe the amounts of trapped melt in the Layered Series decreases upward from the base, suggesting that the rate of cooling into the floor anorthosite decreased as the thickness of the cumulates increased.

- Deformation of the BKSK into a doubly plunging syncline may have started during the crystallisation of the Layered Series and was so protracted that the younger Eia-Rekkefjørd intrusion was also affected. Deformation was the result of postmagmatic gravitational collapse into underlying, ductile, less-dense host rocks concurrent with the final stage of diapiric emplacement of the adjacent anorthosite plutons. The Sokndal LS is 3200 m thick in the axial region of the syncline, twice as much as in the Bjerkreim Lobe. The increased thickness is inferred to be a consequence of subsidence of the floor during crystallisation of the stratified magma, as well as subsequent deformation and tectonic thickening during gravitational collapse.

- MCUs III and IV, uppermost in the Bjerkreim Layered Series, contain a similar sequence of cumulates and cryptic variation. Basal regressions due to crystallisation during magma emplacement and progressive hybridisation culminate with the crystallisation of leucotroctolite of zone b. In MCU III the sequence continues with ilmenite leuconorite (zone c), ilmenite-magnetite leuconorite (zone d) and apatite-bearing gabbronorite (zone e) before fractional crystallisation was interrupted by the last input of magma. MCU IV contains additional, more-evolved cumulates. The layered series in the Sokndal lobe contains a sequence of cumulates similar to those of MCU IV in the Bjerkreim Lobe. Plagioclase varies in composition from An49 in zone b to An30 (antiperthite) in the Transition Zone. Mangerite and quartz mangerite contain exsolved ternary feldspar (mesoperthite). Olivine is magnesian ($Fo_{76-70}$) in zone b but much more iron rich when it reappears in the Transition Zone ($Fo_{44}$) and it becomes rapidly enriched in iron upwards into the mangerite where it reaches Fo9. Cumulus Ca-rich pyroxene appears comparatively late in the LS and varies in Mg#cpx from 74 at the base of zone e to 21 in the mangerite. Ca-poor pyroxene ($Mg\#opx_{75-45}$) is mainly orthopyroxene but is inverted pigeonite in zone f. The content of hematite in ilmenite increases through the ilmenite norite to a maximum of 26% in the basal part of the ilmenite-magnetite norite and thereafter decreases. The Sokndal Layered Series appears to be the product of the protracted and uninterrupted fractional crystallisation of a jotunitic (hypersthene monzodiorite) parental magma. The more sodic plagioclases in BKSK are generally antiperthites and prolonged fractional crystallisation resulted eventually in the crystallisation of ternary feldspar, consistent with the parental magma being dry and K-rich.

- The initial increase of hematite content in the ilmenite at the base of the Sokndal Layered Series peaks in the ilmenite leuconorite of zone c. This suggest that the oxygen fugacity initially increased with fractional crystallisation, but then fell after the appearance of cumulus magnetite at the base of zone e, as expected during fractional crystallisation in a system closed to oxygen.

- One of the most distinctive features of the Layered Series in the Sokndal lobe, and the Bjerkreim-Sokndal Intrusion in general, is the occurrence in the highest temperature cumulates of relatively magnesian olivine together with plagioclase of intermediate composition. This, and the delayed appearance of Ca-rich pyroxene on the liquidus, is a typical trait of rocks associated with Proterozoic massif-type anorthosites. The transition from the crystallisation of orthopyroxene to pigeonite also took place at a considerably lower Mg/Mg+Fe ratio than in most other well known layered intrusions of basaltic parentage.

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