

# Magma influx and mixing in the Bjerkreim–Sokndal layered intrusion, South Norway: evidence from the boundary between two megacyclic units at Storeknuten

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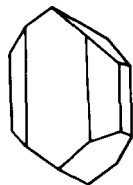
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## LITHOS



### ABSTRACT

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The Bjerkreim–Sokndal layered intrusion belongs to the Proterozoic anorthositic province in the Rogaland area of southern Norway. The northwestern part of the intrusion comprises a ca. 6 km-thick Layered Series made up of megacyclic units (MCU) arranged in a syncline; each megacyclic unit reflects the influx of fresh magma into the chamber. The boundary between megacyclic units III and IV has been studied in detail at Storeknuten on the southern flank of the syncline. The megacyclic units can be subdivided into a series of cumulate stratigraphic zones; the interval from the top of zone IIIe to the base of zone IVd is exposed in the Storeknuten area. Modally layered plagioclase–hypersthene–ilmenite–magnetite–augite–apatite cumulates belonging to zone IIIe are overlain by 30 m of massive plagioclase-rich rocks (commonly containing ilmenite and/or hypersthene) constituting zone IVa. The entry of cumulus olivine defines the base of zone IVb (dominantly plagioclase–olivine–ilmenite cumulates) which is about 100 m thick. Many of the olivines are partly or completely replaced by Ca-poor pyroxene/Fe–Ti oxide symplectites. This massive leucotroctolitic zone is overlain by modally layered, laminated plagioclase–hypersthene–ilmenite cumulates of zone IVc. The successive entry of magnetite, apatite (accompanied by Ca-rich pyroxene) and inverted pigeonite defines zones IVd, e and f respectively. The entry of K-feldspar (accompanied by Fe-rich olivine) defines the base of a jotunitic transition zone which passes upwards into mangerites and quartz mangerites.

There is a compositional regression through zone IVa. The upper part of zone IIIe has Ca-poor pyroxene with about En<sub>68</sub>, plagioclase with An<sub>44–48</sub> and a Sr-isotope ratio of about 0.7062, while the base of zone IVb has olivine with Fo<sub>75</sub> together with En<sub>78</sub>, An<sub>53</sub> and 0.7050 respectively. Similar reversals are shown by the minor element compositions of plagioclase and Fe–Ti oxides. Sr-isotope ratios increase systematically up through zone IVb (reaching 0.7058 in zone IVd) while An% and Sr in plagioclase and Ni and Cr in Fe–Ti oxides decrease. Olivine compositions vary unsystematically and are believed to have changed their Fe:Mg ratios as a result of trapped liquid shift.

The magma residing in the chamber when the influx at the base of megacyclic unit IV took place was compositionally zoned, and assimilation of gneissic country rock at the roof had resulted in the Sr-isotope ratio increasing up through the magma column. The new magma had a Sr-isotope ratio of about 0.7050 while the resident magma had a ratio of 0.7062 at the floor, increasing upwards. The new magma mixed with the basal layer(s) of the compositionally zoned resident magma and crystallization of this hybrid magma during influx and mixing produced the compositional regression in zone IVa. When magma influx

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ceased, olivine-bearing rocks began to crystallize at the base of zone IVb. The leucotroctolites at the base of this zone are the most primitive rocks in the entire intrusion. The systematic increase in Sr-isotope ratios up through zone IVb resulted from progressive mixing between new and resident magma. This mixing either took place during magma influx or by the progressive mixing of overlying resident magma layers during crystallization.

Calculations based on geochemical modelling, the thickness of cumulate stratigraphy repeated and Sr-isotope ratios indicate that the new magma influx had a thickness of 350–500 m in the Storeknuten section and that the leucotroctolites of zone IVb represent about 20–30% crystallization of this influx.

## Introduction

Since the pioneering work by Michot (1960) studies in the Rogaland area of southern Norway have contributed to the debate concerning the origin of anorthosites and related rocks (e.g. Michot and Michot, 1969; Duchesne and Demaiffe, 1978; Demaiffe and Hertogen, 1981; Duchesne et al., 1985, 1989). The Bjerkreim–Sokndal layered intrusion (BKSK) (Fig. 1B) has played an important role in this debate, since the entire span of igneous rock types normally associated with anorthosites occur in the intrusion (Michot, 1965; Wiebe, 1984; Duchesne, 1987). BKSK is, however, also well suited for the study of magma chamber processes.

Michot (1960, 1965) divided the northwestern part of the BKSK (the Bjerkreim lobe) into five major layered units, which he called rhythmic units. These rhythmic units have been interpreted by Duchesne (1972) as reflecting separate influxes of magma into the chamber. Lateral variations related to the boundary between two of these rhythmic units (III and IV) have recently been described by Nielsen and Wilson (1991). This article concentrates on a detailed profile across this boundary. A combination of field and petrographic observations, microprobe analyses, chemical analyses of mineral separates and Sr-isotope analyses allows discussion of a wide variety of magma chamber processes, including the mechanism of magma influx, the role of magma mixing and the contribution of assimilation.

## The Bjerkreim–Sokndal intrusion

The BKSK massif extends for about 40 km from Bjerkreim in the northwest to Sokndal in the south and was emplaced into granulite facies gneisses about 955 million years ago (Pasteels et al., 1979). The massif is younger than the Egersund–Ogna an-

orthosite (Duchesne, 1970) from which it is separated by a thin zone of migmatitic gneisses and older than anorthosites and leuconorites (Helleren lobe) of the Haaland–Helleren massif (Michot, 1961).

The Bjerkreim lobe of the BKSK (Fig. 1B) is made up of lithologies ranging from anorthosite to quartz-mangerite and dominated by leuconorite. A series of layered units define a syncline that plunges SE at about 35°. Michot (1960) described the five major rhythmic units of the Bjerkreim lobe as having an anorthositic or leuconoritic base and becoming more evolved upwards. The uppermost unit grades into a zone of monzonoritic (jotunitic) rocks which form a transition to massive mangerites and quartz mangerites. Michot recognised several distinctive zones, including an olivine-bearing leuconorite (the Svaalestad unit) near the base of rhythmic unit IV. A similar, though less continuous, olivine-bearing unit occurs at the base of rhythmic unit III (Nielsen and Wilson, 1991). The sequence from the base of the lowermost anorthositic rocks (Unit IA in Fig. 1B) to the top of the jotunitic transition zone constitutes the Layered Series of the Bjerkreim lobe. The Layered Series has a thickness of about 6 km measured along the axial surface of the syncline, thinning along the limbs partly because the lower units wedge out (Fig. 1B). The BKSK and its envelope are cut by a series of broadly monzonoritic dykes (Duchesne et al., 1985) which are not shown in Fig. 1B.

The geology of the Bjerkreim lobe is currently being investigated by groups from the Universities of Bergen (led by B. Robins), Liège (J.C. Duchesne) and Aarhus (J.R. Wilson). Work in progress has indicated that Michot's subdivision into five rhythmic units requires revision, particularly in the lower part of the Layered Series. The boundary between units III and IV, however, does not require significant modification, and Michot's numbering system is used in this article. The term megacyclic

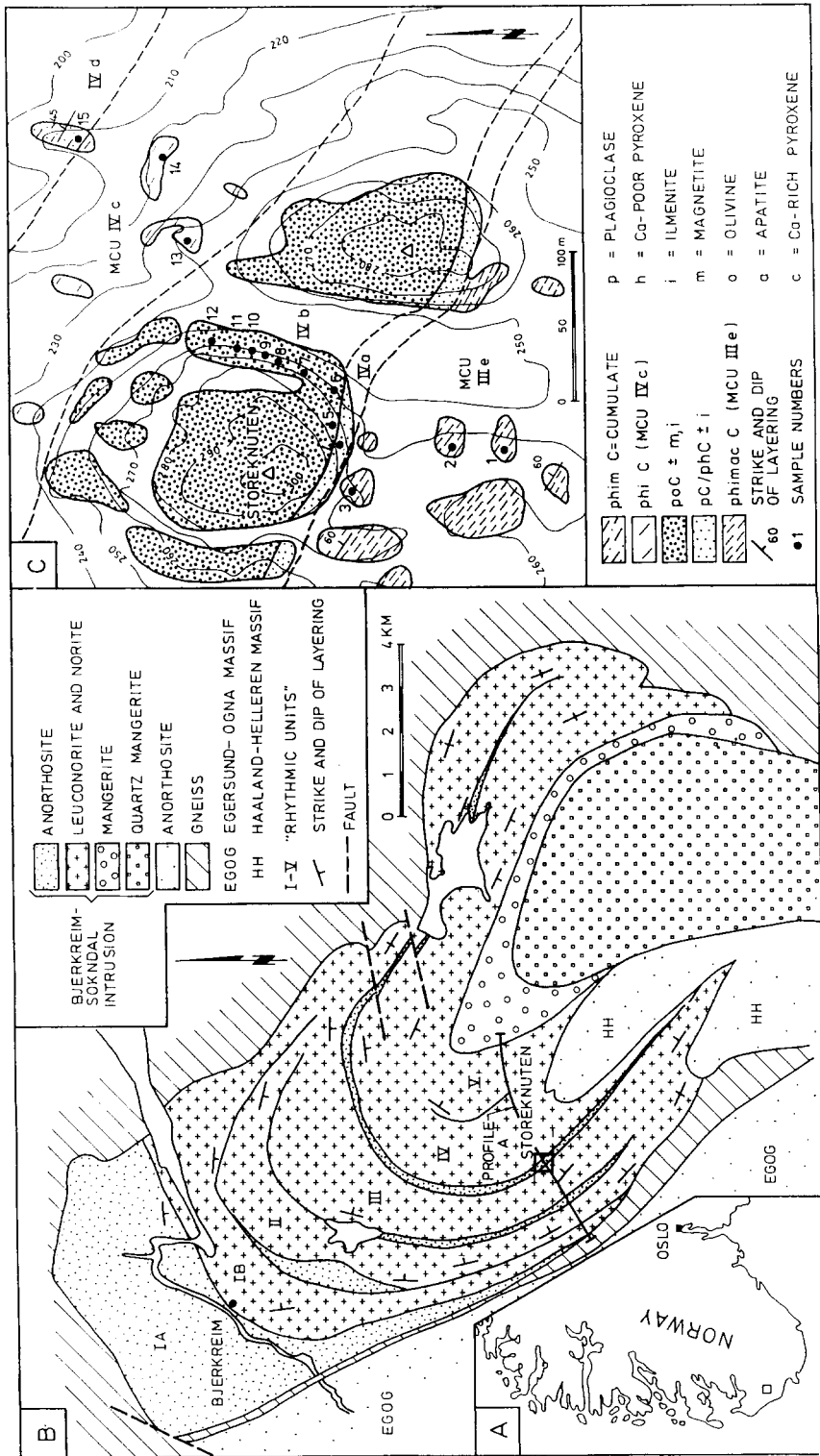


Fig. 1 (A). Location of Fig. 1B in southern Norway. (B). Simplified geological map of the Bjerkreim-Sokndal intrusion, based on fig. 5.8 in Duchesne (1987). The Layered Series consists of five "rhythmic units", referred to here as megacyclic units (MCU). The lithological and cryptic variation along profile A is shown in Fig. 2. The location of Fig. 1C (Storeknuten, in the central part of profile A) is outlined. (C). Geological map of the Storeknuten area showing the distribution of major outcrops, lithologies, strike and dip of layering, and sample locations. The legend explains the abbreviations used for the cumulate nomenclature in the text.

unit (MCU) (Irvine, 1982) is used in this article for the rhythmic units of Michot.

Most of the Layered Series rocks are characterised by igneous lamination and modal layering which are best developed in the upper parts of the MCU's. Cumulate textures can usually be recognised in the field, but in thin section it is apparent that the rocks have recrystallised [referred to as protoclasts by Michot (1965)]. In the limbs of the Bjerkreim lobe there is commonly a steep foliation, essentially in the plane of the layering, related to post-emplacement deformation of the complex. Possible changes of thickness of megacyclic units during deformation are not believed to have been important and have been disregarded here. The MCU's can be subdivided into a series of zones on

the basis of their cumulus mineral assemblages. The thicknesses of the various zones shown in Fig. 2 apply to a profile on the southern limb of the syncline (Fig. 1B) from the country rock contact to the entry of K-feldspar which defines the base of the jofunitic transition zone. The thicknesses of the zones up to MCU IVd are based on profile A in Fig. 1B, but because of poor exposures the thickness data above this are based on exposures up to about one kilometer to the northwest. The boundary between MCU's III and IV at Storeknuten is located near the middle of profile A.

### Profile A

A marginal zone of coarse grained, massive ilmenite-bearing leuconorites ( $\pm$  magnetite), in which orthopyroxene is usually poikilitic, occurs in contact with the country rock gneisses at the base of profile A (Fig. 2). These marginal leuconorites are characterised by the plagioclase being antiperthitic and by the presence of apatite and variable amounts of interstitial quartz. After about 200 m the rocks develop an igneous lamination with prismatic orthopyroxene, and modal layering is sporadically present. These phiC (see Fig. 1C for explanation) are referred to MCU II which has a thickness of about 550 m. The laminated leuconorites at the top of MCU II are overlain by piC and pihC belonging to MCU IIIa. MCU IIIa is dominantly massive, but contains several ilmenite-rich lenses and layers which are usually slumped. MCU IIIa is usually overlain by massive leucotroctolites comprising MCU IIIb in which Ca-poor pyroxene and/or magnetite are locally additional early phases. However, in profile A no olivine has been found in this interval and MCU IIIb is included in MCU IIIa in Fig. 2, with a combined thickness of about 90 m.

The entry of cumulus Ca-poor pyroxene, which coincides with the development of an igneous lamination and sporadically developed modal layering, defines the base of MCU IIIc which has a thickness of 110 m in profile A. The arrival of magnetite as a cumulus phase defines the base of MCU IIIe, and the entry of apatite defines MCU IIIe. MCU IIIe and IIIe are 430 m and 110 m thick respectively. The first occurrence of apatite generally coincides with that of Ca-rich pyroxene. MCU IIIe and MCU IIIe are laminated and are generally characterised by well developed modal layering.

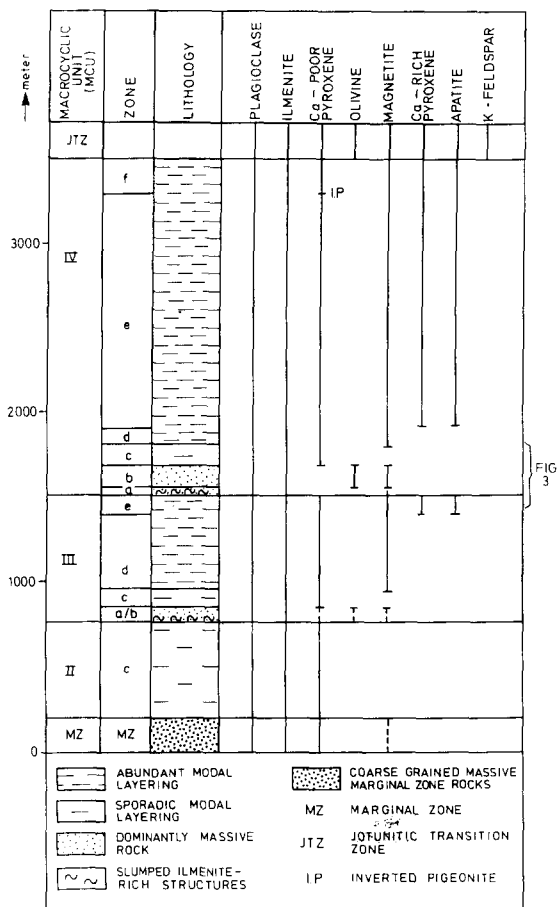


Fig. 2. Zonal subdivision and lithology of megacyclic units in profile A (Fig. 1B) based on cumulus mineral assemblages. Continuous vertical lines = cumulus status; dashed = cumulus status uncertain.

The boundary between MCU's III and IV and the lower part of MCU IV are exposed at Storeknuten and are described in detail below. The sequence of cumulate zones in the lower part of MCU IV is essentially the same as in MCU III; it is noteworthy that MCU IVa and b are thicker than their counterparts in MCU III, while MCU IVc has similar thicknesses to MCU IIIc in profile A. MCU IV reaches more evolved compositions than MCU III; a thick sequence (ca. 1300 m) of modally layered gabbronorites (phimcaC) belonging to MCU IVe is overlain by inverted pigeonite-bearing rocks, defining MCU IVf (ca. 210 m). The subsequent presence of perthitic K-feldspar, which roughly coincides with the entry of Fe-rich olivine, defines the base of the jotunitic transition zone (Duchesne et al., 1987) which grades into massive mangerites and quartz mangerites. Michot (1960) recognised a fifth rhythmic unit in the area near the top of profile A, as shown in Fig. 1B. Our field and laboratory studies have failed to confirm the presence of a MCU V in this part of the intrusion and we consider that MCU IV grades into the overlying mangerites through the jotunitic transition zone.

#### *The Storeknuten profile*

The section exposed at Storeknuten (Fig. 1C) has been chosen as the type locality for the boundary between MCU III and MCU IV because of good exposure, representative development and accessibility. Figure 3 shows the lithological variation in a ca. 300 m thick section, together with compositional variations of the major silicates. These variations are based on 31 samples with an average sample density of about 1:10 m. From the base of MCU IVa to the top of MCU IVb the sample density is about 1:6 m.

The two cumulus pyroxenes in the modally layered, laminated rocks of MCU IIIe have fairly constant compositions [hypersthene with Mg#*opx* (= 100Mg/(Mg + Fe)) values of 68–70 and augite with Mg#cpx72–74]. In a single sample at the top of MCU IIIe the pyroxenes show a reversal to considerably more primitive compositions (Mg#*opx*74; Mg#cpx79). Plagioclases show erratic variations at the top of MCU IIIe (An43–49) but the most primitive composition is again in the uppermost sample. This zone is overlain by about 30 m of plagioclase-rich cumulates (dominant variations between pC

and piC, with magnetite and Ca-poor pyroxene also occurring as sporadic early phases) which constitute MCU IVa. Ilmenite-rich lenses and layers, which in many cases are slumped, are a characteristic feature of MCU IVa. Plagioclase compositions are in the range An45–49, and a Ca-poor pyroxene which is interpreted to be a cumulus phase in sample 4 has Mg#72.

The predominantly massive olivine-bearing rocks of MCU IVb [the Svaalestad unit of Michot (1960)] which form the summit of Storeknuten contain the most primitive mineral compositions in the studied sequence. Olivines at the base and top are the most magnesian (Fo75) while there is a somewhat erratic variation towards more evolved compositions (reaching Fo67) near the centre. The Ca-poor pyroxenes (in which the most primitive composition reaches Mg#78) are of bronzites in corona structures around olivines; the more or less parallel variation of Fo in olivines and Mg# in Ca-poor pyroxenes in Fig. 3E suggests that they are essentially in equilibrium. The original olivine in MCU IVb has commonly been partly or completely replaced by a symplectic intergrowth between Ca-poor pyroxene and Fe–Ti oxide, as described by Barton and Gaans (1988). The compositions of plagioclases (An48–53) vary less systematically than those of the mafic silicates in MCU IVb, but the most primitive composition is at the base. The mineralogical composition of most of the BKSK Layered Series rocks is notably anhydrous, but MCU IVb (and MCU IIIb) are characterised by small amounts of biotite and hornblende.

There are two types of magnetite in MCU IVb. One type occurs as fairly large grains (ca. 1 mm) which are about the same size as the ilmenites. This magnetite, which is considered to be a cumulus phase, contains two generations of spinel exsolution, the first of which occurs as coarse lenses. Thin exsolution lamellae of ilmenite can be observed in some grains. A rim of spinelliferous ilmenite is always developed at the contact between the cumulus magnetite and the cumulus ilmenite, indicating subsolidus readjustment of chemical composition as described by Duchesne (1972). The second type of magnetite occurs in the Ca-poor pyroxene–Fe–Ti oxide intergrowths and is usually devoid of spinel or ilmenite lamellae. Its amount varies considerably, depending on the degree of replacement of the olivines.

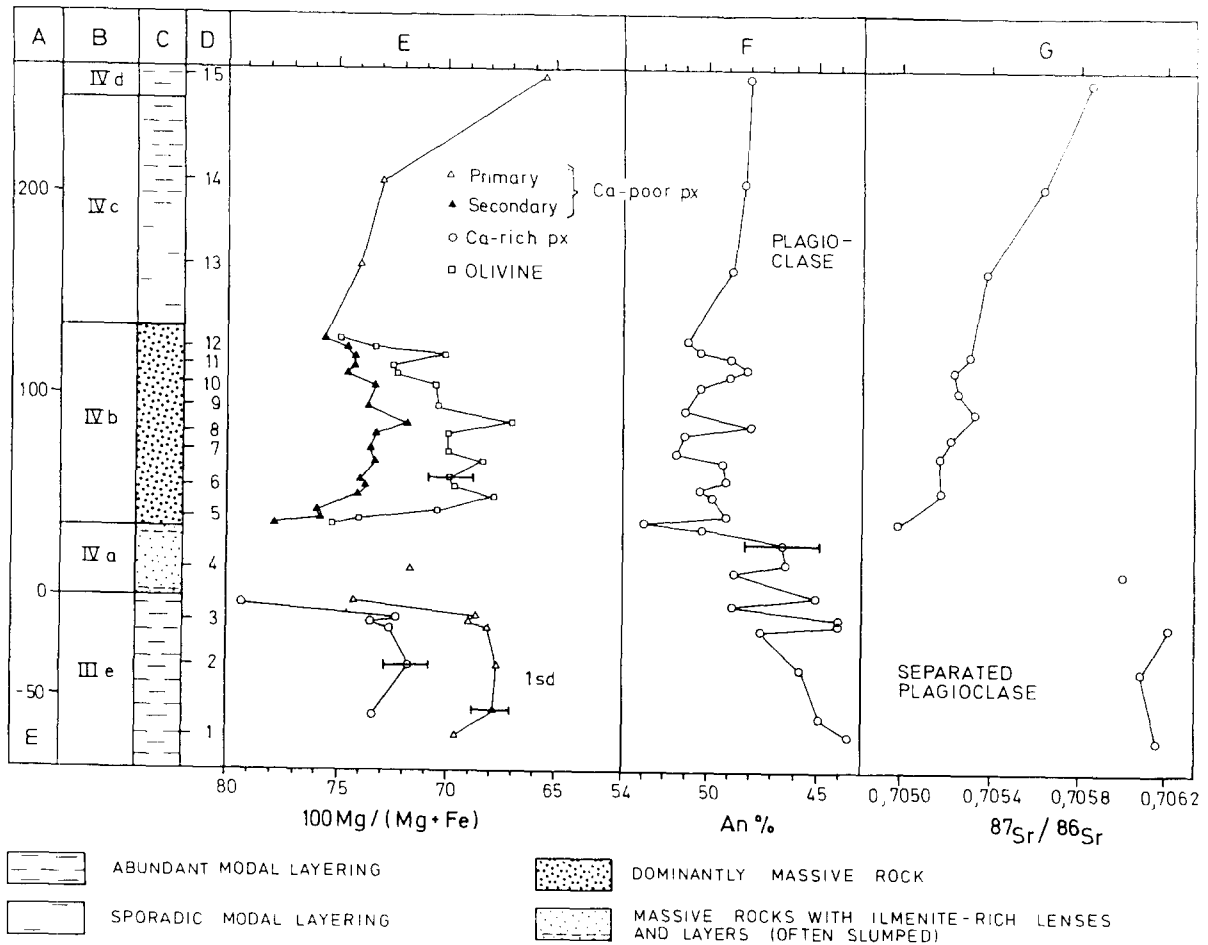


Fig. 3. Compositional variations across the boundary between megacyclic units III and IV at Storeknuten. (A). Thickness in meters above and below the MCU III/IV boundary. (B). Cumulate stratigraphic zonal subdivision. (C). Lithology. (D). Sample numbers of rocks from which minerals have been separated. Locations are shown on Fig. 1C. (E). Variation of  $100\text{Mg}/(\text{Mg} + \text{Fe})$  ratios in Ca-poor pyroxene, Ca-rich pyroxene and olivine. The Ca-poor pyroxenes analysed from MCU IVb are of bronzites which are a reaction product from olivine. They are commonly intergrown with Fe-Ti oxides. (F). Plagioclase compositions. (G).  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios in separated plagioclases.

MCU IVb is overlain by laminated phiC that constitutes MCU IVc in which magnetite is absent. Magnetite reappears, however, as a cumulus phase after about 115 m, defining the base of MCU IVd. Modal layering is sporadically present in the lower part of MCU IVc, but becomes well developed in the upper part and in MCU IVd. The three samples from these zones show a trend of normal fractionation with  $\text{Mg}\#\text{opx}$  varying from 74 to 66 while the plagioclase composition remains fairly constant at An48–49.

$^{87}\text{Sr}/^{86}\text{Sr}$  ratios in separated plagioclases (Fig. 3G and Table 1) in MCU IIIe are in the range 0.7061–

0.7062, decreasing to 0.7060 in MCU IVa. This is followed by a dramatic drop to 0.7050 at the base of MCU IVb, after which the ratios increase fairly systematically, reaching 0.7058 in MCU IVd.

It appears from Fig. 4, which shows the compositional variations in separated minerals, that the compatible elements behave in a predictable fashion if MCU III and MCU IV are considered as two separate, closed systems. Minerals in MCU IVa generally have distinctive compositions and, as will emerge from the discussion below, it is interpreted as a hybrid zone. A potential problem with the interpretation of analyses of mineral separates is that

TABLE 1

Chemical analysis of separated plagioclases

Sample	Sr (ppm)	CaO	K <sub>2</sub> O	Ba (ppm)	<sup>87</sup> Sr/ <sup>86</sup> Sr	St. Dev. (2σ)	N
JL-1	952	9.36	0.78	261	0.70617	0.00002	8
JL-2	927	8.76	0.87	289	0.70609	0.00002	10
JL-3	941	8.97	0.77	266	0.70621	0.00005	6
JL-4	867	9.30	0.67	274	0.70600	0.00002	18
JL-5	1086	10.02	0.55	266	0.70496	0.00001	15
JL-6	1096	9.84	0.54	301	0.70515	0.00001	14
JL-7	1073	9.71	0.55	280	0.70514	0.00002	8
JL-8	1099	9.49	0.58	280	0.70519	0.00001	9
JL-9	1060	9.49	0.58	302	0.70530	0.00002	9
JL-10	1078	9.64	0.53	255	0.70522	0.00001	8
JL-11	1032	9.77	0.48	248	0.70520	0.00001	6
JL-12	1036	9.47	0.52	303	0.70527	0.00002	10
JL-13	998	9.60	0.55	288	0.70534	0.00001	9
JL-14	978	9.34	0.598	295	0.70560	0.00003	13
JL-15	976	9.65	0.68	279	0.70582	0.00003	9

they can contain a mixture of cumulus and inter-cumulus material. However, since most of the BKSK Layered Series rocks are extreme adcumulates (Duchesne, 1978; Roelandts and Duchesne, 1979), this is not a serious problem here.

Strontium in plagioclase is relatively low (927–952 ppm) in MCU IIIe and relatively high in MCU IVb (ca. 1100 ppm), decreasing through MCU IVb and c to 976 ppm in MCU IVd. Nickel, Cr and Co in ilmenite behave in a broadly similar fashion with Ni showing the most and Co the least systematic variation. Nickel increases from < 25 ppm in MCU IIIe to ca. 300 ppm at the base of MCU IVb i.e. an increase by a factor of > 10. The values then decrease fairly systematically to about 40 ppm in MCU IVd. Chromium shows a similar pattern of variation, increasing by a factor of about 5 from MCU IIIe (34–104 ppm Cr) to the base of MCU IV (ca. 500 ppm) and then falling rather irregularly to 111 ppm in MCU IVd. Cobalt likewise increases abruptly by a factor of about 6 at the base of MCU IV but shows erratic variation above this. Nickel and Cr are also compatible in magnetite and show similar variations (it will be recalled that cumulus magnetite is absent in MCU IVa and MCU IVc). The Cr evolution in magnetite supports the interpretation of magnetite as a cumulus phase in MCU IVb and indicates that the role of secondary magnetite is minor since it does not affect the cumulus chemical evolution. Nickel increases by a factor of about 8 and Cr increases from below detection limit to ca. 1.5 % from MCU IIIe to the base of MCU IVb.

Both Ni and Cr fall fairly systematically up through MCU IVb and reach low levels, approaching those in MCU IIIe, in MCU IVd. Vanadium in magnetite is highest in MCU IIIe and MCU IVd; the sharp decrease in MCU IVb may be related to the presence of small amounts of hornblende which has a relatively high partition coefficient for V.

Compared with Sr, the contents of K<sub>2</sub>O, and particularly Ba, in plagioclase vary unsystematically. Potassium roughly follows the An content (Fig. 3F); it is highest in MCU IIIe (0.78–0.87% K) and decreases to 0.67% in MCU IVa. In MCU IVb the values vary between 0.48 and 0.58% K<sub>2</sub>O, increasing to 0.68% K in MCU IVd. Barium in plagioclase varies unsystematically throughout the entire sequence between about 250 and 300 ppm, partly as a result of the relatively large analytical uncertainty for Ba.

MCU IVa is characterised by Ni and Cr in ilmenite having values intermediate between the underlying MCU IIIe and the overlying MCU IVb; the same trend is shown by K in plagioclase. This tendency to have intermediate values was also shown by the <sup>87</sup>Sr/<sup>86</sup>Sr ratio, as outlined above. However, the Sr in plagioclase in MCU IVa is the lowest value in the studied sequence, while the highest level of Co in ilmenite occurs in this zone.

It was noted earlier that the pyroxenes, in particular in the uppermost sample in MCU IIIe, showed a compositional reversal. This feature is also shown by Cr and Co in ilmenite, Ni in magnetite and weakly by Sr in plagioclase. This reversal immediately below MCU IV is not a unique feature re-

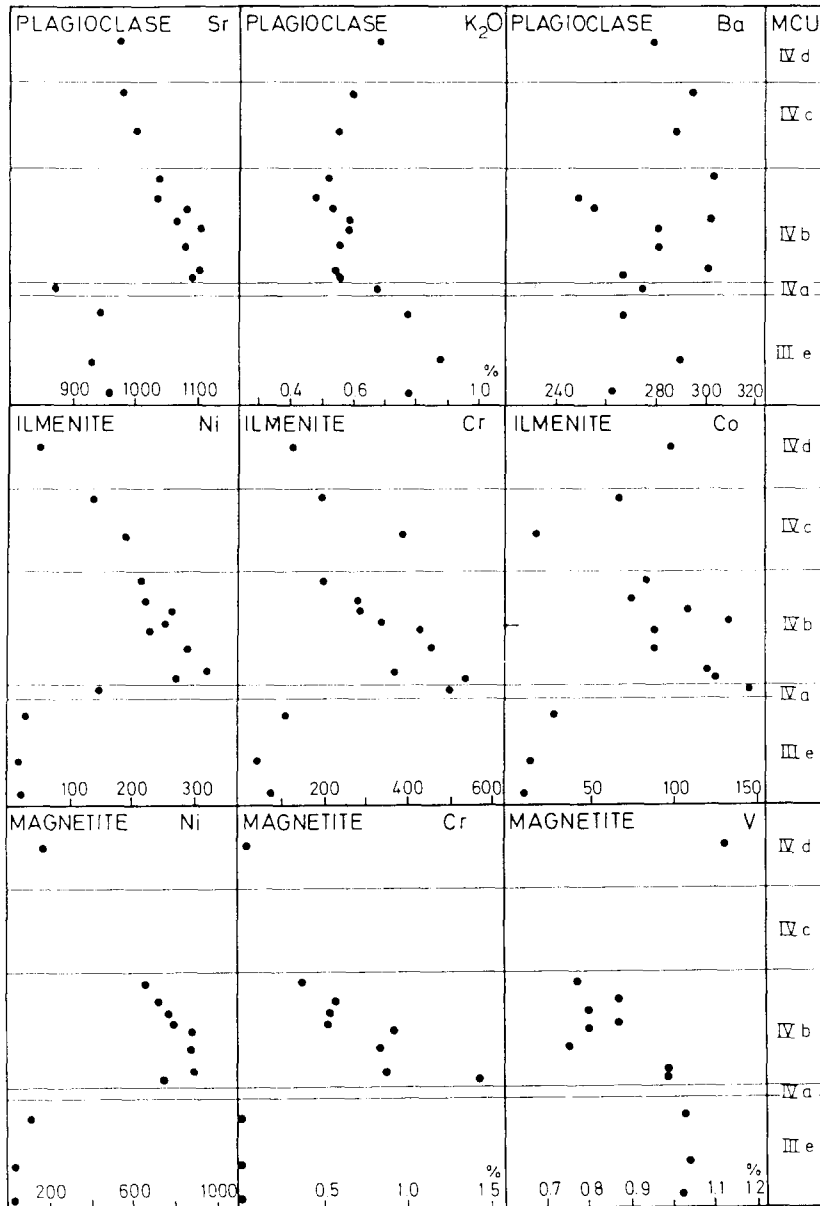


Fig. 4. Compositional variations of separated minerals; Sr, K<sub>2</sub>O and Ba in plagioclase; Ni, Cr and Co in ilmenite; Ni, Cr and V in magnetite. Values in parts per million except where indicated.

stricted to the Storeknuten profile, but is also present in other profiles that cover this interval (Nielsen and Wilson, 1991). This reversal is believed to rep-

resent the first effect of the influx of new magma at the boundary between MCU III and MCU IV, as will be discussed below.

## Discussion

There is overwhelming evidence of a compositional reversal at the base of MCU IV. This is shown by the occurrence of more primitive mineral assemblages, by the Sr-isotope ratios and by the compositions of silicates and oxides. These features are accompanied by a marked change in rock textures across the MCU boundary. As has been noted by previous workers (Duchesne, 1972, 1978; Nielsen and Wilson, 1991), this reversal reflects the influx of primitive magma into the BSKS chamber at this level. This contribution, however, allows consideration of processes such as the mechanism of influx, the degree of contamination of the new and resident magma and the role of magma mixing.

### *Comparison with previous Sr-isotope results*

It is assumed here that virtually all the Sr in the rocks studied is present in plagioclase. The rocks are notably poor in Rb; our recent analyses show that whole rocks from MCU IVa contain about 1 ppm

Rb. Duchesne (1978) has reported Rb values in plagioclase of < 2 ppm from equivalent levels in the intrusion. This means that the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios in plagioclases with 850–1100 ppm Sr have increased by 0.00007–0.00009 by the radioactive decay of  $^{87}\text{Rb}$  since the rocks crystallized about 955 million years ago (Pasteels et al., 1979). The  $^{87}\text{Sr}/^{86}\text{Sr}$  values quoted here have therefore not been corrected for Rb-decay.

Previous workers have reported initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of 0.705–0.706 in the BSKS Layered Series (Demaiffe et al., 1979) and higher values in the range 0.710–0.712 in the mangerites and quartz-mangerites (Verstevee, 1975; Demaiffe et al., 1979; Wielens et al., 1980). In the latter rocks the initial ratios are deduced from Rb–Sr whole rock isochrons which give significantly younger ages (875 Ma) than the U–Pb zircon age of 930 Ma (Pasteels et al., 1979). Assuming an age of 930 Ma the  $^{87}\text{Sr}/^{86}\text{Sr}$  initial ratio is close to 0.7085 (see discussion in Demaiffe et al., 1986). Duchesne and Demaiffe (1978) interpreted the relatively low  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios in the Layered Series as reflecting a somewhat

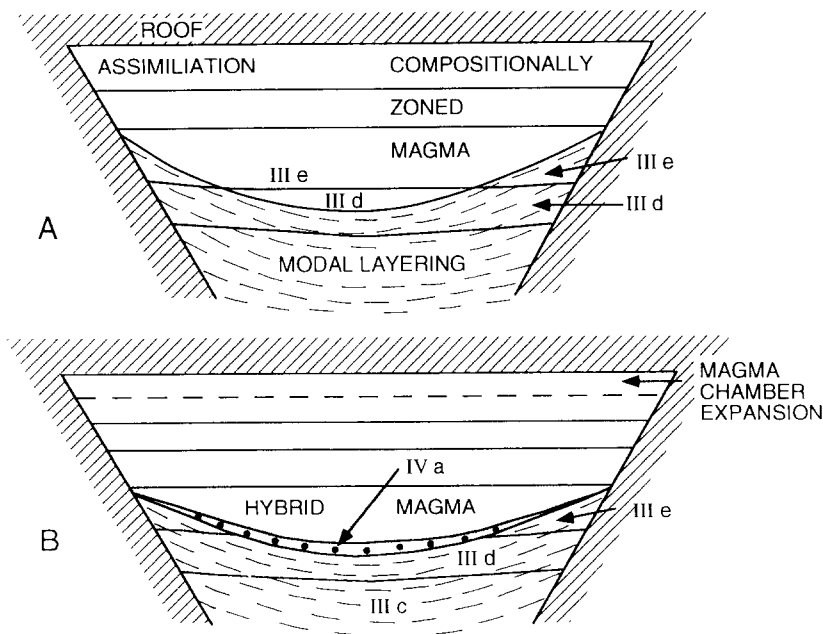


Fig. 5. Sketches of the Bjerkreim-Sokndal magma chamber during formation of the MCU III/IV boundary. Modified after fig. 5 in Nielsen and Wilson (1991). (A). Crystallization of the upper part of MCU III. The magma layer parental to MCU III<sub>d</sub> is only present in the central, lowest part of the saucer-shaped chamber. MCU III<sub>e</sub> is crystallizing from the overlying magma layers towards the margins. (B). Magma replenishment by fountaining into the lowermost residual magma produces a hybrid magma layer. MCU IV<sub>a</sub> crystallizes during influx to produce a compositional reversal. The roof is partly pushed up and partly assimilated to accommodate the volume increase.

contaminated mantle-derived parental magma. The nature of the transition from the low values in the Layered Series to the higher values in the overlying mangerite is being studied by F.M. Nielsen. The high values in the mangerite have been explained by Demaiffe et al. (1979) as reflecting contamination of the BSKS magma by 15–30 wt.% gneissic country rock with an initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio at 950 Ma of 0.7196 (Verstevee, 1975). The quartz-mangerites might also result from the partial melting of the country rocks (Wiebe, 1984) or might constitute one or two separate intrusions on top of the layered sequence (Wilmart, 1988). While the  $^{87}\text{Sr}/^{86}\text{Sr}$  values of 0.705–0.706 reported here are in agreement with previous results from the Layered Series, the variations across the MCU III–IV boundary reveal several interesting features, as will be discussed below.

#### *Evidence for magma stratification.*

It has become increasingly apparent in recent years that magma can become compositionally zoned (Turner and Gustafson, 1978; McBirney and Noyes, 1979; Huppert and Sparks, 1984). Nielsen and Wilson (1991) consider that the magma in the Bjerkreim–Sokndal magma chamber was stratified, at least by the time that MCU III was crystallizing. Since magma stratification is important in the context of this paper, their evidence will be briefly summarized here.

Nielsen and Wilson (1991) studied the MCU III/IV contact in seven profiles (one of which—their profile F—is the Storeknuten section) along its entire strike length of about 24 km. They found that there is a fairly symmetrical discordance related to the boundary between MCU III and MCU IV in that MCU IIIe is absent and MCU IVa is thickest in the central part of the Bjerkreim lobe. The discordance between MCU IIIId/e and the base of MCU IV is explained by the crystallization of compositionally stratified magma along a saucer-shaped floor, so that magma parental to MCU IIIId was crystallizing in the deepest, central part of the chamber while MCU IIIe was crystallizing on the flanks (Fig. 5). It was at the stage of evolution illustrated in Fig. 5A that new magma entered the chamber. This model explains the absence of MCU IIIe in the central part of the chamber and the symmetrically arranged wedge-shape of MCU IIIe on either flank.

#### *The formation of MCU IVa.*

Nielsen and Wilson (1991) proposed that the magma which entered the chamber at the base of MCU IV was relatively dense and initially mixed with the basal magma layers already in the chamber. Mixing was probably achieved by the new magma fountaining into the residual magma, by a process suggested by Turner and Campbell (1986). This hybrid magma crystallized during continued influx to produce MCU IVa which has compositions intermediate between the base of MCU IVb and the underlying unit. The hybrid MCU IVa is thickest in the central part of the chamber (Fig. 5). This is a result of the relatively rapid crystallization of this hybrid magma during influx, filling out the saucer shaped, central part of the chamber floor.

The data presented here support the model outlined above for the hybrid nature of MCU IVa. The Sr-isotope ratios and trace-element data from plagioclases and Fe–Ti oxides all show a variation from evolved compositions in MCU IIIe to primitive compositions in MCU IVb. The values in MCU IVa are, in general, intermediate between those above and below. This supports the formation of this zone from a hybrid magma, intermediate in composition between those parental to MCU IIIe and the basal part of MCU IVb, which became gradually more primitive upwards as increasing proportions of new magma mixed with the resident magma.

The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio in plagioclases in MCU IIIe (0.70616; average value of samples 1–3 in Table 1) is assumed to represent the ratio in the residual magma in the chamber, parental to MCU IIIe, just before the magma influx responsible for the reversal at the base of MCU IV. The lowest  $^{87}\text{Sr}/^{86}\text{Sr}$  value, at the base of MCU IVb (0.70496; sample 5), is assumed to represent the Sr-isotope ratio of the new magma. Based on the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of the top sample in MCU IIIe and the bottom sample in MCU IVb, it is possible to calculate the proportions of magma with these isotopic compositions which mixed to form sample 4 from MCU IVa.

Using the partition coefficients for the relevant plagioclase compositions suggested for BSKS by Duchesne (1978) gives values of 410 and 545 ppm Sr for the magmas parental to MCU IIIe and the basal part of MCU IVb respectively. These values and the determined  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios give calculated mixing proportions of 89% residual magma and 11%

new magma for the analysed sample from MCU IVa. Sample 4 comes from the central part of MCU IVa and samples from higher in this unit can be expected to show progressively more influence from the new magma.

An interesting feature is the compositional reversal shown by the pyroxenes in the top sample from MCU IIIe which is ca. 2 m below the base of MCU IVa. Nielsen and Wilson (1991) suggested that this was formed by reequilibration of the mineral compositions with primitive magma from the new influx which had percolated downwards and exchanged with the more evolved intercumulus melt. An alternative mechanism is related to the elevation of the resident magma column as a result of the influx of dense magma at the floor of the chamber. Since clinopyroxene remains a cumulus phase after the reversal at the top of MCU IIIe, the sloping floor in the Storeknuten section remained within the magma layer parental to MCU IIIe. While the elevation was not sufficient to bring the MCU IIIe parental magma from the deeper part of the chamber into contact with this section, it brought the sloping floor here into contact with a lower level of the magma layers parental to MCU IIIe and crystallized more magnesian pyroxenes.

#### *The crystallization of MCU IVb*

Above the base of MCU IVb the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios gradually increase through MCU IVb and MCU IVc to MCU IVd. The most obvious source with a relatively high  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio is the resident magma already in the chamber during the crystallization of MCU III. Since the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio at the top of MCU IIIe is 0.7062, the resident magma (strictly the basal layer of the compositionally zoned magma) is assumed to have had a similar ratio before the influx of fresh magma.

There are two possible models for the crystallization of MCU IVb. One involves the dense new magma ponding on the floor after initial mixing to form the hybrid MCU IVa (Fig. 6A). The other assumes that the new and resident magma mixed to form a hybrid zone which was parental to MCU IVa during influx and to MCU IVb after influx ceased (Fig. 6B). According to Turner and Campbell (1986), the first would imply that the dense magma input from below was initially fairly rapid, forming the hybrid IVa, but that it slowed down and ponded

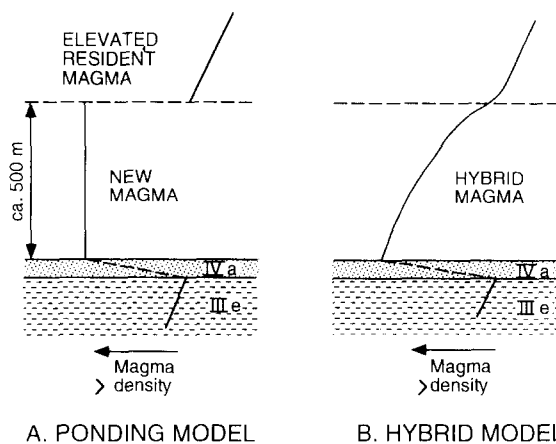


Fig. 6. Schematic sections through the magma chamber after the formation of the hybrid reversed zone MCU IVa showing alternative magma density evolutions. (A). Ponding model. The new magma influx has a thickness of about 500 m (see text) and did not mix with the resident magma to any significant extent. The base of the elevated resident magma has the same density as that parental to the top of MCU IIIe. (B). Hybrid model. Magma mixing during influx resulted in the formation of a hybrid zone several hundreds of meters thick. Note that the magma layering of the compositionally zoned resident magma is not shown. As a first approximation, the Sr-isotope ratio is envisaged as being inversely proportional to magma density. In (A) the Sr-isotope ratio of the new magma is gradually increased by progressive mixing with the overlying resident magma. In (B) the Sr-isotope profile is essentially established during magma influx and mixing.

without further mixing. The alternative model involves fairly rapid replenishment with turbulent mixing throughout.

#### *A ponding model for MCU IVb*

According to the ponding model, the new, dense magma would elevate the resident magma column as illustrated in Fig. 6A. This relatively dense, primitive magma had olivine on the liquidus and crystallized fairly rapidly to form the massive leucotroctolites of MCU IVb. Fractional crystallization of this magma would give rise to the mineral compositional trends illustrated in Figs. 3 and 4. While the mineral compositional trends can result from fractional crystallization with or without major mixing, the Sr-isotope trend can only have developed by the resident magma mixing with the new magma.

Fractionation density considerations involving the removal of olivine, Fe-Ti oxides and plagioclase would decrease the density of the ponded

magma and when its density reached that of the basal overlying layer, the two would mix. Vigorous thermal convection in the rapidly cooling ponded layer would cause effective mixing, so that the composition of the entire ponded layer would become slightly more evolved. The ponded layer would initially have a  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio close to 0.7050, but the successive mixing in of overlying magma layers would gradually increase this value. After about 50 m of MCU IVb had accumulated, its Sr-isotope ratio had increased from 0.7050 to 0.7053 (Fig. 3). The resident magma (or the magma layer parental to MCU IIIe) is assumed to have had a ratio of 0.7062. This would require that about 25% resident magma was mixed with new magma at this level. In an alternative model, the magma mixing took place during influx and not during crystallization of MCU IVb.

#### *A hybrid model for MCU IVb*

If magma replenishment was rapid throughout, turbulent mixing would occur with the resident magma, resulting in a density gradient in the lower part of the magma chamber. We have argued earlier that the resident magma was compositionally zoned before the formation of MCU IV, and the density gradient in the lower part of the chamber would be reinforced by this input (Fig. 6). The magma above the mixing zone will simply have been elevated. According to this model the mineral compositional and isotope trends resulted from the fractional crystallization of compositionally zoned hybrid magma.

#### *Estimating the volume of new magma emplaced at the base of MCU IV*

The volume of new magma emplaced at the base of MCU IV can be estimated in a variety of ways. These involve geochemical modelling, the thickness of cumulate stratigraphy repeated and Sr-isotope ratios.

#### *Geochemical modelling*

If we assume that MCU IVb crystallized essentially from ponded magma, the well defined trace-element patterns in plagioclases and oxides allow its crystallization to be modelled. As already mentioned, the cumulus minerals in MCU IVb are plagioclase, olivine, ilmenite and magnetite, and there is no indication that their compositions have been

significantly modified by post-cumulus processes (Duchesne, 1978; Roelandts and Duchesne, 1979), particularly when compatible trace elements are considered. The smooth and continuous evolution in the Sr content in plagioclase shows a variation from ca. 1090 ppm at the base of MCU IVb down to 1036 ppm at the top. The partition coefficient for Sr between plagioclase and liquid can be taken as varying from 2.0 at the base to 2.1 at the top, values well supported by Duchesne's (1978) model describing the evolution in the whole intrusion and in agreement with values in the literature (e.g. Henderson, 1982). The proportion of plagioclase—the only Sr-bearing mineral in the rock—in the cumulate has been estimated at 75% by point counting and norm calculations of whole rock analyses. Solving the Rayleigh equation between the base and the top of MCU IVb [see Duchesne (1978) for details] gives a fraction of liquid of 0.82 at the top of MCU IVb, which suggests that ca. 20% of the new influx of magma has crystallized at the base of MCU IVc.

The evolution of Cr in magnetite also gives interesting information, though rather less constrained. Point counting on the oxide minerals shows that cumulus magnetite represents  $15 \pm 2\%$  of the oxides. The amount of ilmenite in the rock (5%) can be assessed accurately through norm calculations. Parallel evolution of Cr in magnetite and ilmenite through MCU IVb allows the ratio of the partition coefficient ( $K_D$ ) for Cr between magnetite and ilmenite to be fixed at 22. Introducing these values into the Rayleigh equation, together with the fraction of liquid deduced from the Sr evolution in plagioclase, allows calculation of the partition coefficient between magnetite and liquid. This value varies between 520 and 710 and is strongly dependent on the amount of cumulus magnetite. A large interval of  $K_D$  values for Cr in magnetite (100–620) has been reported by Lindstrom (1976) on the basis of experimental data and a value of 200 has been adopted by McCarthy et al. (1985) in the modelling of magnetite in the Bushveld intrusion. On the other hand, Duchesne and Hertogen (1988) used major and trace elements to constrain the composition of the parental magma to MCU III and IV and suggested that a fine grained (chilled) monzonite found at Tjørn has the appropriate composition. The Cr content at Tjørn is 28 ppm which gives a  $K_D$  value of 510 for Cr in magnetite, a value close to the upper limit found here.

This internally consistent model thus permits us to conclude that the new influx of fresh magma that gave rise to MCU IVb was approximately five times thicker than the MCU IVb rock unit, and therefore was of the order of 500 m thick. However, this modelling assumes that we are dealing with a closed system. As discussed above, the Sr-isotope profile developed as a result of progressive mixing with the overlying resident magma, and consequently a model of assimilation-fractional crystallization (AFC) (DePaolo, 1981) would theoretically better account for the evolution, assuming that the contaminant is the elevated resident magma itself.

In fact, an AFC model brings no further information because of the geochemical characteristics of the elements considered here. Cr has a high bulk partition coefficient (ca. 5) and a very low concentration in the contaminating magma ( $< 0.2$  ppm). Its behaviour is therefore mainly constrained by fractional crystallization and not by assimilation. On the other hand, Sr has a bulk partition coefficient close to unity and its concentration in the contaminant (451 ppm) is similar to that in the fresh magma (545 ppm). For high values of the fraction of melt ( $F=0.7-1.0$ ), simple fractional crystallization and AFC processes become indistinguishable under these conditions.

#### *Repetition of the cumulate stratigraphy*

The new influx at the base of MCU IV arrived in the profile in Fig. 2 after about 100 m of MCU IIIe had crystallized; the same level of evolution is reached in MCU IV after about 500 m. This 500 m-thick reversal represents the thickness of rocks which crystallized before the conditions prevailing at the top of MCU IIIe were reestablished. If there was no mixing during emplacement it would represent the minimum thickness of the new magma influx since this would also be parental to more evolved magma as a result of fractionation. On the other hand, mixing would produce hybrid magmas which would be parental to MCU IVb, c and d; these are consequently thicker than if they crystallized exclusively from the new influx.

#### *Sr-isotopes*

Extrapolation at the top of Fig. 3G indicates that an  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of 0.7062, the same as that in the rocks at the top of MCU IIIe before the new influx, would be present at a height of about 350 m above

the base of MCU IVa. If the resident magma was simply elevated without any mixing, this value would represent the thickness of the new magma influx. Progressive mixing during influx would have two opposing effects: the Sr-isotope ratio in the hybrid magma would gradually increase; at the same time the resident magma would, in part, be elevated and the Sr-isotope ratio of the lowest magma layer(s) would decrease by the mixing process. Continuous assimilation of gneiss at the roof would gradually increase the ratio in the resident magma. The temperature increase associated with magma influx would fairly rapidly propagate up through the magma column, increasing the rate of roof melting. However, in view of the relatively rapid process of magma influx compared with the assimilation and crystallization history of the intrusion, the latter effect is thought to be minor compared with the former.

Three independent estimates of the thickness of the new magma influx at the base of MCU IV are therefore  $> 500$  m (geochemical modelling), about 500 m (phase layering) and about 350 m (Sr isotopes). Considering the sources of error in each of these methods of estimation there is reasonably good agreement; MCU IVb therefore represents 20–30% crystallization of the new influx.

#### *Comparison of the Sr-isotope and mineral cryptic variations in MCU IVb.*

As discussed above, the gradual increase in Sr-isotope ratios through MCU IVb reflects progressive mixing between the new, primitive magma influx and the more evolved resident magma. Trace elements in Fe–Ti oxides (Fig. 4) indicate progressively more evolved compositions through MCU IVb, as do plagioclases (Fig. 3F), although the latter trend is very erratic. The trend shown by olivines (Fig. 3E) is, however, distinct and cannot be explained by progressive mixing and/or fractional crystallization. The olivines are clearly not in equilibrium with the coexisting plagioclases. It should be recalled here that the Ca-poor pyroxenes in MCU IVb are secondary reaction products from olivine and therefore show the same trend. It therefore seems likely that olivines have not retained their primary compositions.

A process by which the olivines could have changed their compositions involves trapped liquid

shift (Barnes, 1986). By this process, cumulus solid solution minerals reequilibrate towards more evolved compositions by reaction with intercumulus melt. A trapped liquid shift of about 5% Fo in the lower half of MCU IVb, decreasing upwards to close to zero at the top, may explain the observed trend. Since the rocks contain about 10% cumulus olivine, a shift of 5% Fo would require about 10% trapped liquid (Barnes, 1986). It has been argued above that MCU IVb crystallized fairly rapidly in the initial stages, so that the proportion of trapped liquid would be expected to be high. The amount of trapped liquid decreased upwards together with the rate of crystallization. While olivines readily reequilibrate, plagioclases do so more reluctantly because of the more complicated cation exchanges involved; plagioclase zoning is therefore common in cumulates while olivines are generally homogeneous. Plagioclases in MCU IVb are not zoned, but this is believed to be a result of extensive post-cumulus recrystallization under granulite facies conditions. It therefore seems likely that the plagioclases originally had slightly Ab-enriched rims because of trapped liquid shift, although the large modal proportion of plagioclase in these rocks (ca. 80%) means that the effect is less than with olivine. The present erratic plagioclase trend in both MCU IVa and b is therefore a result of a combination of factors.

While the olivine trend in MCU IVb is relatively systematic in the Storeknuten profile, the pattern is not generally repeated in MCU IVb in other profiles (fig. 3 in Nielsen and Wilson, 1991). The processes responsible for the olivine compositional trends in Fig. 3E were therefore of local character; this is consistent with varying amounts of trapped liquid.

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### Appendix

*Mineral separation.* The samples were crushed to a grain size of 60–150  $\mu\text{m}$  and split in bromoform. The buoyant plagioclase fraction was purified by passage through a Frantz isodynamic magnetic separator. Magnetite was separated by a hand magnet and ilmenite by passage through the Frantz separator. Both Fe–Ti oxides were purified using thallium formate. Trace element analyses of the separated minerals were carried out at the Collectif Interinstitutionnel de Géochimie Instrumentale, Université de Liège, by X-ray fluorescence following methods described in Duchesne (1972, 1978).

*Isotope analyses.* Strontium isotope analyses were performed at the Laboratoires associés de Géologie–Pétrologie–Géochronologie, Université Libre de Bruxelles. Plagioclase was dissolved in a 9:1 mixture of hydrofluoric and perchloric acid and Sr separated in an ion exchange column. The Sr isotope composition was measured using a double Re filament on a Finnigan MAT 260 mass spectrometer. The NBS 987 standard gave a  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of  $0.710219 \pm 0.000024$  ( $2\sigma$ ).

*Microprobe techniques.* Microprobe analyses were performed at the Department of Earth Sciences, University of Aarhus, using the energy-dispersive method. The analyses are usually an average of 4–5 points from different grains in a polished thin section. The error bars in Fig. 3 are at the one standard deviation level, based on about ten separate grains of the mineral in typical thin sections. The values obtained are: olivine  $2\text{sd} = 1.70\%$  Fo, Ca-poor pyroxene  $1.24\%$  Mg#, plagioclase  $2.75\%$  An. Since the mineral compositions in Fig. 3 are averages of several points, the appropriate error bars are considerably less than these values. All analyses are with a focused beam. Pyroxenes usually show exsolution textures and analyses represent subsolidus compositions. Plagioclases are not usually optically zoned, but grains within a thin section often vary in composition by 2–3 mol% An.

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