

# A Sr-, Nd- and Pb-isotopic investigation of the transition between two megacyclic units of the Bjerkreim–Sokndal layered intrusion, south Norway

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## Abstract

The Bjerkreim–Sokndal layered intrusion forms part of the Proterozoic South Rogaland Igneous Complex of southwest Norway. The intrusion has been divided into two parts; an anorthositic to gabbro-noritic Layered Series, and a generally more massive mangeritic, quartz-mangeritic to charnockitic upper part. On the basis of repeated lithological sequences, the Layered Series has been divided into a number of megacyclic units which are interpreted as reflecting magma chamber replenishment. Initial (940 Ma) Sr, Nd and Pb isotope ratios for plagioclases separated from samples crossing the transition between megacyclic unit III and megacyclic unit IV range from  $^{87}\text{Sr}/^{86}\text{Sr}_i = 0.7048$ ,  $^{143}\text{Nd}/^{144}\text{Nd}_i = 0.51156$  ( $\epsilon_{\text{Nd}} = +2.6$ ) and  $^{206}\text{Pb}/^{204}\text{Pb}_i = 17.50$ ; to  $^{87}\text{Sr}/^{86}\text{Sr}_i = 0.7061$ ,  $^{143}\text{Nd}/^{144}\text{Nd}_i = 0.51143$  ( $\epsilon_{\text{Nd}} = +0.1$ ) and  $^{206}\text{Pb}/^{204}\text{Pb}_i = 17.73$ . The isotopic compositions vary systematically with stratigraphic height, and the interplay between the three isotopic systems is used to divide the stratigraphic profile into two parts: replenishment and post-replenishment. Across the replenishment interval isotopic variations are consistent with mixing between a resident and a replenishing magma. The replenishing magma was characterized by  $^{87}\text{Sr}/^{86}\text{Sr}_i = 0.7048$ ,  $^{143}\text{Nd}/^{144}\text{Nd}_i = 0.51156$  ( $\epsilon_{\text{Nd}} = +2.6$ ) and  $^{206}\text{Pb}/^{204}\text{Pb}_i = 17.50$ . The positive  $\epsilon_{\text{Nd}}$  of this magma indicates that its source region was either in the mantle or was itself recently derived from the mantle. In contrast the resident magma had  $^{87}\text{Sr}/^{86}\text{Sr}_i = 0.7061$ ;  $^{143}\text{Nd}/^{144}\text{Nd}_i = 0.51143$  ( $\epsilon_{\text{Nd}} = +0.1$ ) and  $^{206}\text{Pb}/^{204}\text{Pb}_i = 17.73$  indicating that it had assimilated crustal material. In addition, the isotopic correlations across the replenishment interval indicate that prior to mixing the concentrations of Nd and Pb in the resident magma had been strongly reduced, probably by fractionation of apatite. Above the replenishment interval, Nd and Pb isotopic variations are apparently decoupled from Sr isotopic variations. Two mechanisms are proposed for achieving this. The first is heterogeneous mixing of up to 20% of a third magmatic component into an already isotopically stratified magma chamber. The second is the presence of 10%–20% of post-cumulus plagioclase that crystallized from a migrating intercumulus melt. © 2000 Elsevier Science B.V. All rights reserved.

**Keywords:** Bjerkreim–Sokndal layered intrusion; Megacyclic units; Sm-Nd isotopes; Rb-Sr isotopes; Magma chamber processes; Hybridization

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## 1. Introduction

Layered intrusions are generally interpreted as resulting from the solidification of magma undergoing fractional crystallisation. At one extreme this may be a closed system process involving the crystallisation of a single influx of magma with little or no recharge (e.g., Skaergaard, Stewart and DePaolo, 1990) whilst at the other extreme there may be evidence of open system behaviour with repeated cycles of replenishment by parental magma (e.g., Muscox, Irvine, 1980; Rum, Palacz, 1985). In many cases these processes are accompanied by crustal contamination of the magma by the surrounding country rock.

Isotopic studies are particularly suited to the investigation of replenishment events and crustal contamination, especially in cases where there is a large contrast in chemical and isotopic characteristics between magma and country rock, e.g., in the case of a mantle-derived magma residing in a continental crustal magma chamber. A wide variety of processes can influence the resulting isotopic variations. The isotopic and chemical characteristics of the contaminant may be strongly influenced by the preferential consumption of accessory phases during partial melting of the country rock; the interaction of both the replenishing magma and the contaminant with resident magma may involve at one extreme, physical mixing and at the other, diffusion between compositionally distinct layers within the magma body. Superimposed on these processes are the effects of crystal fractionation and accumulation and, at a late stage, the interaction of accumulated crystals with trapped or migrating intercumulus melts.

The Bjerkreim–Sokndal layered intrusion in southern Norway is interpreted as having crystallised in a magma chamber which underwent several replenishment events (Michot, 1960, 1965; Duchesne, 1972a; Nielsen et al., 1996; Wilson et al., 1996). In this isotopic study we have analysed plagioclase separated from a sequence of samples crossing one of these replenishment intervals. These samples therefore provide an opportunity to characterise the processes occurring in a magma chamber during a magma replenishment event.

## 2. Geological setting and previous studies

The Bjerkreim–Sokndal intrusion forms part of the South Rogaland Igneous Complex of southwest Norway (Fig. 1). This complex consists of three large anorthosite massifs (Egersund–Ogna, Håland–Helleren and Åna–Sira) and a number of smaller intrusions (Michot and Michot, 1969; Duchesne et al., 1985). These fall into two compositional suites; (i) an anorthosite–leuconorite–norite–gabbro–norite–quartz–mangerite suite (which includes the Bjerkreim–Sokndal and Hydra intrusions) and (ii) a granite–charnockite suite. The intrusions were emplaced into Sveconorwegian (= Grenvillian) granulite facies gneisses as late- to post-orogenic plutons. Field evidence indicates that the Bjerkreim–Sokndal intrusion is younger than the anorthosite massifs (Michot and Michot, 1969), however, radiometric dating has yet to yield a consistent chronology. Until recently the anorthosite massifs were thought to be 1000–1200 Ma, based on zircon ages of gneissic country-rock near the contact with the massifs (Pasteels and Michot, 1975). A zircon from a monzonite dyke related to the Bjerkreim–Sokndal intrusion gave an age of  $946 \pm 14$  Ma for the lower part of the intrusion (Pasteels et al., 1979). A similar age ( $955 \pm 8$  Ma) was given by a monazite in the gneissic country rock 5 m from the contact with the lower part of the Bjerkreim–Sokndal intrusion. This age was interpreted as corresponding to the isotopic resetting of the monazite due to the emplacement of the lower part of the intrusion (Pasteels et al., 1979). However, a U–Pb zircon study by Schärer et al. (1996) suggests that the three anorthosite massifs (Egersund–Ogna, Håland–Helleren and Åna–Sira) were emplaced in a 10 Ma period between 920 and 930 Ma. Obviously, the age of the Bjerkreim–Sokndal intrusion must be re-examined in the light of the results of Schärer et al. (1996). For the present study we have used an age of 940 Ma to calculate initial isotope ratios for samples from the intrusion.

The Bjerkreim–Sokndal intrusion is roughly 40 km in length, up to 15 km wide with an area of about 230 km<sup>2</sup>. The present form of the intrusion is that of a doubly plunging syncline whose southern end is divided into two lobes. It has been divided on the basis of field and petrographic observations into two

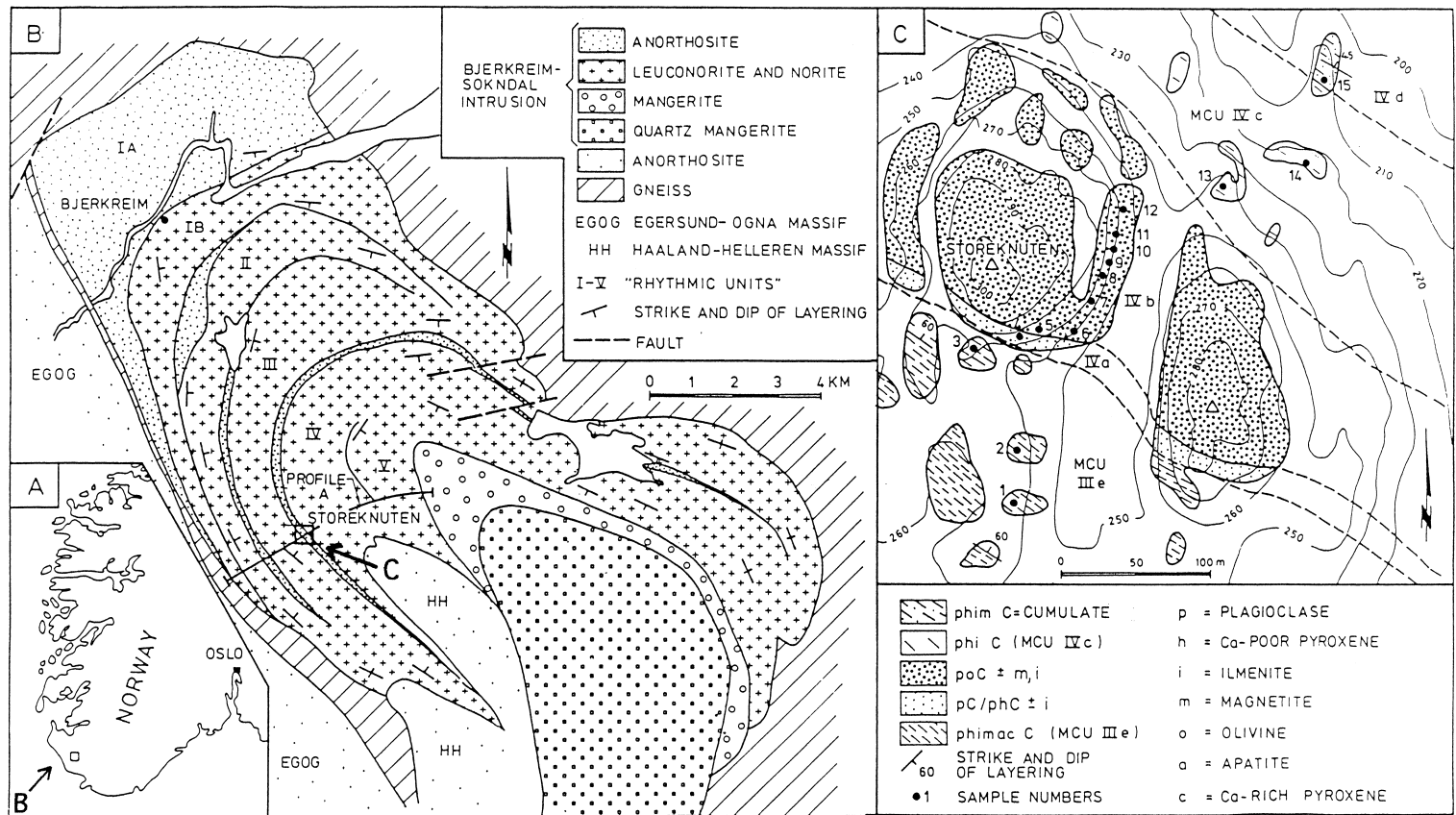


Fig. 1. Bjerkreim-Sokndal layered intrusion. (A and B) Location map. (C) Sample locations. From Jensen et al. (1993).

parts. An anorthositic to gabbro-noritic Layered Series which outcrops in the northern part of the intrusion and in the two southern lobes, and a generally more massive mangeritic, quartz-mangeritic to charnockitic upper part which outcrops in the core of the syncline (Michot, 1960; Duchesne, 1972a; Nielsen et al., 1996; Wilson et al., 1996; Duchesne and Wilmart, 1997). These are separated by a Transition Zone. The roof of the intrusion has been entirely removed by erosion.

The Layered Series has a maximum (stratigraphic) thickness of approximately 6700 m. Originally it was divided by Michot (1960) into five major rhythmic units on the basis of repeated anorthosite–norite cycles; recent studies have adopted the terminology of Irvine (1982) and these units are now referred to as megacyclic units (MCU). Remapping in progress by groups from the University of Aarhus (J.R. Wilson) and the University of Bergen (B. Robins) suggests that the original unit 4 (MCU IV here) grades directly into the Transition Zone and that unit 1 should be subdivided (MCU 1A and 1B). The megacyclic units have variable stratigraphic thickness, lateral persistence and modal layering and range in composition from anorthosite or leuconorite at the base to more mafic lithologies at the top. 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. Olivine is present in narrow, laterally persistent intervals just above the base of MCU III and IV; more Fe-rich olivine is present in the Transition Zone. Magnetite, clinopyroxene and apatite appear in the upper parts of MCU III and IV (Duchesne, 1972a,b; Nielsen and Wilson, 1991; Wilson et al., 1996).

The transition between MCU III and IV is marked by well defined compositional reversals from evolved to more primitive compositions in plagioclase ( $An_{44-45}$  to  $An_{53}$ ), orthopyroxene ( $En_{68-70}$  to  $En_{76}$ ) and oxides and by the appearance of Mg-rich olivine ( $Fo_{67-77}$ ) just above the base of MCU IV (Nielsen and Wilson, 1991; Jensen et al., 1993; Jensen, personal communication). The olivine-bearing (leucotroctolite) layer (zone IVb) contains the most primitive mineral assemblage in the intrusion; minor amounts of biotite and hornblende are present.

The sequence of samples forming the basis for this study traverses the MCU III/IV boundary at

Storeknuten (Fig. 1). The mineralogy, petrography and Sr-isotope stratigraphy of this traverse are described in detail by Nielsen and Wilson (1991) (Traverse F), Nielsen et al. (1996) and Jensen et al. (1993). According to these studies the base of MCU IV marks an influx of fresh magma which fountained into, and mixed with, the basal magma layers of a compositionally and isotopically zoned resident magma. This hybrid magma crystallised the rocks of zone IVa. Subsequently, the relatively dense replenishing magma ponded on the floor of the chamber and crystallised the leucotroctolitic rocks of zone IVb. Above this level there was a return to normal magma chamber conditions (zones IVc to IVf) which duplicate those seen in MCU III (zones IIIc to IIIe).

### 3. Sampling and analytical methods

The fifteen plagioclase separates analysed in this study were sampled and investigated by Jensen et al. (1993) who presented partial major and trace element analyses and Sr isotope ratios. The separates were prepared at the University of Liège from the 60–150  $\mu\text{m}$  fraction of the crushed sample in two stages. The first stage involved separation of plagioclase from denser minerals by flotation in bromoform; the second, purification by means of a Frantz isodynamic magnetic separator (Jensen et al., 1993).

Sr and Nd isotope analyses were carried out on unleached powdered fractions of the plagioclase separates which were dissolved in a mixture of HF, HNO<sub>3</sub> and HClO<sub>4</sub> in the proportions 6:1:1. Surface-held, non-lattice U and Pb in plagioclase can result in significant perturbation of primary U–Pb systematics (Zartman, 1965; Weis and Deutsch, 1984). For this reason Pb isotope ratios and U and Pb concentrations were measured on granular fractions of the plagioclase separates which were thoroughly cleaned and strongly leached before dissolution. For the cleaning stage of the pre-dissolution treatment, the plagioclase grains were immersed in acetone and agitated for 15 min in an ultrasonic bath in order to remove organic contaminants resulting from sample preparation and mineral separation. The cleaned grains then underwent a three-stage leach with the residues thoroughly rinsed after each stage. The first leach was for 1.5–2 h in hot 6 N HCl. The second and third leaches were each of 5 min in hot 5%

HF-HBr (Weis and Deutsch, 1984). Dissolution of the residues was also in a mixture of HF, HNO<sub>3</sub> and HClO<sub>4</sub>, but in this case the quantity of HClO<sub>4</sub> was reduced to 200 µl. The separation of Nd and Pb was similar to the procedure described by Weis and Deutsch (1984). Sr was eluted in 2.5 N HCl prior to the elution of Nd as described by Weis and Deutsch (1984). Rb, Sm, Nd, U and Pb concentrations were determined by isotope dilution techniques. Rb, Nd and Sm concentrations were measured on a separate dissolution of the powdered separate. U and Pb concentrations were measured on an aliquot taken from the dissolved leached sample.

Sr and Nd isotope ratios were measured on a VG sector 54 mass spectrometer using dynamic multicollection. Pb isotope ratios and U, Pb, Rb, Sm and Nd isotope dilution measurements were measured on a VarianMAT 260 single collector mass spectrometer. <sup>87</sup>Sr/<sup>86</sup>Sr ratios are normalised to <sup>86</sup>Sr/<sup>88</sup>Sr = 0.1194 and during the period of measurement <sup>87</sup>Sr/<sup>86</sup>Sr for the NBS 987 Sr standard was 0.710238 (sigma = 0.000009; *n* = 14). <sup>143</sup>Nd/<sup>144</sup>Nd ratios are normalised to <sup>146</sup>Nd/<sup>144</sup>Nd = 0.7219 and during the period of measurement <sup>143</sup>Nd/<sup>144</sup>Nd for the Merck Nd standard was 0.511740 (sigma = 0.000011; *n* = 9). Pb isotope ratios were corrected for fractionation relative to the NBS 981 Pb standard by 0.1% amu<sup>-1</sup>. Reproducibility of NBS 981 was better than 0.037% amu<sup>-1</sup> (2 SD; *n* = 6).

Total analytical errors on the concentration determinations are estimated at better than 2% (2 SD) for Rb, Sm, Nd and Pb. However, due to the very low concentrations involved (less than 0.008 ppm) and the necessity of overspiking in order to be able to detect U, errors on the U determinations are subject to high error propagation factors (up to times 20). The errors on the measurements for U, generally less than 10% (SD), are probably more representative of the error on the concentrations. At these low concentrations this level of error on the U concentrations has little effect on the calculated initial Pb isotope ratios. Sr concentrations were determined by X-ray fluorescence spectrometry (Jensen et al., 1993).

#### 4. Results

Sr-, Nd- and Pb-isotope ratios and Rb, Sr, Sm, Nd, U and Pb concentrations for the 15 plagioclase

separates are presented in Table 1. Measured <sup>87</sup>Sr/<sup>86</sup>Sr ratios range from 0.704855 to 0.706201, <sup>143</sup>Nd/<sup>144</sup>Nd ratios from 0.511890 to 0.512246 and <sup>206</sup>Pb/<sup>204</sup>Pb, <sup>207</sup>Pb/<sup>204</sup>Pb and <sup>208</sup>Pb/<sup>204</sup>Pb ratios from 17.549–17.766; 15.509–15.544 and 36.924–37.104, respectively. These data agree well with the whole rock Sr- and Nd-isotope data of Nielsen et al. (1996) for samples from the same stratigraphic sequence (Fig. 2).

The <sup>143</sup>Nd/<sup>144</sup>Nd and <sup>147</sup>Sm/<sup>144</sup>Nd ratios show a positive correlation defining a 738 ± 158 Ma isochron (MSWD = 0.08). This age is not in agreement with previous radiometric age determinations (946 ± 14 Ma and 955 ± 8 Ma, Pasteels et al., 1979) and is not considered to have any chronological meaning. Rb/Sr and U/Pb data do not retain any geochronological information.

Fig. 2 places the Bjerkreim–Sokndal data into local context in terms of Sr and Nd isotope ratios at their time of formation (940 Ma). The Bjerkreim–Sokndal plagioclase separates have positive ε<sub>Nd</sub> at 940 Ma, but with increasing <sup>87</sup>Sr/<sup>86</sup>Sr ratio ε<sub>Nd</sub> approaches 0. The positive ε<sub>Nd</sub> of 2.6 of the plagioclase at the base of IVb indicates that it crystallised from a magma that came either directly from a source in the depleted mantle or a source which was itself recently derived from the mantle at 940 Ma. The correlation between initial Sr and Nd isotope ratios for the Bjerkreim–Sokndal intrusion is typical of mantle-derived material, reflecting a time-integrated LREE depleted character (at 940 Ma), contaminated by material which has a time-integrated LREE enrichment such as the continental crust (e.g., the gneissic country rock surrounding the Bjerkreim–Sokndal intrusion). It is worth noting that some samples from the adjacent Håland–Helleren anorthosite massif fall within the field of data from the Bjerkreim–Sokndal intrusion and therefore the incorporation of significant quantities of Håland–Helleren material into the Bjerkreim–Sokndal magma cannot be excluded on the basis of the Sr and Nd isotopic data.

Fig. 3 shows the variation in initial (940 Ma) Sr, Nd and Pb isotope ratios and Sm/Nd ratio with respect to stratigraphic height. The interplay between the three isotopic systems enables us to divide the isotopic stratigraphic profile into two parts: above and below the base of zone IVb. The lower part,

Table 1  
Sr, Nd, and Pb isotopic compositions for plagioclase separates from MCU III and IV of the Bjerkreim–Sokndal layered intrusion  
Initial isotopic compositions at 940 Ma.

Sample <sup>a</sup>	MCU	Height (m) <sup>b</sup>	Ar% <sup>c</sup>	$^{87}\text{Sr}/^{86}\text{Sr} \pm 2\sigma$ (m)	$^{143}\text{Nd}/^{144}\text{Nd} \pm 2\sigma$ (m)	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	Rb (ppm)	Sr (ppm)	Sm (ppm)	Nd (ppm)	U (ppm)	Pb (ppm)	$^{87}\text{Sr}/^{86}\text{Sr}_i$	$^{143}\text{Nd}/^{144}\text{Nd}_i$ (940 Ma)	$^{206}\text{Pb}/^{204}\text{Pb}_i$	$^{207}\text{Pb}/^{204}\text{Pb}_i$	
JL-1	IIIe	-90	44	0.706116 ± 8	0.512246 ± 17	17.766	15.531	37.104	1.34	952	1.08	5.07	0.007	0.82	0.706062	0.511455	0.6	17.684	15.525
JL-2	IIIe	-61	45	0.706201 ± 7	0.512066 ± 42	17.766	15.539	37.083	1.62	927	0.42	2.46	0.003	0.85	0.706134	0.511432	0.1	17.732	15.536
JL-2L				0.706137 ± 8															
JL-3	IIIe	-16	44	0.706185 ± 7	0.512178 ± 12	17.738	15.539	37.069	1.03	941	0.52	2.70	0.005	0.73	0.706143	0.511463	0.7	17.672	15.535
JL-4	IVa	12	49	0.705995 ± 7	0.511988 ± 20	17.600	15.518	36.937	1.38	867	0.21	1.65	0.005	1.14	0.705934	0.511516	1.8	17.558	15.515
JL-5	IVb	23	53	0.704855 ± 10	0.511915 ± 33	17.567	15.525	36.962	0.85	1086	0.20	1.77	0.005	0.71	0.704825	0.511559	2.6	17.499	15.521
JL-5L				0.704912 ± 11	0.511978 ± 11														
JL-6	IVb	37	51	0.705104 ± 10	0.511978 ± 11	17.619	15.543	37.044	1.15	1096	0.21	1.85	0.002	0.87	0.705064	0.511510	1.7	17.597	15.541
JL-6L				0.705102 ± 10	0.511931 ± 9														
JL-7	IVb	53	52	0.705140 ± 10	0.511942 ± 13	17.624	15.543	37.037	1.13	1073	0.26	2.20			0.705099	0.511503	1.5		
JL-8	IVb	64	51	0.705167 ± 8		17.624	15.543	37.037	1.31	1099	0.27	2.20	0.002 <sup>d</sup>	0.88	0.705121	0.511547	2.4	17.602	15.541
JL-8L				0.705169 ± 11	0.512002 ± 10														
JL-9	IVb	75	51	0.705223 ± 10	0.511932 ± 23	17.572	15.513	36.950	4.55	1060	0.22	1.93	0.002	1.37	0.705057	0.511509	1.6	17.558	15.512
JL-10	IVb	82	51	0.705234 ± 7	0.511890 ± 30	17.587	15.530	36.993	1.19	1078	0.193, 1.78, 0.190 <sup>c</sup>	1.80 <sup>c</sup>	0.006	1.44	0.705191	0.511494	1.3	17.547	15.527
JL-11	IVb	91	48	0.705217 ± 7	0.511922 ± 14	17.597	15.523	36.996	0.58	1032	0.16	1.56	0.007	1.59	0.705195	0.511541	2.3	17.554	15.520
JL-12	IVb	97	50	0.705246 ± 10	0.512022 ± 13	17.632	15.529	37.005	1.22	1036	0.34	2.44	0.005	1.09	0.705201	0.511505	1.6	17.588	15.526
JL-13	IVc	137	49	0.705298 ± 8	0.512007 ± 15	17.549	15.509	36.924	0.82	998	0.309, 2.30, 0.306 <sup>c</sup>	2.30 <sup>c</sup>	0.002	2.2	0.705266	0.511507	1.6	17.540	15.508
JL-14	IVc	176	48	0.705609 ± 8	0.511973 ± 28	17.620	15.534	37.024	6.61	978	0.280, 2.10, 0.281 <sup>c</sup>	2.19 <sup>c</sup>	0.002	1.73	0.705348	0.511478	1.0	17.609	15.533
JL-15	IVd	228	48	0.705701 ± 8	0.512063 ± 16	17.729	15.544	37.092	1.81	976	0.35	2.31	0.006	0.8	0.705629	0.511501	1.5	17.657	15.539

<sup>a</sup>L after the sample number indicates Sr and Nd isotope ratios on leached sample.

<sup>b</sup>Stratigraphic height relative to 0 at the base of MCU IVa.

<sup>c</sup>Duplicate chemistry.

<sup>d</sup>U content for JL-8 estimated.

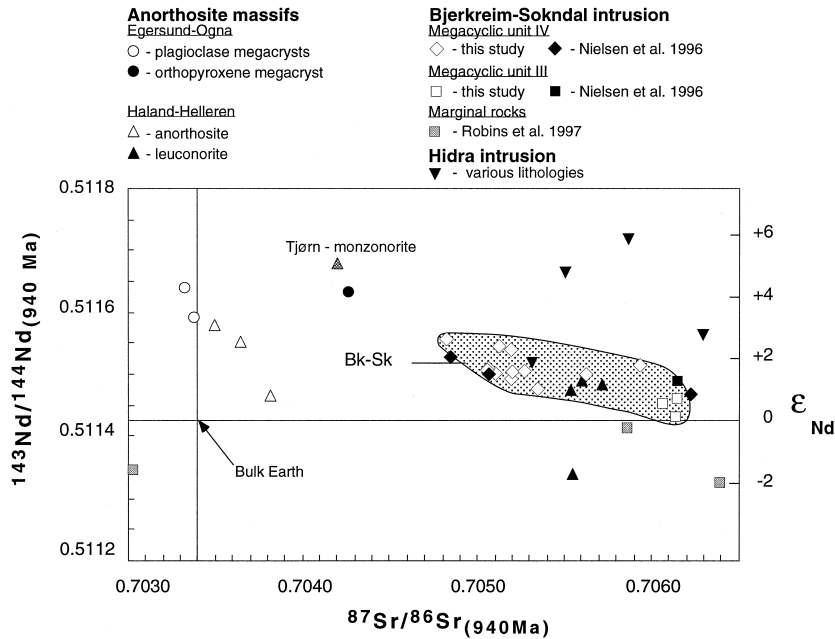


Fig. 2. Nd- vs. Sr-isotope ratios at 940 Ma for intrusions of the South Rogaland Igneous Complex. Additional data from: Demaiffe et al. (1986), Menuge (1988), Nielsen et al. (1996) and Robins et al. (1997).

from the base of the profile in MCU IIIe to the base of zone IVb (samples JL-1 to JL-5) includes the MCU III/IV boundary. As previously described (Jensen et al., 1993; Nielsen et al., 1996) the initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio decreases dramatically across the MCU III/IV boundary. The new Sr isotope data presented here confirm this and are matched by a decrease in initial  $^{206}\text{Pb}/^{204}\text{Pb}$  ratio and an increase in initial  $^{143}\text{Nd}/^{144}\text{Nd}$  ratio across this boundary (Fig. 3).

The initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio in zone IIIe (samples JL-1 to JL-3) at the bottom of the profile is relatively high (0.7061) and decreases across zone IVa to 0.7048 at the base of zone IVb (JL-5). The sample from zone IVa (JL-4) has an initial  $^{87}\text{Sr}/^{86}\text{Sr}$  value (0.7059) closer to that of zone IIIe than to that of the overlying IVb. Initial Pb isotopic ratios also decrease across zone IVa (from  $^{206}\text{Pb}/^{204}\text{Pb} = 17.66$ –17.73 in zone IIIe to 17.49 at the base of zone IVb) but in this case the initial Pb isotope ratio in zone IVa ( $^{206}\text{Pb}/^{204}\text{Pb} = 17.55$ ) is closer to that of the overlying zone IVb. If plagioclase in zone IVa crystallised from a simple binary mixture of replenishing magma

(reflected by plagioclase composition at the base of zone IVb) and resident magma (reflected by zone IIIe plagioclase composition), then the Sr and Pb isotope ratios of the zone IVa sample indicate that the Sr/Pb concentration ratio in the replenishing magma was significantly lower than that in the resident magma.

Initial Nd isotope ratios increase across zone IVa from  $^{143}\text{Nd}/^{144}\text{Nd} = 0.51143$ –0.51146 ( $\epsilon_{\text{Nd}} = 0.1$ –0.7) in zone IIIe to 0.51155 ( $\epsilon_{\text{Nd}} = +2.6$ ) at the base of zone IVb. The initial Nd isotope ratio in zone IVa ( $^{143}\text{Nd}/^{144}\text{Nd} = 0.51151$ ;  $\epsilon_{\text{Nd}} = 1.6$ ) is slightly closer to that of the overlying zone IVb. As with the initial Pb ratios, the relative shift in the zone IVa initial Nd ratio towards zone IVb values is far greater than that seen in the initial Sr ratio in zone IVa; indicating, in this case, that the Nd/Sr concentration ratio is significantly higher in the replenishing magma than in the resident magma.

These coupled changes in isotopic compositions at the base of our isotopic profile are consistent with past interpretations of the MCU III/IV boundary as marking a magma chamber replenishment event, dur-

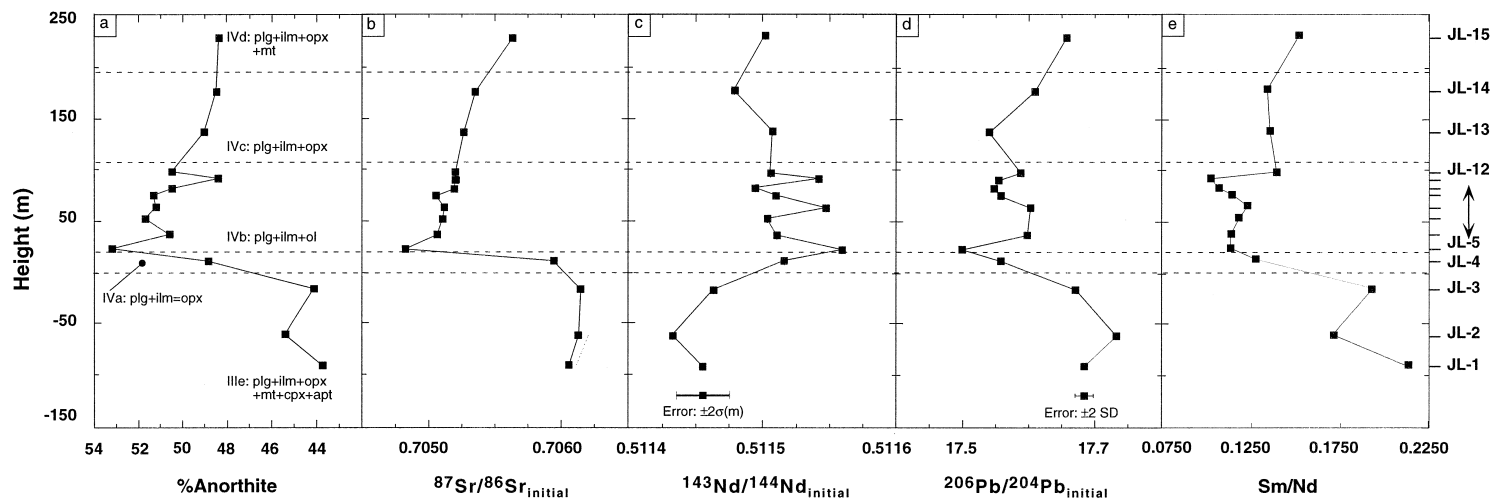


Fig. 3. (a) Cumulate mineralogy and variation of percent anorthite in plagioclase (Jensen et al., 1993) with stratigraphic height (0 = base of MCU IVa). (b–d) Variation of initial Sr-, Nd- and Pb-isotope ratios with stratigraphic height. The  $\pm 2\sigma(m)$  error on measured Sr-isotope ratios is smaller than the data points. (e) Variation of Sm/Nd ratio with stratigraphic height.

ing which an influx of relatively mafic, isotopically relatively depleted magma, mixed with more evolved, crustally contaminated magma resident in the chamber (Nielsen and Wilson, 1991; Nielsen et al., 1996; Jensen et al., 1993). Since MCU III and IV show similar lithological sequences from zone a to zone e (Nielsen and Wilson, 1991), the resident magma at the time of the MCU IV influx probably evolved from a replenishing magma compositionally similar to the MCU IV replenishing magma. If this is true, then the intermediate isotopic composition of the zone IVa sample indicates that the resident magma had been depleted in Pb and Nd relative to Sr.

Above the base of zone IVb the variations in initial Sr isotope ratios are decoupled from variations in initial Nd and Pb isotope ratios (Fig. 3). Whereas the initial Sr isotope ratio is lowest at the base of zone IVb ( $^{87}\text{Sr}/^{86}\text{Sr} = 0.7048$ ) and increases smoothly up profile to zone IVd ( $^{87}\text{Sr}/^{86}\text{Sr} = 0.7056$ ), the initial  $^{206}\text{Pb}/^{204}\text{Pb}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios show significant fluctuations within zone IVb. Such variations cannot be explained by simple binary mixing whether between replenishing and resident magmas or between resident magma and crustal contaminant. It is necessary therefore to consider additional and/or alternative processes in interpreting the profile from zone IVb upwards.

Rb/Sr and U/Pb ratios in the plagioclase separates exhibit limited range of values, however, there are systematic variations in the Sm/Nd ratios with respect to stratigraphic height (Fig. 3(e)). The Sm/Nd ratio is high and variable in MCU IIIe (0.17–0.21) and shows a sharp decrease across MCU IVa to a Sm/Nd ratio of  $0.11 \pm 0.01$  for most of MCU IVb. From the top of MCU IVb to the top of the sampled sequence (MCU IVd) the Sm/Nd ratio is again higher (0.13–0.15). The origin of the variations in Sm/Nd ratio in the plagioclases are discussed in a later section.

## 5. Discussion

### 5.1. Replenishment and magma mixing

Considerable attention has been given to the identification of the parental magma composition for the

Bjerkreim–Sokndal intrusion (e.g., Duchesne and Hertogen, 1988; Robins et al., 1997). A monzonitic parental composition is generally accepted and a chilled monzonorite from the Bjerkreim–Sokndal intrusion (the Tjørn composition) has been investigated experimentally by Vander Auwera and Longhi (1994). These authors found that a composition similar to the Tjørn one, but slightly more magnesian, has phase equilibria at  $\leq 5$  kbar appropriate for the crystallisation sequence observed in the Bjerkreim–Sokndal intrusion. Although the isotopic composition of the Tjørn monzonorite is inappropriate for the MCU IV replenishing magma (cf. Figs. 2 and 5), it is the only Rogaland monzonorite for which there are Sr, Nd and Pb concentration data, we therefore assume that these concentrations (Weis, 1986; Duchesne and Hertogen, 1988; Duchesne et al., 1989) would be representative of a monzonitic replenishing magma.

Correlations between initial  $^{87}\text{Sr}/^{86}\text{Sr}$ ,  $^{143}\text{Nd}/^{144}\text{Nd}$  and  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios for the MCU III and IV Bjerkreim–Sokndal plagioclases are rather scattered and roughly linear (Fig. 5). However, if the  $(^{143}\text{Nd}/^{144}\text{Nd})_i - (^{87}\text{Sr}/^{86}\text{Sr})_i$  and  $(^{87}\text{Sr}/^{86}\text{Sr})_i - (^{206}\text{Pb}/^{204}\text{Pb})_i$  correlations are examined sequentially up section, it becomes apparent that plagioclases from the five samples traversing the replenishment interval show convex upward correlations. The  $(^{143}\text{Nd}/^{144}\text{Nd})_i - (^{206}\text{Pb}/^{204}\text{Pb})_i$  correlation for these five samples is linear; i.e., similar to the overall Bjerkreim–Sokndal trend. These correlations are consistent with binary mixing between an isotopically depleted replenishing magma and a resident magma that has become isotopically enriched by assimilation of continental crust. Interpreted in this way, the data reflect the relative Nd/Sr and Sr/Pb concentration ratios in the resident and replenishing magmas as deduced previously from examination of the isotopic stratigraphic profiles. That these correlations involve plagioclase from zone IIIe (i.e., pre-replenishment) suggests that mixing involved not only resident and replenishing magmas but also magma in the top layer of crystal mush in the magma chamber.

By means of a hyperbolic regression ( $Ax + Bxy + Cy + D = 0$ ) of samples JL-1 to JL-5 and the assumption that the plagioclases from zone IIIe and the base of zone IVb crystallized in isotopic equilibrium from the resident and replenishing magmas,

respectively, we can calculate the value of the coefficient  $r$  from the coefficients of the hyperbolae (Vollmer, 1976; Langmuir et al., 1978; Juteau et al., 1986; Barling et al., 1994). This coefficient corresponds to the ratio of the element concentration ratios of the resident and replenishing magmas (e.g.,  $r = (\text{Sr/Pb}_{\text{resident}})/(\text{Sr/Pb}_{\text{replenishing}})$ ). Using the Sr, Nd and Pb concentrations of the Tjørn monzonite as representative of the concentrations of these elements in the replenishing magma, we can now calculate the Nd/Sr and Sr/Pb ratios of the resident magma and then, with an estimate of the Sr concentration of the resident magma (400–460 ppm;

Duchesne, 1978) its Nd and Pb concentrations (Table 2). The calculated Nd/Sr and Sr/Pb ratios and Nd and Pb concentrations of the resident magma are completely independent of the concentrations of these elements measured in the plagioclase separates and thus avoid uncertainties associated with mineral/melt partition coefficients, with purity and homogeneity of the plagioclase separate and with the use of a separate (leached) sample aliquot for the determination of the initial Pb isotopic composition.

The resulting Nd and Pb concentrations for the resident magma (Table 2) are extremely low (2.4–2.7 ppm and 0.18–0.20 ppm, respectively) compared

Table 2

(A) Regression of isotopic compositions across the MCU III/IV boundary in the Bjerkreim–Sokndal intrusion. (B) Sr, Nd and Pb concentrations for replenishing and resident magmas. (C) Sr, Nd and Pb concentrations for monzonorites and evolved igneous compositions from the South Rogaland Igneous Complex and for gneissic country-rock from South Norway

A: Regression	Nd–Sr		Sr–Pb		
Max. $^{87}\text{Sr}/^{86}\text{Sr}$ for resident magma	0.70624	$\pm 0.00020$	0.70620 $\pm 0.00016$		
Max. $^{143}\text{Nd}/^{144}\text{Nd}$ for replenishing magma	0.51157	$\pm 0.00002$			
Min. $^{206}\text{Pb}/^{204}\text{Pb}$ for replenishing magma			17.486	$\pm 0.027$	
$r$ value ( $= (y/x)_{\text{resident}}/(y/x)_{\text{replenishing}}$ )	0.08		20.83		
B: Magma characteristics	Sr (ppm)	Nd (ppm)	Pb (ppm)	Nd/Sr	Sr/Pb
Replenishing magma (Tjørn composition)	530	39.6	4.9	0.075	108
Resident magma (calculated)	400	2.38	0.18	0.006	2253
	460	2.74	0.20		
C: Compositions for comparison					
Average monzonorite <sup>a</sup>	399	70	7.8	0.17	78
Range	315–593	13–296	5.3–9.9	0.04–0.50	
$n$	21	21	5	21	1
Average (quartz-)mangerite/charnockite	196	69	20	0.42	8
Range	44–840	21–117	9–43	0.05–0.89	1.2–34
$n$	136	33	72	33	71
Average leucogranitic enclave <sup>b</sup>	84	8.6	22	0.14	4.5
Range	25–203	1.6–13	17–30	0.04–0.26	0.8–12
$n$	4	4	4	4	4
Average augen gneiss <sup>c</sup>	809	39	24	0.05	36
Range	346–1212	17–64	18–30	0.03–0.07	11.5–67.3
$n$	19	19	17	19	17
Average gneiss (incl. augen gneiss)	447	38	25	0.05	36
Range	28–1212	17–64	7.9–42	0.03–0.07	11.5–67.3
$n$	41	23	23	19	17

<sup>a</sup>Excluding Tjørn composition.

<sup>b</sup>Wilmart and Duchesne, personal communication.

<sup>c</sup>Bingen, 1988; Bingen et al., 1993.

Other data sources: Versteve, 1975; Demaiffe et al., 1979; Pasteels et al., 1979; Wielens et al., 1980; Weis, 1986; Weis and Demaiffe, 1983; Wiebe, 1984; Menuge, 1988; Wilmart et al., 1989; Duchesne and Wilmart, 1997; Duchesne et al., 1987, 1989; Robins et al., 1997.

both to typical evolved magma compositions from the South Rogaland Igneous Complex (mangerites and quartz-mangerites) and to likely contaminants such as leucogranitic enclaves (found in the upper part of the intrusion, Wilmart and Duchesne, 1992; Duchesne and Wilmart, 1997 and personal communication) and gneissic country-rock (Demaiffe et al., 1979; Wielens et al., 1980; Weis and Demaiffe, 1983; Menuge, 1988; Bingen et al., 1993). If the Nd and Pb concentrations in the resident magma are in fact higher, then our choice of replenishing magma composition was too depleted in Nd and Pb. However, although the Tjørn composition has amongst the lowest Nd and Pb concentrations measured in Rogaland monzonorites (Table 2), the work of Vander Auwera and Longhi (1994) indicates that the parental (replenishing) magma was probably more magnesian, i.e., more primitive, than the Tjørn composition. Furthermore, five of the seven marginal jotunitic (monzonoritic) rocks from the Bjerkreim–Sokndal intrusion, interpreted by Robins et al. (1997) as marginal chills, have Nd concentrations lower than the Tjørn composition (13.42 to 29.47 ppm compared to 39.6 ppm). Although no Pb concentrations are available for these marginal rocks, it is likely that, if anything, the replenishing magma would have had lower, and not higher Nd and Pb concentrations than the Tjørn composition.

It seems then that the resident magma had extremely low Nd and Pb concentrations. If it was initially similar to other evolved magma compositions from the South Rogaland Igneous Complex (Table 2), then a decrease in Nd and Pb concentration could occur as a result of extensive crystal fractionation culminating in the crystallization of a Nd- and Pb-rich accessory phase. The most obvious accessory phase to effect such a depletion in Nd and Pb would be apatite, which first appears in the Bjerkreim–Sokndal stratigraphy in the MCU IIIe gabbro-norites. However, while the anorthite content of plagioclase in MCU IV decreases upwards from  $An_{53}$  in MCU IVb to  $An_{48}$  in MCU IVd, the Sm/Nd ratios of plagioclase increases from  $0.11 \pm 0.01$  in MCU IVb to 0.15 in MCU IVd (Fig. 3(e)). If the replenishing magmas for MCU III and IV were similar, then the even lower anorthite contents ( $An_{44}$ ) and higher Sm/Nd ratios (0.21) of plagioclases in MCU IIIe suggest that plagioclases in both MCU III

and IV crystallised from magmas that became progressively LREE depleted as they evolved. For almost all common minerals, including apatite, crystal fractionation results in LREE enrichment of residual liquids. Very few minerals have the LREE enriched distribution coefficient patterns and compatible REE distribution coefficients necessary to effect both a LREE and overall REE depletion in a residual liquid. The most likely minerals with these characteristics are allanite and monazite, but neither is observed in the Bjerkreim–Sokndal Layered Series.

The simplest explanation for the correlation between increasing Sm/Nd ratio and decreasing anorthite content in MCU III and IV plagioclases is the presence of minute apatite inclusions in the plagioclase separates. Using rare earth element abundances of apatites from the Bjerkreim–Sokndal intrusion (Roelandts and Duchesne, 1979), it can be calculated that addition of less than 0.6 wt.% of apatite to plagioclase with Nd and Sm concentrations similar to plagioclase separates from MCU IVa/IVb is sufficient to produce the increase in Sm/Nd ratio and high Sm and Nd concentrations seen in the most extreme plagioclase separate (JL-1 from MCU IIIe). Less than half this amount of apatite would be required to produce the enrichment in Sm and Nd seen in the other plagioclase separates from MCU IIIe, IVc and IVd compared to plagioclase separates from MCU IVa and IVb. The presence of apatite in the plagioclase separates would also explain the unreasonably high plagioclase/liquid partition coefficients calculated for Nd and Pb in plagioclase with respect to the Nd and Pb concentrations in the model resident magma ( $D_{Nd} = 0.9–2.1$  and  $D_{Pb} = 3.6–4.8$ ).

Examination of the plagioclase separates from zones IIIe and IVd by electron microprobe found a single apatite inclusion in one (JL-2) of the four separates. It therefore seems probable that the plagioclase separates contain a small amount of minute apatite inclusions and that these are the cause of the observed variation in Sm/Nd ratio in ‘plagioclase’ with stratigraphic height. Assuming that the apatite inclusions and the host plagioclase were in isotopic equilibrium at their time of crystallisation, then the presence of such inclusions would have no effect on the calculated initial Nd, Sr and Pb isotopic ratios or the interpretation of the correlations between them.

## 5.2. Post-replenishment processes: zone IVb upwards

In this section we consider what additional processes might come into play as the magma chamber re-stabilised after replenishment (zones IVb–IVd) and whether or not these processes could have decoupled the Nd and Pb isotope variations in the plagioclases from the Sr isotope variations. For example, was this decoupling a feature of the magma from which the plagioclase crystallized or did it occur after crystallization of the cumulus plagioclase?

If the apparent decoupling of Nd and Pb isotope variations from Sr isotope variations were a feature of the magma, then diffusion or ternary mixing could have been the controlling process. However, if decoupling occurred after crystallization of the cumulus plagioclase then it could have resulted either from the presence of intercumulus residual melts in the cumulate pile (e.g., re-equilibration of cumulus plagioclase or crystallization of postcumulus plagioclase) or from the observed recrystallisation of the plagioclase (Jensen et al., 1993; Jensen, personal communication).

In considering diffusion it is necessary to distinguish between chemical and tracer (and self) diffusion. Chemical diffusion is driven by the presence of a chemical gradient. In the case of silicate liquids the rate of chemical diffusion of all elements, except alkalis, appears to be controlled primarily by the rate of diffusion of silicon and aluminium, the network-forming elements in silicate liquids (e.g., Baker, 1989, 1990). Thus, chemical diffusion of Sr, Nd and Pb should proceed at similar rates.

The rate of homogenisation of isotopic variations for a given element will be controlled by tracer diffusion, the rate of which is related to the size and charge of the ion and is a measure of the mobility of an ion in the melt. This type of diffusion occurs whether or not a chemical gradient is present. An experimental study by Baker (1989) has shown that the tracer diffusivity of Sr in silicate liquids is an order of magnitude higher than its chemical diffusivity, and that with time this leads to decoupling of element concentration and isotopic systematics.

Hofmann (1980) gives an empirical formula relating charge, ionic radius and diffusivity, to estimate

the diffusivity for tracer diffusion based on experimental data from basalts ( $\text{SiO}_2 = 48\%–49.68\%$ ) at  $1300^\circ\text{C}$ . The proposed parental/replenishing magma for the Bjerkreim–Sokndal intrusion has a  $\text{SiO}_2$  content of 49.7% (Duchesne and Hertogen, 1988), we have therefore used this formula to estimate the diffusivity for tracer diffusion of Sr, Nd and Pb. The estimated diffusivities for Sr and Pb, both of which are 2+ in silicate melts and have similar ionic radii, are very similar ( $2.71 \times 10^{-7}$  and  $2.56 \times 10^{-7} \text{ cm}^2 \text{ s}^{-1}$ , respectively) and larger than the diffusivity estimated for Nd ( $1.00 \times 10^{-7} \text{ cm}^2 \text{ s}^{-1}$ ), which is 3+ and has a much smaller ionic radius.

The possibility that such a difference in diffusivity for tracer diffusion could have a detectable effect in geological processes is supported by the work of Leshner (1990, 1994) who demonstrated in an experimental study of liquid state interdiffusion between natural felsic and mafic silicate compositions that isotopic homogenisation of Sr is faster than that of Nd. Perez and Dunn (1996) also found, in an experimental study of a natural rhyolite melt, that the diffusivities of Sr and Pb were similar and higher than the diffusivity of Nd. The difference was sufficient to produce contrasting behaviour in Sr–Pb and Nd in a model magma chamber with two isotopically distinct layers. In their model, significant diffusion controlled isotopic exchange of Sr and Pb could occur during the likely lifetime of the magma chamber. For Nd however, the diffusivity was low enough that the magma chamber was likely to solidify before the Nd isotopes were greatly perturbed.

We conclude that diffusion-controlled processes are most likely to result in the decoupling of Nd isotopic variations from those of Sr and Pb and therefore such processes are unlikely to be the primary cause of the variations seen in zone IVb of the Bjerkreim–Sokndal intrusion where Sr isotopic variations are decoupled from those of Nd and Pb.

Mixing of a third magmatic component into an isotopically stratified magma chamber can also cause apparent decoupling between different isotope systems, but only under certain circumstances. If the third component is identical in terms of isotopic composition and Sr, Nd and Pb concentration to either the replenishing magma, the original resident magma or any mixture of the two, then addition of the third component will merely shift the bulk iso-

topic composition of the magma along the original (primary) mixing trajectory between the replenishing and resident magmas. Interestingly though, if there is sufficient contrast in concentration of the elements of interest (Sr, Nd or Pb) between the more enriched and the more depleted components of the stratified magma and if the third component is closest in composition to the more enriched of the two primary components, then this kind of model can perturb the primary isotopic stratigraphy of the magma chamber, resulting in an apparent decoupling of the isotope ratios of one or more of the enriched elements from the isotope ratios of the other elements (Fig. 5(a)). In order for a third component to cause isotopic decoupling both in isotope stratigraphy and in isotope ratio diagrams (Fig. 5(b)), as is the case for the Bjerkreim–Sokndal plagioclases (e.g., Fig. 4) it must differ significantly from the primary mixing components, in the concentration of one or more of the elements of interest.

If the primary stratification in the Bjerkreim–Sokndal magma chamber resulted from mixing between a resident and replenishing magma, as reflected in the plagioclase separates from across the replenishment horizon, then the third component would have needed to be enriched in Nd and Pb compared to the original evolved magma in the magma chamber prior to the replenishment event. The degree of decoupling seen in the Bjerkreim–Sokndal isotope data can be achieved by heterogeneous mixing of between 0 and 20% of a Nd- and Pb-rich crustally contaminated magma into an already isotopically stratified magma chamber (Fig. 5(b)). Of the likely evolved melts from the Bjerkreim–Sokndal intrusion (Table 2), only the mangerite–quartz–mangerite–charnockite suite are sufficiently enriched in Nd and Pb to effect a decoupling of the isotopes of both these elements without at the same time effecting the Sr isotope stratigraphy. The leucogranitic enclaves, believed to represent roof melts (Duchesne and Wilmart, 1997), are too depleted in Nd to cause any significant shift in Nd isotopic composition.

This model can account for the general isotopic characteristics of plagioclases in zone IVb, but does not yield coherent results for each individual plagioclase separate. Unlike the simple binary mixing model for plagioclases from zone IIIe to the base of

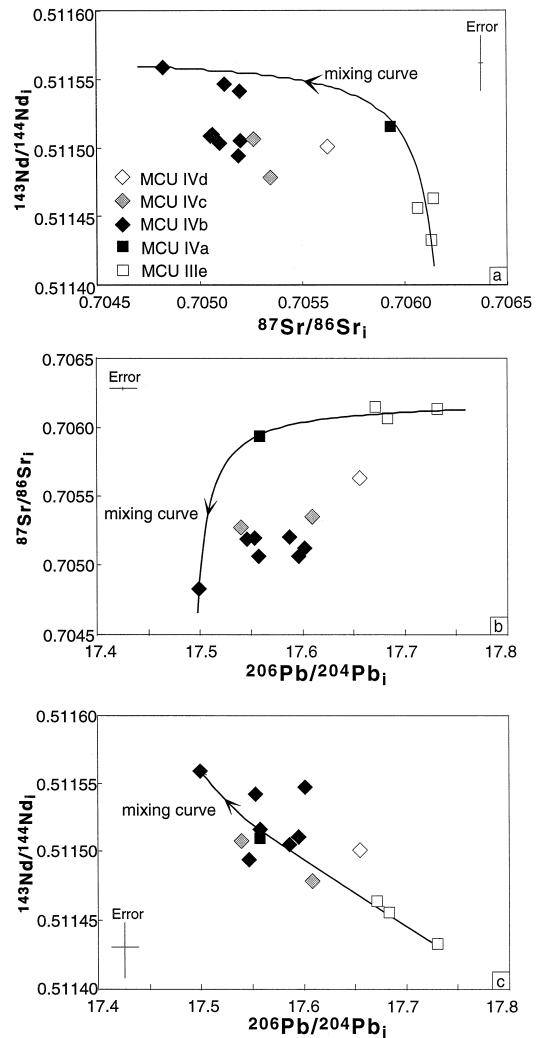


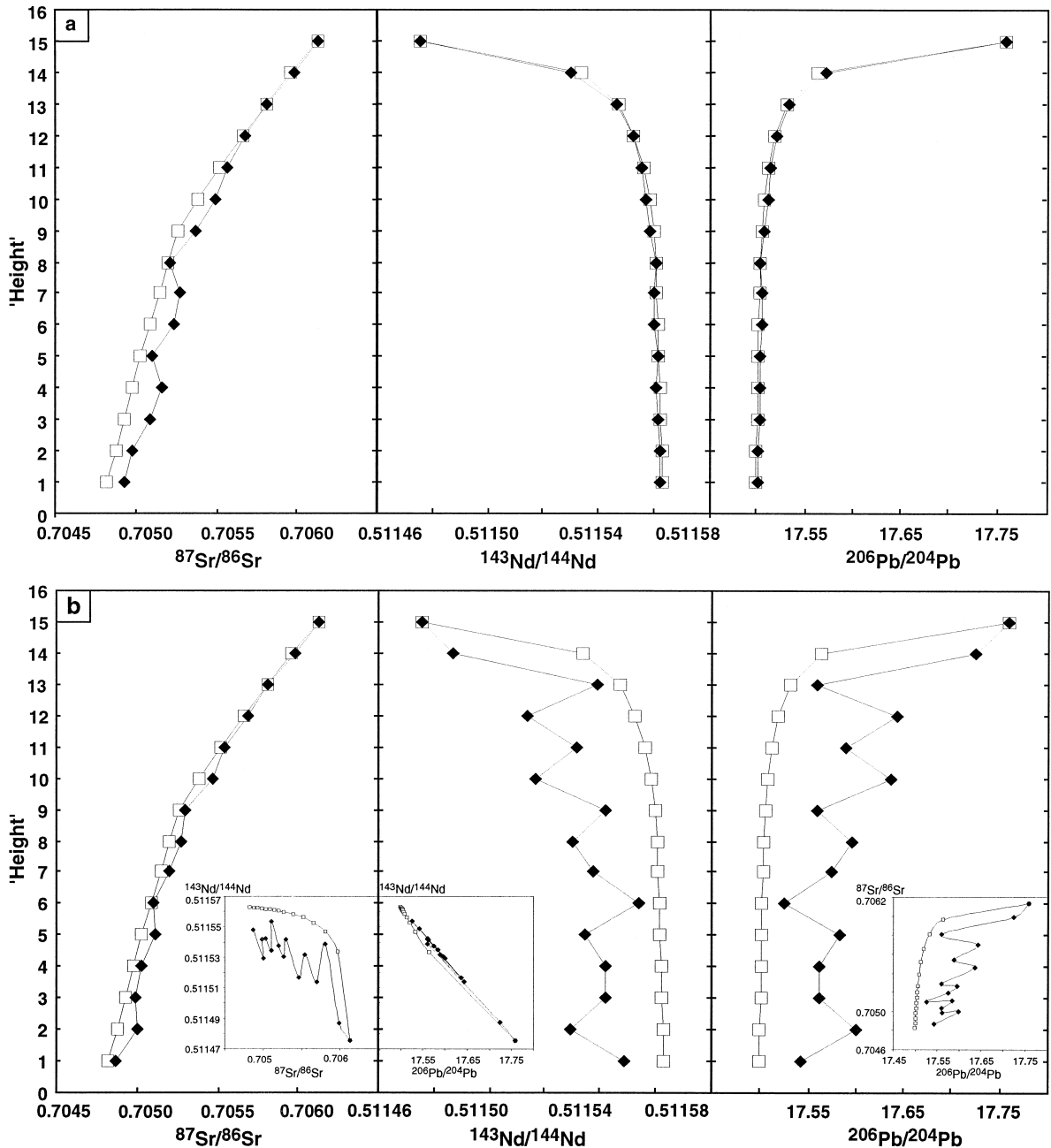
Fig. 4. (a) Nd- vs. Sr-isotope ratios, (b) Sr- vs. Pb-isotope ratios, and (c) Nd- vs. Pb-isotope ratios for Bjerkreim–Sokndal MCU III/IV plagioclase separates. Mixing curves between resident and replenishing magma indicated. Error bars for Sr- and Nd-isotope ratios are  $\pm 2\sigma(m)$  and for Pb-isotope ratios  $\pm 2$  SD.

IVb, in this model each individual plagioclase in IVb does not fall at the same point relative to the model, in each of the isotopic diagrams. We attribute this, at least in part, to the relative insensitivity of Nd isotope ratios as a tracer in this particular case. This is because the error on the measured Nd isotope ratios (typically  $\pm 0.00002$ ;  $2\sigma(m)$ ) is large (about 25%) compared to the range of initial Nd isotopic ratios (IVb–IVd: 0.511559–0.511478). The equivalent er-

rors for Sr ( $2\sigma(m)$ ) and Pb ( $2\text{ SD}$ ) are 1.25% and 8.25%, respectively.

Processes occurring after the crystallisation of the cumulus plagioclase could also effect the isotopic composition of the plagioclase. The last of these was

recrystallisation (Jensen et al., 1993; Jensen, personal communication). If the observed decoupling is related to recrystallisation, then the effects should be seen throughout the Storeknuten profile. This is not the case since, as demonstrated, the isotopic varia-



tions in Sr, Nd and Pb in plagioclases from zones IIIe to the base of IVb are coherent and consistent with a simple binary mixing model.

One feature which distinguishes zone IVb from other zones in MCU IV is the presence of small amounts of biotite and hornblende. These minerals, which are interpreted by Nielsen and Wilson (1991) as indicating the former presence of intercumulus melt, suggest that zone IVb was more porous than preceding and succeeding zones. Nielsen and Wilson (1991) and Jensen et al. (1993) suggest that postcumulus reaction between cumulus olivine and plagioclase and intercumulus melt (i.e., the “trapped liquid shift” of Barnes, 1986) was responsible for the local variations in the compositions of these minerals in zone IVb. Similar effects have been observed in other layered intrusions. In the Rum intrusion for example, downward migration of dense mafic replenishing magma into the cumulate pile at the unit 10–11 boundary is thought to be responsible for the reversal in the trend of decreasing Fo content in olivine at the top of unit 10 (Tait and Kerr, 1987). In contrast, in the Muskox intrusion upward migration of evolved intercumulus melt due to compaction of the cumulus pile is thought to be responsible for the upward displacement of chemical indications of replenishment (e.g., increase in Mg number, Ni and Cr content) relative to the modally defined level of replenishment (“infiltration metasomatism” of Irvine, 1980).

In the Storeknuten profile, olivine at the base and at the top of zone IVb is Fo<sub>75</sub> but decreases to Fo<sub>67</sub> in the middle, whilst plagioclase is An<sub>53</sub> at the base and fluctuates between An<sub>52</sub> and An<sub>48</sub> above this (Nielsen and Wilson, 1991; Jensen et al., 1993; Jensen, personal communication). If these variations were due to the presence of intercumulus melt, then the lower forsterite compositions in the middle of

zone IVb suggest that this melt was more evolved than the magma from which the cumulus olivine originally crystallised. An experimental study of dissolution kinetics of plagioclase by Tsuchiyama (1985) showed that at sub-liquidus temperatures a plagioclase which is more calcic than the equilibrium plagioclase of the melt surrounding it does not react appreciably, but acquires a more sodic overgrowth. This is the expected situation for cumulus plagioclase and intercumulus melt in the Bjerkreim–Sokndal magma chamber.

In order for such a melt to perturb the isotopic composition of the plagioclase in zone IVb, it cannot be residual melt trapped in the cumulate pile since the crystallisation of the cumulus plagioclase would have the same isotopic composition as the magma from which the cumulus plagioclase crystallised. Nor, as with the ternary mixing model, can it be identical in terms of isotopic composition and Sr, Nd and Pb concentration to either the replenishing magma, the original resident magma or any mixture of the two. If we look at the more general case of a contaminated, relatively evolved intercumulus melt in which concentrations of Sr, Nd and Pb are not those of any mixture of replenishing magma and original resident magma; for example if it has undergone crystal fractionation, but not to the extent of crystallizing a Nd- and Pb-rich accessory phase, then the isotopic composition of a bulk plagioclase separate (mixing curves 2 and 3 in Fig. 6(a) and (b)) could deviate substantially from the original isotopic composition of cumulus plagioclase crystallised from a mixed magma lying on the binary mixing curve between replenishing and resident magmas (mixing curve 1 in Fig. 6(a) and (b)). Numerically, this model is identical to the ternary magma mixing described previously and produces stratigraphic profiles similar to the ternary mixing model illustrated in Fig. 5. A

Fig. 5. Model stratigraphic profiles for Sr-, Nd- and Pb-isotopes in an isotopically stratified magma chamber (open symbols) into which up to 20% of a third component has been heterogeneously mixed (closed symbols). (a) Primary isotopic stratification is due to mixing between model resident magma and replenishing magma (Table 2). The third component is identical to the original resident magma. Nd and Pb are very depleted in this component and thus the Nd and Pb isotope profiles are unaffected by addition of the third component. The Sr-isotope profile, however, is slightly perturbed. (b) Primary isotopic stratification as for (a); but in this case the third component is a Nd and Pb rich magma (see Fig. 6 for details). The primary Nd- and Pb-isotope profiles are strongly perturbed and decoupled from the Sr-isotope record which is only slightly affected. Insets show isotope ratio diagrams for the model illustrated in the profiles. Note: for simplicity, the isotopic composition of this third component is the same as that of the original resident magma in this model. If a more contaminated magma is used, then a smaller amount is required to effect the same degree of perturbation.

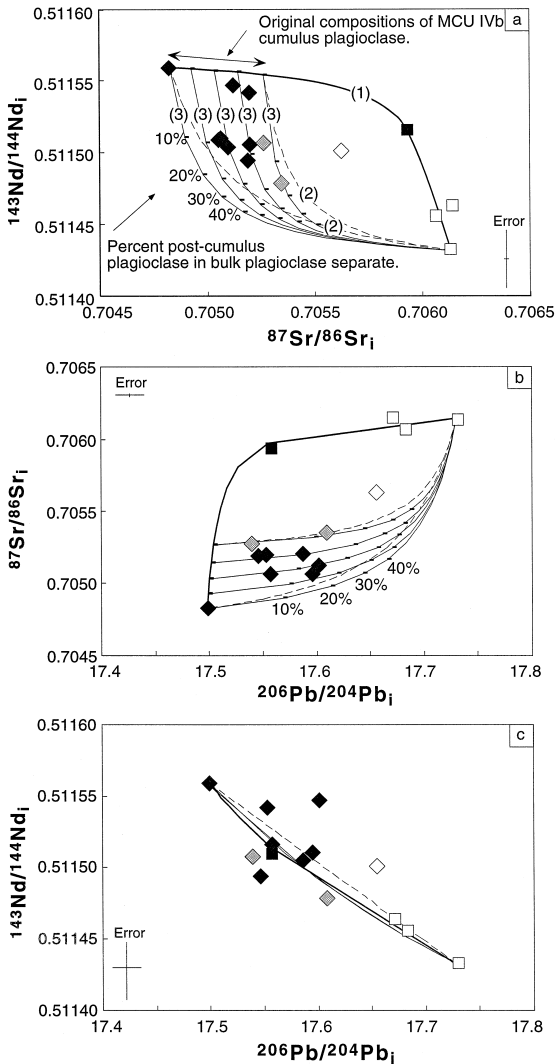


Fig. 6. Effect of addition of post-cumulus plagioclase crystallized from a Nd- and Pb-rich intercumulus melt on the isotopic compositions of the bulk plagioclase separate. In this model the isotopic composition of the circulating intercumulus melt is the same as that of the original contaminated resident magma, but its Sr concentration is lower (250 ppm) and its Nd and Pb concentrations are higher (100 ppm and 12.5 ppm, respectively). These values are within the range of values for mangerites and quartz mangerites from the South Rogaland Igneous Complex (Table 2). Curve (1) is for mixtures of resident and replenishing magma. For mixing curves (2) plagioclase/liquid partition coefficients for Sr, Nd and Pb are the same during crystallization of cumulus and post-cumulus plagioclase. For mixing curves (3), plagioclase/liquid partition coefficients for Sr, Nd and Pb are higher during crystallization of post-cumulus plagioclase ( $D_{\text{Sr}} = 2.3$ ,  $D_{\text{Nd}} = 0.10$ ,  $D_{\text{Pb}} = 0.225$ ) than during crystallization of cumulus plagioclase ( $D_{\text{Sr}} = 2.05$ ,  $D_{\text{Nd}} = 0.04$ ,  $D_{\text{Pb}} = 0.14$ ).

relatively Nd- and Pb-rich intercumulus melt might originate as an accumulated residual melt migrating upward from MCU I to III. Such a melt would probably show little evidence of fractionation of apatite since this mineral first appears in MCU IIIe, and might remain relatively isolated from interaction with cumulate minerals if melt migration occurred via chimneys like those described by Tait and Jupart (1992). An alternative origin for the Nd- and Pb-rich melt could be as evolved melts from higher up in the magma chamber. However, in this case a mechanism is required to gravitationally destabilise presumably more buoyant evolved melt in order for it to interact with the cumulate pile deeper within the magma chamber.

It is worth emphasising that in this model there is little change in the Sr isotopic composition of the bulk plagioclase, i.e., the variations in Sr isotopic composition record primarily the original mixing event (Figs. 5 and 6). In contrast, the Nd and Pb isotope fluctuations record secondary processes (Fig. 6(a) and (b)). However, when Nd and Pb isotope ratios are considered together (Fig. 6(c)), it is not possible to distinguish between cumulus and post-cumulus plagioclase as the isotopic trends for both are identical within the error of our measurements of Nd and Pb isotope ratios. This is because the Nd/Pb concentration ratios are very similar in both the replenishing and resident magmas and the proposed intercumulus melt, and thus in this case, the various mixing trends are all close to linear.

We can also observe in Fig. 6 that the entire range of deviation of the plagioclase isotopic compositions from the assumed original mixing line (mixing curve 1 in Fig. 6(a) and (b)) can result from crystallisation of post-cumulus plagioclase equivalent to < 20% of the total plagioclase. If the post-cumulus plagioclase occurs as rims on the cumulus plagioclase grains, then this amount of post-cumulus plagioclase is equivalent to the growth of a < 40  $\mu\text{m}$  rim on a 1 mm cube.

Although neither the ternary magma mixing model nor the crystallisation of post-cumulus plagioclase model can account for the isotopic data on a point by point basis, we feel that they provide relatively simple mechanisms to account for the observed decoupling of the Nd and Pb isotopic variations from Sr isotopic variations. The two models could poten-

tially be distinguished by the presence of a compositionally distinct rim on plagioclases which have undergone crystallisation of post-cumulus plagioclase. Unfortunately, recrystallisation of the plagioclase from the Bjerkreim–Sokndal intrusion (Jensen et al., 1993; Jensen, personal communication) has removed the possibility of making this observation.

## 6. Conclusions

(1) Plagioclase separated from samples traversing the MCU III/IV boundary in the Bjerkreim–Sokndal layered intrusion shows systematic variations in initial Sr-, Nd- and Pb-isotope ratios with stratigraphic height.

(2) On the basis of the interplay between the three isotopic systems, the isotopic stratigraphic profiles can be divided into replenishment and post-replenishment segments.

(3) Across the replenishment interval isotopic variations are consistent with the interpretation that mixing between a resident and a replenishing magma was the dominant process during replenishment, but that there was probably some interaction between the top layer of crystal mush in the magma chamber and the replenishing magma.

(4) The replenishing magma was characterized by  $^{87}\text{Sr}/^{86}\text{Sr}_i = 0.7048$ ,  $^{143}\text{Nd}/^{144}\text{Nd}_i = 0.51156$  ( $\epsilon_{\text{Nd}} = 2.6$ ) and  $^{206}\text{Pb}/^{204}\text{Pb}_i = 17.50$ . The positive  $\epsilon_{\text{Nd}}$  of this magma indicates that its source region was either in the mantle or was itself recently derived from the mantle.

(5) The isotopic characteristics of the resident magma ( $^{87}\text{Sr}/^{86}\text{Sr}_i = 0.7061$ ;  $^{143}\text{Nd}/^{144}\text{Nd}_i = 0.51143$  ( $\epsilon_{\text{Nd}} = 0.1$ ) and  $^{206}\text{Pb}/^{204}\text{Pb}_i = 17.73$ ) indicate that it had assimilated crustal material. In addition, the isotopic correlations across the replenishment interval indicate that, prior to mixing, the resident magma had been strongly depleted in Nd and Pb, probably by fractionation of apatite. This is consistent with the presence of apatite in cumulates immediately below the replenishment interval.

(6) Above the replenishment interval, Nd and Pb isotopic variations are apparently decoupled from Sr isotopic variations.

(7) Two mechanisms are proposed for achieving this. The first is heterogeneous mixing of up to 20%

of a third magmatic component into an already isotopically stratified magma chamber. The second is the presence of 10–20% of post-cumulus plagioclase that crystallized from a migrating intercumulus melt. In both cases, the third component, like the original resident magma, had been contaminated by crustal material, but unlike the original resident magma it was less extensively fractionated and therefore had not been depleted in Nd and Pb.

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