33 IGC, The Nordic Countries

Magma Geopark - The Rogaland Anorthosite Province

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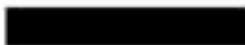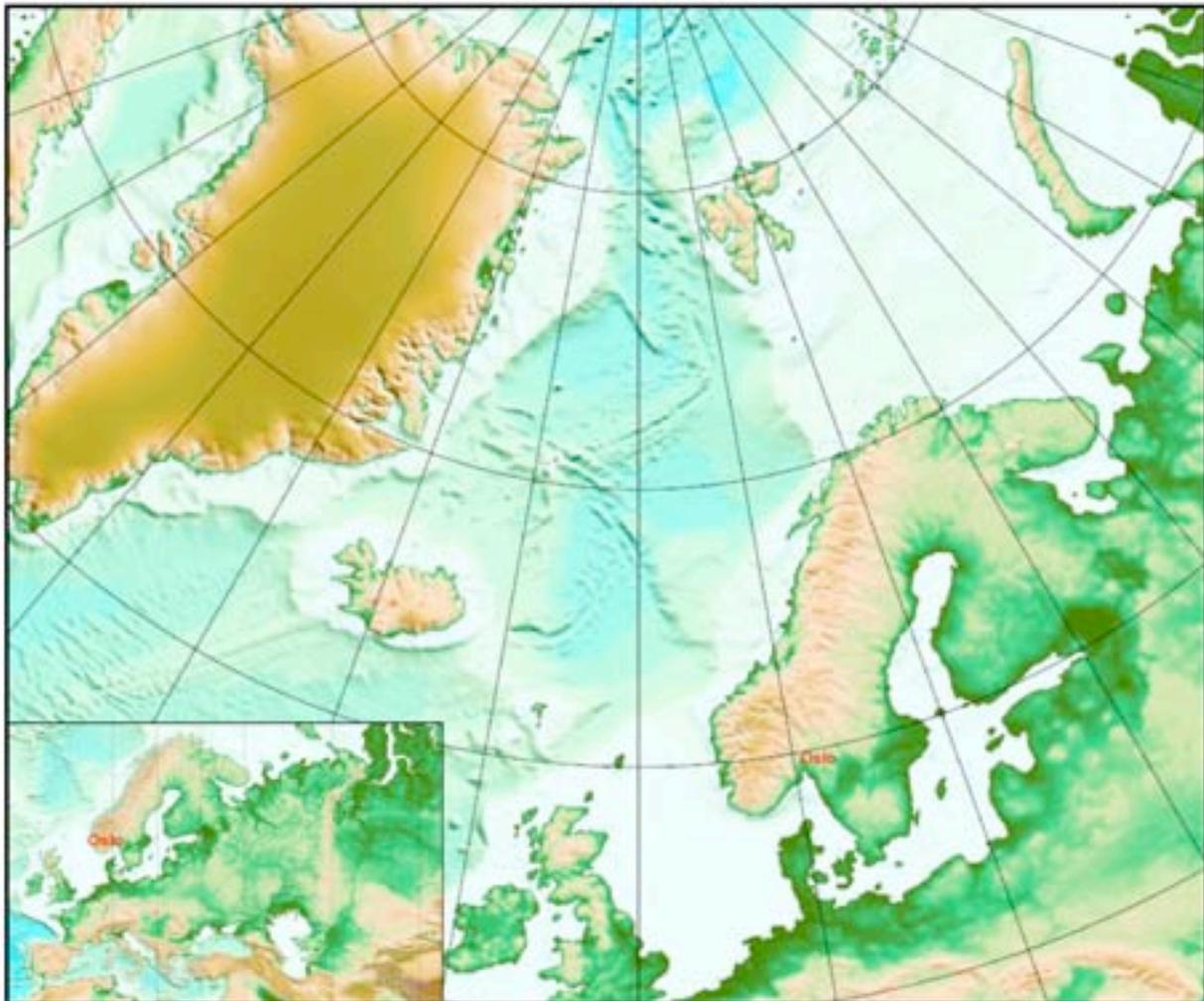
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Magma Geopark - The Rogaland Anorthosite Province: an excursion guide

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J. Richard Wilson, Brian Robins and Pål Thjømøe
(with technical assistance from Benjamin D. Heredia)

Abstract

Igneous rocks belonging to the Rogaland Anorthosite Province were intruded into gneisses of the Sveconorwegian orogenic belt in southern Norway. The province comprises three major anorthosite massifs (Egersund-Ogna, Åna Sira and Håland-Helleren), Norway's largest layered intrusion (Bjerkreim-Sokndal), two smaller anorthosite bodies, several broadly mangeritic (= hypersthene monzonite) intrusions, charnockites, and many minor intrusions of jotunite (= hypersthene monzonorite). The igneous activity took place over a surprisingly short period of time (at 931±3 Ma) at a depth of ~16-20 km. Contact metamorphism influenced gneisses that had previously reached granulite facies regional metamorphism and produced very high temperature mineral assemblages in the inner aureole. There is a long history of exploitation of iron-titanium ores in the province and it contains the largest active titanium mine in Europe at Tellnes.

The Rogaland Anorthosite Province forms the most important part of the Magma Geopark. The landscapes here are unique with bare, rounded, rocky outcrops stretching for as far as the eye can see. The mining history can be studied at several locations, including Blåfjell (titanium), Gursli (molybdenum) and Ørsdalen (tungsten and molybdenum). The landscape was strongly influenced by the Ice Age and many glacial features are well preserved, including chatter marks, glacial striations, perched erratics, end moraines, an esker (the superbly exposed St. Olav´s Orm) and many rock falls (including the huge block field in Gloppedal).

Logistics

Dates and location

Timing: The excursion runs from July 31st until August 5th.
Start location: For most participants this will be Stavanger Airport (Sola). We will collect participants from Sola after personal agreement with the leaders. Anyone travelling by car can meet in Egersund.
End location: Egersund (for those travelling by car) or Stavanger (Sola) airport.

Travel arrangements
Transport will be in a 16-seater minibus driven by the excursion leaders.

Accommodation
Egersund culture school (or the Grand Hotel).

Field logistics
Some of the localities involve walking for up to 2-3 km in fairly rough terrain. Walking boots and wet weather clothes are essential. Mosquito repellent and sun blocker may be required.

General Introduction

The purpose of the excursion is two-fold. It is partly to present the main rock types of the Rogaland Anorthosite Province and discuss the processes involved in their formation. It is also to present the concept of a geopark since the province forms a major part of the aspiring "Magma Geopark".

Foreword

This guide is, to a large extent, based on the comprehensive excursion guide to the Rogaland Intrusive Massifs published by Duchesne (2001) that describes a total of 42 localities.

The introductory text here is largely a modified and updated version of the 2001 text. Many of the figures here are, however, new. The localities described here are specifically those that we plan to visit during the 2008 excursion; these are mostly presented in greater detail than in the 2001 guide. Some of the sites to be visited have been described elsewhere as "Magma Geopark" localities. In these cases the relevant brochure is included as an enclosure.

J. Richard Wilson, Brian Robins and Pål Thjømøe

May 2008

Regional Geology

The Rogaland Anorthosite Province
(by J.C. Duchesne and B. Bingen; modified by J. R. Wilson)

The Sveconorwegian Orogenic Belt

The Rogaland Igneous Province is situated at the southwestern end of the exposed Sveconorwegian orogenic belt in Rogaland–Vest Agder. The Sveconorwegian belt of Fennoscandia is generally correlated with the Grenvillian belt of Laurentia. Both belts formed during a polyphase orogenic event between 1.25 and 0.90 Ga, at the transition between the Meso- and Neoproterozoic (Berthelsen 1980; Falkum 1985; Rivers et al. 1989; Gorbatschev & Bogdanova 1993; Davidson 1995; Rivers & Corrigan 2000). They are generally depicted as the product of collision between an unknown plate and the margin of the Fennoscandian and Laurentian shields respectively.

The Sveconorwegian orogen (Figure 1) is situated to the west of the 1.9 - 1.8 Ga Svecofennian domain and the 1.85 - 1.65 Ga Transcandinavian Igneous Belt. It is made up of a number of Palaeo- to Mesoproterozoic lithotectonic domains separated by major shear zones, and cut obliquely by the Palaeozoic Oslo rift (Berthelsen 1980; Gorbatschev & Bogdanova 1993; Åhäll & Gower 1997). No consensus exists today regarding the nomenclature of the lithotectonic domains; in the following text, crustal domains are divided into major domains called segments or terranes and smaller domains called sectors. The easternmost domain of the orogen, the Eastern Segment, is parautochthonous, and consists mainly of reworked granitoids of the Transcandinavian Igneous Belt foreland (Christoffel et al. 1999; Söderlund et al. 1999). The other domains, to the west of the Mylonite Zone, are Sveconorwegian allochthons (Park et al. 1991; Stephens et al. 1996; Möller 1998). Three major terranes, bounded by orogen-parallel shear zones, can be defined (Figure 1). These are, from east to west, the Idefjorden terrane (Åhäll et al. 1998), the Telemark - Bamble terrane and the Rogaland - Hardangervidda terrane. In this subdivision, the Idefjorden terrane extends on both sides of the Oslo rift and the Telemark - Bamble terrane includes the Telemark, Bamble and Kongsberg sectors, although the link between the Telemark sector and the Bamble and Kongsberg sectors is a matter of debate. To the west of the Mandal - Ustaoset Line, the Hardangervidda and the Rogaland - Vest Agder sectors are considered as a parts of a single terrane.

In the Sveconorwegian orogen, Sveconorwegian igneous rocks increase in volume westwards. 1.3 - 1.2 Ga pre- to early-Sveconorwegian igneous rocks of various types are distributed all over the orogen. The volume of this magmatism is poorly assessed in southern Norway. It comprises, among others, 1.20 Ga syenite plutons along the Sveconorwegian Frontal Deformation Zone (Jarl 1992), 1.20 Ga low-K diorite - tonalite plutons in the Bamble sector (Knudsen & Andersen 1999), the 1.28 Ga Iveland - Gautestad metagabbroic complex of low- to medium-K tholeiitic to calc-alkaline signature in the Telemark sector (Pedersen & Konnerup-Madsen 2000) and 1.27 - 1.25 Ga acidic volcanic rocks (Breive Group) of undefined geochemical signature in the Hardangervidda sector (Sigmond 1978; Bingen unpublished data). 1.19 - 1.15 Ga igneous rocks form a well-defined magmatic suite in the western part of the orogen in the Telemark - Bamble and Rogaland - Hardangervidda terranes. This suite includes (deformed) charnockitic to granitic plutons, volcanic rocks of the Bandak Group and minor (meta)gabbro bodies (Dons 1960; Dahlgren et al. 1990; Kullerud & Machado 1991; Heaman & Smalley 1994; Nordgulen et al. 1997; Zhou et al. 1995; Bingen & van Breemen 1998a). Granitoids in this suite display an A-type geochemical signature. As opposed to the Grenvillian orogen, no coeval anorthosite massifs are reported in the

Sveconorwegian orogen. A short-lived suite of high-K calc-alkaline porphyritic granodiorite plutons (Feda suite) intruded at 1.05 Ga in (and only in) the westernmost Rogaland - Hardangervidda terrane (Bingen et al. 1993; Bingen & van Breemen 1998a). Voluminous 1.00 - 0.90 Ga late- to post-tectonic plutonism occurs in the Idefjorden terrane and westwards (compilation in Andersson et al. 1996). The largest of these complexes are the 0.93 - 0.92 Ga Flå, Iddefjorden and Bohus granite plutons in the Idefjorden terrane (Eliasson & Schöberg 1991; Nordgulen et al. 1997) and the anorthosite massifs and related rocks in Rogaland - Vest Agder that are the subject of this guidebook. The emplacement of the Rogaland anorthosite complex is estimated to have taken place at 931 ± 3 Ma (Schärer et al. 1996), and represents a surprisingly short igneous event (<10 m.y.).

Sveconorwegian metamorphism varies in intensity from greenschist to granulite facies, and is not coeval in the different sectors. The Eastern Segment displays an amphibolite facies domain and a high-pressure granulite facies domain in the southern part with local occurrence of eclogite-facies rocks (Johansson et al. 1991; Möller 1998; 1999). The timing of high-grade metamorphism, including eclogite-facies overprint, is well constrained between 0.98 and 0.96 Ga (Connelly et al. 1996; Söderlund 1996; Andersson et al. 1999; Söderlund et al. 1999). In the Idefjorden terrane, the intensity and timing of Sveconorwegian metamorphism is not well constrained but it is older than 1.04 Ga (Romer & Smeds 1996). In the centre of the Telemark sector, metamorphism is generally of low grade and deposition of the impure clastic sediments of the Bandak and Heddal Groups (cover to the volcanic rocks) took place in an intraorogenic basin between 1.12 and 1.05 Ga and later (Bingen et al. 1999; de Haas et al. 1999). In the coastal regions of the Bamble sector, early-Sveconorwegian medium-pressure (~7.5 kbar) granulite facies metamorphism (Touret 1971; Lamb et al. 1986; Nijland & Maijer 1993; Knudsen 1996) is bracketed between 1.15 and 1.10 Ga (Kullerud & Machado 1991; Knudsen et al. 1997; Cosca et al. 1998). In the Rogaland - Vest Agder sector three phases of Sveconorwegian metamorphism are reported (Tobi et al. 1985, Maijer 1987). The main phase of regional metamorphism (M1, see below) is estimated to have taken place at 1.02 - 0.97 Ga (Bingen and van Breemen 1998b).

All the major Sveconorwegian shear zones were active during orogeny, but some may have formed initially during older events (Sigmond 1985; Heaman & Smalley 1994; Page et al. 1996). To the east of the Oslo rift, major shear zones display a sinistral shear component (Hageskov 1985; Park et al. 1991; Stephens et al. 1996). From the age of deformed intrusive rocks, ductile deformation in amphibolite facies conditions is constrained to be younger than 1.13 Ga along the Kristiansand - Porsgrunn shear zone (separating the Bamble and Telemark sectors, Figure 1) and younger that 1.04 Ga along the Mandal - Ustaoset Line (separating the Rogaland - Hardangervidda from the Telemark - Bamble terrane). Direct zircon dating of amphibolite facies metamorphism and associated ductile deformation yield ages of 0.98 - 0.97 Ga along the Mylonite zone (separating the Eastern Segment from the Idefjorden terrane) (Larson et al. 1999; Andersson et al. submitted) and 1.01 Ga along the Åmot - Vardefjell shear zone (separating the Idefjorden and Telemark terranes).

Understanding of the Sveconorwegian orogenic evolution on a continental scale is speculative today. Compilation of the ages of regional metamorphism indicates that the main orogenic phase took place between 1.02 and 0.96 Ga, with maximum shortening of the orogen at 0.97 Ga (age of eclogite facies metamorphism in the parautochthonous Eastern Segment). The age of metamorphism tends to decrease eastwards, suggesting that this phase propagated towards the foreland. This phase included large (sinistral transpressive?) displacement of terranes and thrusting of allochthon terranes on the parautochthonous Eastern Segment, and was followed by relaxation.
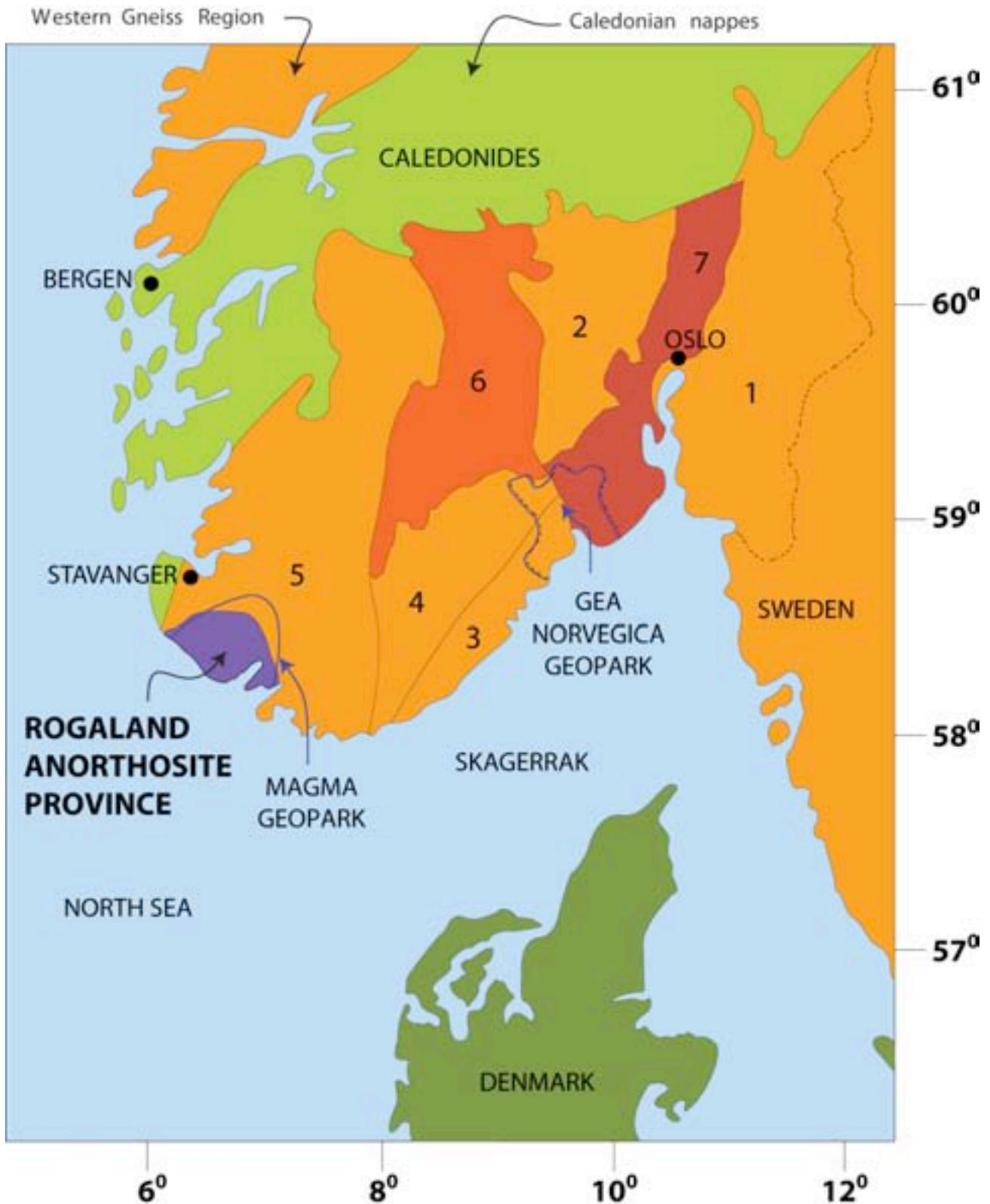
Figure 1. Key map of SW Scandinavia showing the major lithotectonic domains of the Sveconorwegian orogen. 1) Østfold sector; 2) Kongsberg sector; 3) Bamble sector; 4) Telemark sector; 5) Rogaland - Vest Agder sector (including the Rogaland Anorthosite Province); 6) Telemark Supracrustals (Precambrian); 8) Oslo Rift (Permian). Denmark consists of Mesozoic and younger deposits. The locations of Gea Norvegica and Magma Geoparks are shown.

The high-K calc-alkaline signature of 1.05 Ga granodiorite plutons (Feda suite in the west) led Bingen et al. (1993) to suggest that a subduction regime prevailed at 1.05 Ga and thus that the 1.02 - 0.97 Ga orogenic phase marked the end of subduction. The existence of a subduction regime is nevertheless not the only possible interpretation of geochemical data, as melting of a juvenile component of the lower crust in a distinct geotectonic environment is a possible alternative to generate this type of magmatism (Roberts & Clemens 1993; Liégeois et al. 1998). So far, no satisfactory geotectonic interpretation has been proposed for the early-Sveconorwegian 1.19 - 1.15 Ga magmatism and the following 1.15 - 1.10 Ga high-grade metamorphism preserved in the Bamble sector. Although the 1.19 - 1.15 Ga granitoids display an A-type geochemical signature, they cannot be considered as anorogenic. This early-Sveconorwegian magmatism and subsequent metamorphism possibly correspond to (1) docking of the allochthonous terranes, some of which would be exotic to the Fennoscandian shield before colliding, (2) closure of a back arc basin as represented by the Stora Le Marstrand belt in the Idefjorden terrane, or (3) large scale strike-slip motion of terranes of Fennoscandian affinity at the margin of the Fennoscandian shield.

Geological setting in Rogaland – Vest Agder

Following Falkum (1985; 1998), the amphibolite to granulite facies basement complex in the Rogaland - Vest Agder sector includes three main lithological units (Figure 2): banded gneiss, granitic "pink" gneiss and augen gneiss (Feda suite). The banded gneisses are strongly migmatitic and consist of alternating mafic and felsic bands ranging in thickness from less than a centimetre to several metres. Mafic rocks are amphibolite to norite and felsic rocks are leuco-granitoids. Intercalation of kinzigitic (garnet-cordierite-sillimanite-biotite) gneiss, metaquartzite, and marble are evidence of a supracrustal origin for at least part of the banded gneiss units. They have poorly defined Palaeo- to Mesoproterozoic ages (Versteeve 1975; Menuge 1988). Granitic pink (ortho-) gneiss intruded the banded gneiss and forms monotonous domains. Augen gneiss with large alkali feldspar phenocrysts (cm to dm size) form elongate bodies parallel to the regional structure. Intrusion of the porphyritic granodiorite plutons and their deformation to augen gneiss is estimated to have taken place at 1050 +2/-8 Ma (Bingen and van Breemen 1998a). Other major components of the Rogaland - Vest Agder sector are large c. 1.19 - 1.15 Ga meta-granitic to charnockitic plutons of A-type geochemical affinity (Gloppurdi, Botnevatn and Hidderskog bodies) (Versteeve 1975; Wielens et al. 1980; Zhou et al. 1995), ~ 0.98 - 0.90 Ga post-tectonic granites (Falkum 1966; Wilson et al. 1977; Pasteels et al. 1979) and the 0.93 Ga anorthosite massifs and related rocks (Schärer et al. 1996).

The Rogaland - Vest Agder sector is limited to the east by the Mandal - Ustaoset Line, a lithospheric scale deformation zone (Sigmond 1985). In the Mandal region, the Line is made up of a N - S trending amphibolite facies banded gneiss unit bordered to the west by an elongate augen gneiss body, the 1049 +2/-8 Ma Mandal augen gneiss. Post-tectonic granites straddle the Mandal - Ustaoset Line (Sigmond 1985; Andersson et al. 1996). They are especially voluminous directly to the west of the Line. This distribution suggests that the Mandal - Ustaoset Line channelled emplacement of post-tectonic granitoids. The Line is clearly a Sveconorwegian tectonic zone as deformation affected 1.05 and 1.035 Ga granitoids (Bingen and van Breemen 1998a). Nevertheless, along the northern part of the Line, evidence of deformation as old as 1.5 Ga is reported (Sigmond 1985; 1997), which implies that the tectonic zone was possibly active over a long time interval. Offshore geophysics indicate large offsets of the Moho south of the Mandal - Ustaoset Line and of the Feda zone (in Fig. 9 of Andersson et al. 1996), which suggests discontinuities of lithospheric scale. The Feda augen gneiss, which outcrops some 12 km east of the anorthosite massifs (Figure

2), might have intruded in a zone of weakness, in a similar way to the Mandal augen gneiss. Duchesne et al. (1999) have proposed that it could represent the zone along which the anorthosite bodies were emplaced. These basement rocks in Rogaland - Vest Agder underwent a long and complex tectonic and metamorphic evolution that includes several phases of folding and of interaction with plutonic rocks. North of the anorthosite province, Michot (1956b; 1960) recognized two phases of isoclinal folding with large recumbent folds (Storefjell nappe), followed by a vertical axial plane fold phase (Lakksvelefjeld syncline), which he extended into the Bjerkreim-Sokndal synform. Northeast and east of the anorthosite province, Hermans et al. (1975) identified four deformation phases and southeast of the province, in the Flekkefjord area, Falkum (1966; 1998) defined six fold phases. Detailed correlation between the deformation phases as defined by the various authors is still unclear, although the two phases of isoclinal folding that have been identified on a regional scale presumably resulted from the same events.

The grade of Sveconorwegian metamorphism increases from E to W and can be described as a succession of four isograds (Figure 2) (Tobi et al. 1985; Maijer 1987; Bingen et al. 1990): (1) clinopyroxene-in (Cpx-in) isograd, defined in the Feda augen gneiss suite, which marks the appearance of Cpx joining the amphibolite facies biotite + amphibole paragenesis; (2) orthopyroxene-in (Opx-in) in rocks of leucocratic composition; (3) osumilite-in (Osum-in) in supracrustal gneisses; (4) (inverted) pigeonite-in (Pig-in) in mafic rocks. The last two isograds wrap around the intrusions. The other two are parallel to the igneous contact southeast of the complex, but diverge from it in the north.

The isograd pattern results from the superposition of three major metamorphic phases, M1, M2 and M3 (Tobi et al. 1985; Maijer 1987). To account for some old age determinations, Priem & Verschure (1982) postulated another, older M0 phase, but the existence of this phase has not been substantiated by petrological data. A Caledonian prehnite-pumpellyite to lower greenschist facies M4 phase has been documented (Hermans et al. 1975). The intensity of M4 increases to the north and a green biotite-in isograd can be defined parallel to the Caledonian front to the north of the anorthosite province (Figure 2). The M2 metamorphism was the most intense phase and erased most of the M1 parageneses. It was not associated with pervasive deformation (as indicated by the preservation of corona-like textures and non-oriented mineral assemblages) and most likely corresponds to a thermal aureole around the anorthositic intrusions. Geothermobarometric methods provide temperatures for the M2 phase as high as 800–900°C in various lithologies, including osumilite + spinel + orthopyroxene and quartz + spinel parageneses in pelitic protoliths (Jansen et al. 1985; Wilmart & Duchesne 1987). The pressure conditions of crystallisation of the Bjerkreim-Sokndal intrusion were experimentally determined to be less or equal to 5 kbar (Vander Auwera & Longhi 1994), providing a good estimate for the pressure of the M2 contact metamorphism. This estimate is equivalent to the 5.5 kbar determined by thermodymamic modelling of osumilite-bearing mineral assemblages in the granulite-facies gneisses (Holland et al 1996) and is narrower than the previously estimated range, extending from 3 - 4 kbar (Jansen et al. 1985) to 6 - 7 kbar (Wilmart & Duchesne 1987), estimated by geothermobarometric methods in various gneisses and in charnockitic igneous rocks. A hornblende + quartz out isograd (not shown in Figure 2) has been documented by Maijer (1987) between the Opx-in and the Osum-in isograds.
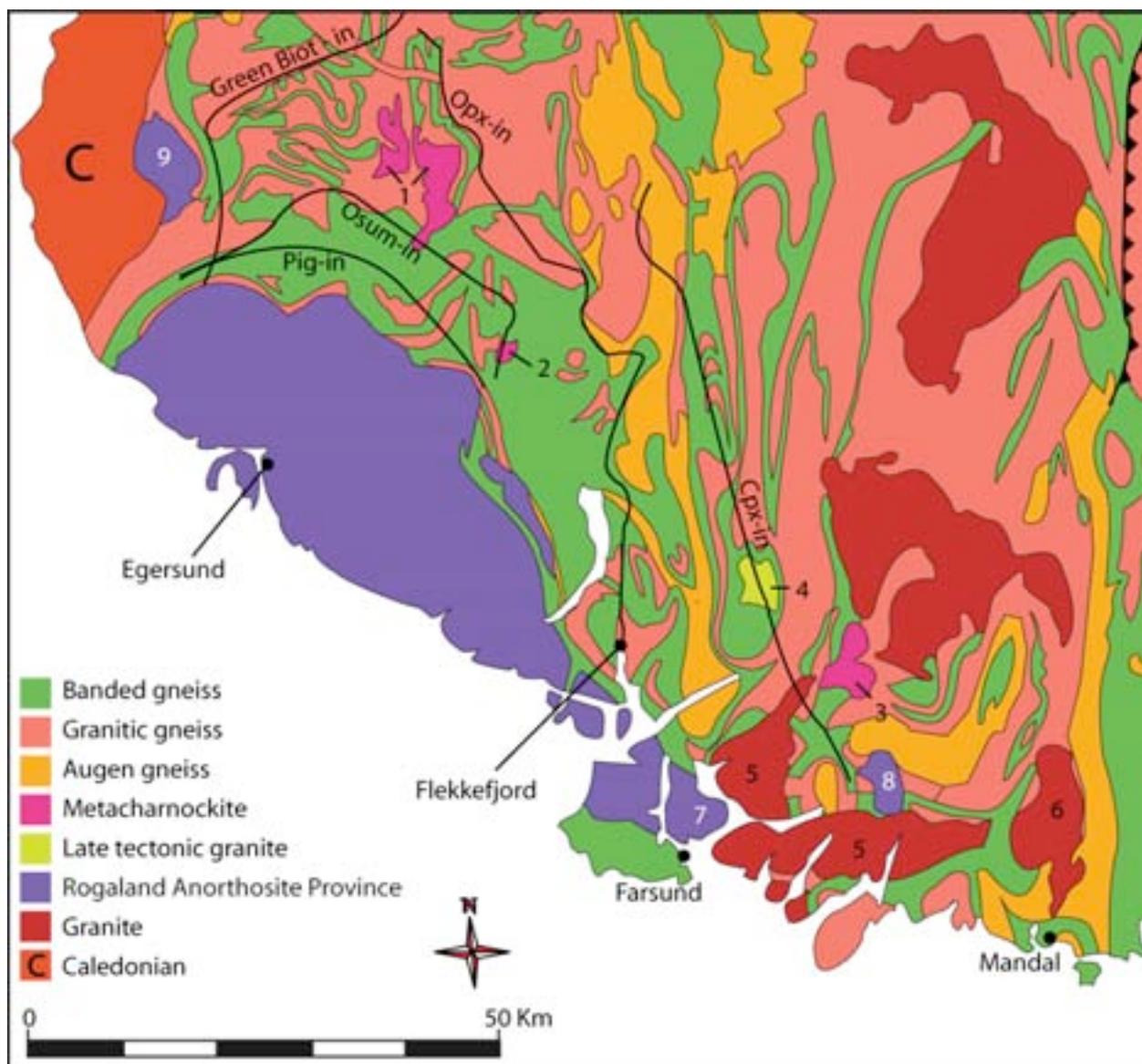
Figure 2. Geological map of the southern part of the Rogaland - Vest Agder segment. Isograds in the area: Pig-in = pigeonite-in, Osum-in = osumilite-in and Green Biot-in = green biotite-in, plotted after Tobi et al. (1985); Opx-in = orthopyroxene-in, after Falkum (1982); isograd Cpx-in = clinopyroxene-in, after Bingen et al. (1996). 1: Gloppurdi metacharnockite; 2: Botnevatnet metacharnockite; 3: Hidderskog metacharnockite; 4: Homme granite; 5: Lyngdal hornblende granite; 6: Holum granite; 7: Farsund charnockite; 8: Kleivan granite; 9: Sjelset charnockitic rocks.

To the west of this isograd, towards the contact of the anorthosite massif, 1 - 2 cm-thick "dehydration rims" of noritic composition are observed whenever amphibolites are in contact with quartzo-feldspathic rocks, i.e. in the banded gneiss or around mafic inclusions in acidic igneous rocks. They result from a metasomatic SiO_2 diffusion mechanism (Vander Auwera 1993). The constant rim thickness suggests static (atectonic) conditions during formation. The M3 phase, only very locally associated with a late deformation, is a phase of retrograde metamorphism producing a variety of corona textures, symplectites and exsolutions. A range of PT conditions (500 - 700°C and 3 - 4 kbar) have been reported (Jansen et al. 1985; Wilmart & Duchesne 1987). The composition of

metamorphic fluids changed from CO_2-rich fluids during the M2 phase to CH_4 and N_2 during the M3 phase (Van den Kerkhof et al. 1991). Relics of M1 mineral assemblages occur in metapelitic rocks (biotite + garnet + sillimanite), in mafic rocks (green hornblende + biotite + cpx) and in rocks with granitic composition (biotite + green hornblende). Sapphirine occurs locally in Mg-rich compositions (Hermans et al. 1975; Tobi et al. 1985; Maijer 1987).

The origin of the Opx-in isograd has long been debated. When it was originally mapped, it was interpreted as a product of the same contact metamorphism that produced the Osum-in and Pig-in isograds, although it is not strictly parallel with them (Tobi et al. 1985; Maijer 1987). Tobi and Jansen (cited in Maijer, 1987) were, however, not completely convinced by that interpretation because they suspected that granulite facies conditions were reached during the M1 phase in the western part of the area. For them, the Opx-in isograd reflects the transition from regional amphibolite facies in the east to granulite facies in the west, and is therefore older than the M2 phase. Later Bingen et al. (1990) mapped the Cpx-in isograd grossly parallel to the Opx-in isograd and showed that both isograds cut across the well-dated (1050 +2/-8 Ma) Feda augen gneiss suite. The emplacement age of the whole anorthosite complex was then measured by the U - Pb method on zircon and baddeleyite at 931 ± 3 Ma (Schärer et al. 1996). Recently Bingen & van Breemen (1998b) measured the age of a prograde breakdown reaction of monazite in the Feda suite, which they correlate with the Opx-in reaction, at 1024 - 970 Ma. This supports the hypothesis that the M2 phase and the Opx-in reaction can be decoupled, that the climax of metamorphism affecting the whole area is younger than 1050 Ma, and that the M1 phase of regional metamorphism reached granulite facies condition around 1.02 - 0.97 Ga. A cluster of monazite U - Pb ages in the range 930 - 925 Ma probably reflects the timing of M2 metamorphism. Titanite sampled at regional scale provides a well-grouped U - Pb average age of 918 ± 2 Ma reflecting regional cooling below ca. 610°C (Bingen and van Breemen 1998b).

The intrusive units in the Rogaland anorthosite province

The Rogaland anorthosite province comprises three large massif-type anorthositic bodies (Egersund, Håland-Helleren and Åna-Sira), a layered intrusion (Bjerkreim-Sokndal), two smaller bodies of leuconorite (Hidra and Garsaknatt) and to the south three acidic intrusions: the Farsund charnockite, the Lyngdal and the Kleivan granites (Figure 3). They are emplaced in an envelope of granulite facies gneisses with which most massifs show broadly concordant contacts. The geology of the Rogaland anorthosite province is shown in Enclosure 1 in a map on a scale of 1:75.000 (Marker et al. 2003).

The Egersund-Ogna body is made of monotonous anorthositic rocks. It is characterized by a central part somewhat enriched in aggregates of giant orthopyroxene and plagioclase crystals and by a leuconoritic marginal zone that is strongly foliated. The contact with the envelope is generally concordant. The overall structure is that of a mantled dome (Michot 1957b). The petrology of the Egersund-Ogna body is summarized and discussed later in this guidebook.

The Håland-Helleren body has been divided into two different units by Michot (1961a; 1961b). The Håland massif is made up of folded and foliated anorthosite and leuconorite in various proportions, with granoblastic structure, locally grading into an igneous-like association between anorthosite and (leuco)-norite. The progressive transition between metamorphic and igneous textures has beeninterpreted by P. Michot (1955b) and J. Michot (1957a) as due to a leuconoritic anatexis of pre-existing anorthosito-noritic gneisses.

The Helleren massif (formerly also called the Amdal-Helleren-Rödland massif) cuts across the Håland and the Egersund-Ogna massifs. It is dominated by coarse-grained anorthosite but includes leuconoritic parts and anorthosito-leuconoritic domains similar to those in Egersund-Ogna. It has other similarities with Egersund-Ogna, namely the presence of Al-rich orthopyroxene megacrysts and of inclusions of foliated anorthosito-noritic rocks. However, it lacks the foliated margin characteristic of the Egersund-Ogna body. The massif has been studied by Michot (1961a; 1961b) and interpreted as the result of a regional leuconoritic anatexis (basic palingenesis) of an anorthosito-noritic gneissic basement, similar to the Håland massif. The occurrence of Al-rich opx megacrysts, however, indicates a polybaric evolution (Longhi et al. 1993) and precludes the formation of melts at the level of emplacement. An alternative explanation is to consider the anorthositic-noritic gneiss not as an old basement but as the margin of the intrusion, similar to the margin of the Egersund-Ogna body, and produced by syn-emplacement deformation. The Håland massif could thus represent the cap of a diapir and the Helleren body its more central part that cut through its roof.

The Åna-Sira body has many features in common with the Helleren massif and was possibly emplaced in a similar way, though somewhat earlier in the igneous evolution. Detailed mapping has been carried out by geologists from Clausthal Technical University under the leadership of H. Krause (Krause & Pedall 1980). The massif contains two large ilmenite-ore deposits, the Storgangen sheet and the Tellnes ilmenite norite lens. Tellnes is in active production and yields a substantial amount of the world´s ilmenite. Krause and co-workers have produced detailed studies of the various ore-deposits of the massif (Krause & Zeino-Mahmalat 1970; Gierth & Krause 1973; Krause & Pape 1975; Knorn & Krause 1977).

The Bjerkreim-Sokndal layered intrusion comprises lithologies of the entire anorthosite-charnockite suite of rocks and thus remains a key for our understanding of the "anorthosite problem". Since the 1960 guidebook (Michot 1960), more data has been made available by Michot (1965) and by other authors. They are summarized later in this guidebook. The SW flank of the intrusion, at the contact with the neighbouring anorthositic Helleren massif, is intruded by the Eia-Rekefjord jotunitic body which is related to an extended dyke-system that cuts across all the massif-type anorthosite bodies and the Bjerkreim-Sokndal intrusion. The Hidra and Garsaknatt leuconoritic bodies, of smaller size, intruded into the metamorphic envelope at a late stage of the igneous evolution (Michot & Michot 1969; Demaiffe et al. 1973). Their most typical features are, for the former, the occurrence of a conspicuous fine-grained jotunitic margin (the sole occurrence in all massifs of a continuous "chilled margin"), and for the latter, numerous massive or foliated anorthositic and leuconoritic inclusions. In contrast with the other massifs, plagioclase is not granulated and the subophitic character of the texture, typical of atectonic conditions, is well preserved.

A mangero-noritic body is located in a southwards prolongation of the Mydland lobe of the Bjerkreim-Sokndal intrusion (Michot & Michot 1969; Demaiffe 1972; Bolle 1996; Bolle et al. 1997). Because of this location, it is called the Apophysis. It intrudes the eastern contact between the Åna-Sira body and its metamorphic envelope.
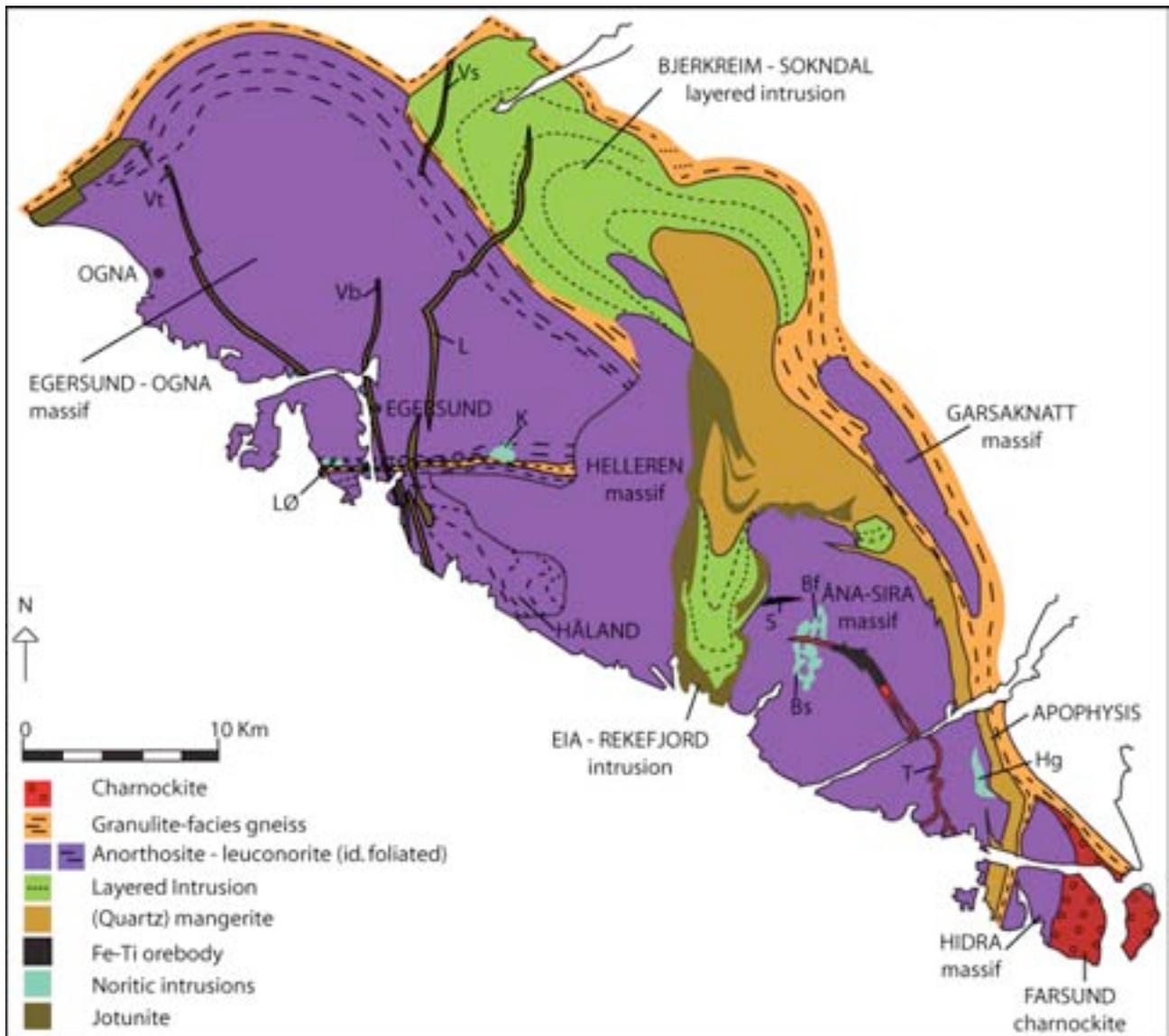
Figure 3. The Rogaland anorthosite province (after Michot 1960; Michot & Michot 1969; Rietmeijer 1979; Wilmart 1982; Duchesne et al. 1985a; Krause et al. 1985; Duchesne 1987b; Duchesne 1987a; Wilson et al. 1996; Bolle 1998). Bs: Bøstølen intrusion; Bf: Pegmatitic norite of the Blåfjell deposit; Hg: Hogstad noritic intrusion; LØ: Løyning noritic intrusion; K: Koldal noritic intrusion; S: Storgangen deposit; T: Tellnes dyke; Vb: Varberg dyke; L: Lomland dyke; Vt: Vettaland dyke; Vs: Vaersland dyke. Note that the Egersund dolerite dyke swarm is not shown.

The Puntavoll-Lien norito-granitic zone (Michot 1955a) and the septum that separate the Egersund-Ogna body from the Håland massif and from the Bjerkreim-Sokndal intrusion are of complex origin. Michot (1956a) concluded that a norite intrusive in the contact zone was transformed into norito-granitic banded gneiss by metasomatic fluids that leached out the mafic minerals and redeposited them into Fe-Ti oxide bodies (mafic front), leaving behind an anorthositic residue. The occurrence of garnet-cordierite-sillimanite gneisses within the norito-granitic banded gneiss unit (indicating a pelitic protolith) and the overall similarity of these gneisses with banded gneisses commonly found in the metamorphic envelope, however, strongly suggest that the norito-granitic

zone of Michot is in fact a septum of highly deformed metamorphic supracrustal rocks wedged in between the anorthosite massifs.

The Farsund charnockite and the Lyngdal and Kleivan granites are fully described in the Maijer and Padget (1987) guidebook, to which the reader is referred.

A system of Neoproterozoic WNW-ESE dolerite dykes - the Egersund dyke swarm - with aphanitic chilled margins, intrudes the whole igneous complex and the metamorphic envelope (Bingen et al. 1998b).

Geophysical data

Geophysical data on the Rogaland anorthositic province have been synthesized by Smithson & Ramberg (1979). The Mohorovicic discontinuity is presently about 28 km deep near Egersund (Sellevoll & Aalstad 1971), and the heat flow through the anorthositic bodies is 0.4 to 0.5 HFU (Swanberg et al. 1974). Gravity measurements have led to an overall confirmation of the geological interpretation. A positive gravity anomaly, ranging from 10 to 30 mgal, is centred on the Bjerkreim-Sokndal intrusion, which has been modelled as a syncline containing a 4 km-thick sequence of noritic material. A seismic image of the basal portion has been recently acquired (Deemer & Hurich 1997). No positive anomalies are associated with the massif-type anorthosites, indicating that no complementary mafic material is present beneath them. The Åna-Sira body has been inferred to be 4 km thick, which, combined with the heat flow measurement, suggests that the crust below is made up of low heat-producing, deep crustal rocks.

A deep seismic profile (ILP-11) has been collected offshore from Rogaland and has been interpreted by Andersson et al. (1996). Similarly, an undersea extension of the Rogaland anorthosite complex has been drawn on the basis of aeromagnetic data (Smethurst et al. 1994).

Tentative reconstruction of the geological evolution in Rogaland–Vest Agder

In view of the recent age determinations and structural studies, we suggest the following sequence of tectono-metamorphic and plutonic events in the Rogaland - Vest Agder sector. We are still in doubt, however, as to the exact relationship between the M1 metamorphism and the two major isoclinal recumbent fold phases (F2 and F3 phases of Falkum (1998) and D2 and D3 of Hermans et al. (1975)) and the two phases of Michot (1956b; 1960). Pervasive deformation on such a large scale must have been associated with a (high grade) metamorphic event older than the intrusion of the Feda porphyritic granite suite. We have chosen to push the first isoclinal recumbent fold phase (F2) into Gothian times, before the emplacement of early-Sveconorwegian charnockitic bodies at ~1.19 - 1.15 Ga. The age constraints for F2, F3 and F4 are, nevertheless, very poor and, for example, these phases could result from continuous deformation in a relatively short time interval. The F3 phase must have started before intrusion of the porphyritic Feda granodiorite suite and the latter is folded by the F4 phase. We therefore propose the following sequence of events in the Rogaland - Vest Agder sector. A schematic, simplified time-event diagram for the Rogaland Anorthosite Province and surrounding area is shown in Figure 4.

Pre-Sveconorwegian and Gothian times (>1.25 Ga)

(a) Extraction of crustal material from the mantle (island arc material) given by Nd-depleted mantle model ages (TDM) at 1.5 - 1.9 Ga (Menuge 1988).

(b) Detrital zircon in metaquartzite of the Faurefjell metasediments clustering around 1.65 Ga (de Haas et al. 1999).

(c) F1 and possibly F2 fold phases of Falkum (1998) coeval with M0 phase of metamorphism and or plutonism (Versteeve 1975, Pasteels & Michot 1975; Priem & Verschure 1982).

(d) Intrusion of various granitoids with U–Pb ages between 1.6 and 1.4 Ga (Pasteels & Michot 1975; Priem & Verschure 1982).

(e) Old inherited components in zircon from Tellnes deposit (1.69 Ga) and Helleren anorthosite (1.45 Ga) (Schärer et al. 1996).

Sveconorwegian orogeny (1.25 – 0.98 Ga)

(f) Intrusion of A-type granitic to charnockitic plutons: Gloppurdi and Botnevatn bodies at 1180 ± 70 Ma (WR Rb - Sr age) (Versteeve 1975; Wielens et al. 1981), and Hidderskog body at 1159 ± 5 Ma (U - Pb zircon age) (Zhou et al. 1995).

(g) Inherited component in zircon from the margin of the Egersund-Ogna body (1.24 Ga) (Schärer et al. 1996).

(h) Beginning of the M1 upper amphibolite facies metamorphism and F2 - F3 isoclinal recumbent folds of Falkum (1998). These episodes probably started before the intrusion of the Feda porphyritic granodiorite suite at 1050 +2/-8 Ma.

(i) Intrusion of the Feda porphyritic high-K calc-alkaline granodiorite suite at 1051 +2/-8 Ma (U- Pb zircon age)(Bingen & van Breemen 1998a).

(j) Climax of the M1 upper amphibolite (E) facies and granulite (W) facies metamorphism, separated by an Opx-in isograd at 1024 - 970 Ma (monazite U - Pb ages) (Bingen & van Breemen 1998b); F4 tight to isoclinal fold phase (Falkum 1998)

(k) Intrusion of the Homme granite at 998 ± 14 Ma (WR Rb - Sr age) (Falkum & Pedersen 1979)

(l) F5 tight to close amphibolite facies deformation

(m) F6 open to gentle (non-penetrative) deformation (Falkum 1998).

(n) End of the regional deformation regime between 998 Ma and 980 Ma.

Post-collisional regime (0.98 - 0.90 Ga)

(o) Intrusion of the Holum granite, which is the first post-orogenic granite situated on the western side of the Mandal - Ustaoset Line at 980 ± 34 Ma (WR Rb-Sr age) (Wilson et al. 1977).

(p) Intrusion of the massif-type anorthosite bodies and related rocks at 931 ± 3 Ma (U - Pb zircon ages) (Schärer et al. 1996).

(q) M2 thermal metamorphism at 930-925 Ma (monazite U - Pb ages) (Bingen & van Breemen 1998b).

(r) Intrusion of the Tellnes ilmenite norite at 920 ± 3 Ma (U - Pb zircon age) (Schärer et al. 1996) or earlier (Charlier et al. 2007).

(s) Granitic plutonism straddling the Mandal - Ustaoset line between ~0.98 and 0.90 Ga, ending with the intrusion of the Bessefjell granite at 904 ± 16 Ma (WR Rb - Sr age) (compilation in Andersson et al. 1996).

(t) Regional cooling through closure temperature for Pb-diffusion in titanite (~610°C) at 918 ± 2 Ma (titanite U - Pb ages) (Bingen & van Breemen 1998b) and cooling through closure temperature for Ar-diffusion in hornblende (~550°C) at 916 +12/-14 Ma (^{40}Ar/^{39}Ar ages on amphibole in pyroxene-rich samples) (Bingen et al. 1998a).

(u) Intrusion of mineralized pegmatites, namely the Rymteland pegmatite at 916 ± 6 Ma (U - Pb uraninite age) (Pasteels et al. 1979).

(v) Crystallization of low-U (hydrothermal?) monazites in the Feda augen gneiss suite at 912 - 904 Ma (monazite U - Pb ages) (Bingen & van Breemen 1998b).

(w) Closure of the Rb - Sr isotopic system at mineral scale in biotite and feldspar between 895 - 853 Ma (Verschure et al. 1980; Bingen et al. 1990).

(x) Intrusion of the WSW–ENE trending undeformed Hunnedalen dyke swarm at 855 ± 59 or 835 ± 47 Ma (Sm - Nd mineral ages) or 848 ± 27 Ma (^{40}Ar/^{39}Ar age on biotite)(Maijer & Verschure 1998; Walderhaug et al. 1999).

Pre-Caledonian rifting and Caledonian period (0.61 - 0.4 Ga)

(y) Intrusion of the WNW–ESE trending Egersund swarm of basaltic dykes at 616 ± 3 Ma (U - Pb baddeleyite age) (Bingen et al. 1998b).

(z) M4 pumpellyite-prehnite facies and greenschist facies metamorphism (~400 Ma based on lower intercepts zircon U - Pb discordia lines and secondary K-Ar ages on green biotite (Verschure et al. 1980; Priem & Verschure 1982).
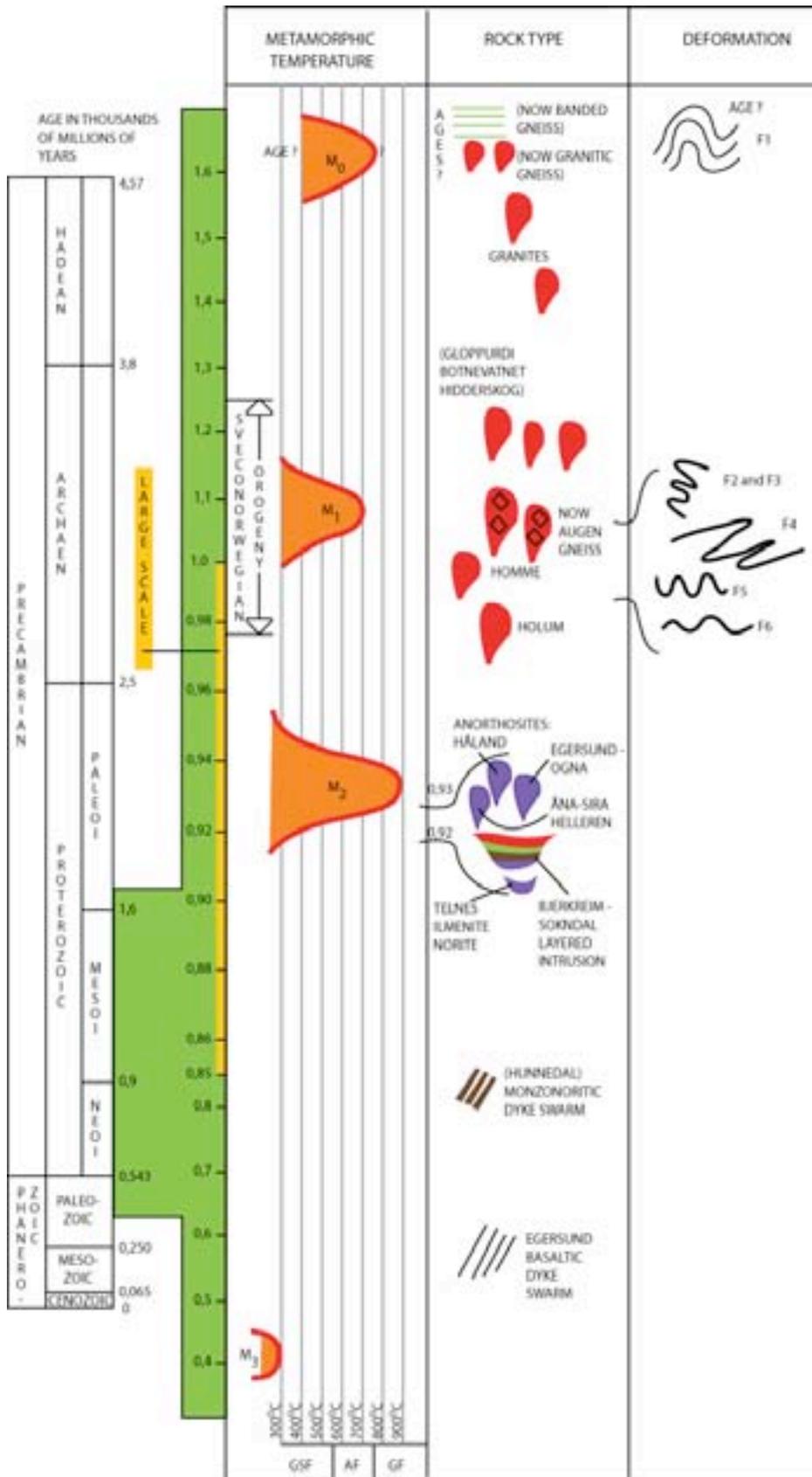
Figure 4. Schematic, simplified time-event diagram for evolution of the Rogaland Anorthosite Province and surrounding area.

The Egersund-Ogna Massif
(by J.C. Duchesne and R. Maquil; modified by J. R. Wilson)

The Egersund-Ogna massif (EGOG) is an anorthositic dome, approximately 20 km in diameter, emplaced in granulite facies gneisses (Enclosure 1). Petrographically and chemically, the anorthosite is very uniform and made up of granulated, equal-sized (1-3 cm), homogeneous plagioclase (An_{40-45}), locally with megacrysts of orthopyroxene and plagioclase. The marginal zone of the massif (1-3 km wide) is generally leuconoritic and has a pronounced foliated texture. This marginal foliation is generally concordant with the contact with the gneisses and the gneissic foliation. This overall concordance which was recognized by P. Michot (1957, p.28), has local exceptions. For example, P. Michot has described, on the NW contact (Roligheden), a recumbent fold whose inverse flank is cross-cut by the foliated leuconorite. This was taken by him as evidence for the contemporaneity of the intrusion with a first phase of isoclinal folding affecting the region. For the present authors, local discordant contacts are not inconsistent with the model of intrusion developed below.

Field relations

Detailed mapping by Maquil (1980) (Figure 5) has identified several varieties of anorthosites and leuconorites that form a more or less concentric structure. In the central part of the massif (along the coast near Hellvik), the concentration of phenocrysts of plagioclase (5-20 cm) and megacrysts of orthopyroxene (opx) are higher than elsewhere. The latter forms metre-sized subophitic aggregates with megacrysts of plagioclase. Medium-grained norite or leuconorite also occurs as patches or lenses (usually oriented) in the anorthosite. This structure commonly merges into its inverse - norite or leuconorite with lenses of medium-grained to coarse-grained anorthosite (aggregates of plagioclase grains) - and forms what is called the anorthositic - noritic complex. It can be viewed as consisting of metre-sized, lens-shaped aggregates or megacrysts of plagioclase and orthopyroxene, embedded in a finer-grained matrix, grading from pure anorthosite to norite. The noritic material characteristically varies in grain size. It can pass over short distances from a pegmatite to a fine-grained rock. The relationship with the anorthosite shows all gradations between diffuse, anastomosed contacts and sharp, abrupt, dyke-like contacts. These various characters are not restricted to the core of the massif but can be observed at several places in the anorthosite. Small hemo-ilmenite veinlets occur exclusively in the core of the massif.

The marginal zone of the massif can be considered as being formed of lithologies and associations similar to those of the core of the massif but in various degrees of deformation, producing a variety of microstructures from a simple igneous texture to a completely recrystallised granoblastic texture.

The opx megacrysts (Figure 6) are kinked, granulated and stretched over several metres in the plane of the foliation. The aggregates of plagioclase phenocrysts give rise to bands, streaks or lenses of meta-anorthosite, foliated norite, noritic gneiss, etc. The foliation always coincides with the lithological banding. Rapid variation of grain-size in the foliated rocks can be attributed to differing deformation rates and/or to variations in grain size of the original rock. Dykes of noritic material cut across the foliation: a single, unfoliated dyke may be sheared (and foliated) in one place and faulted and displaced a few metres along strike. This indicates that deformation in the marginal zone took place in several episodes and has become less and less pervasive and progressively restricted to discrete areas. This is good evidence for continuous deformation.
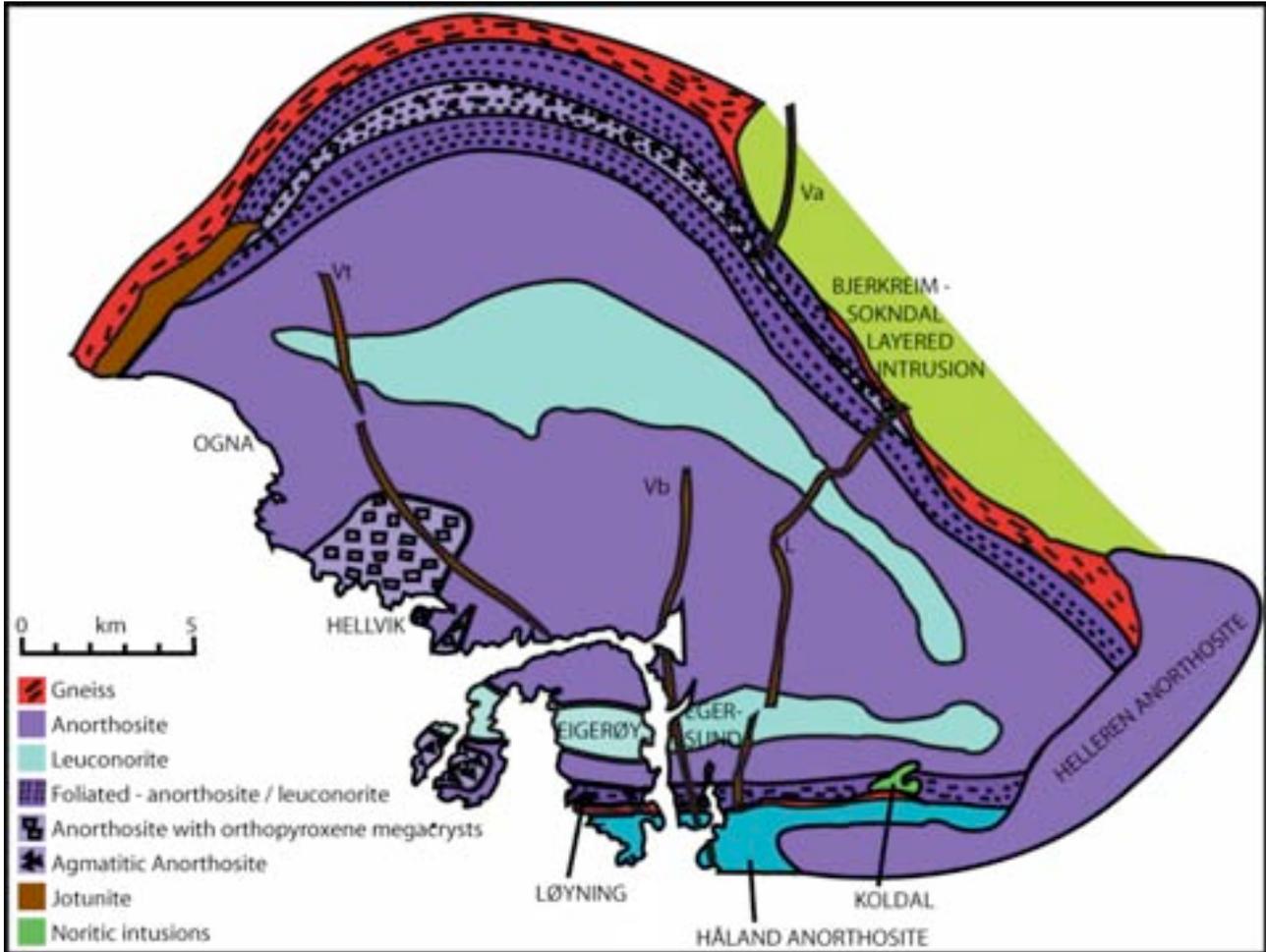
Figure 5. Simplified geological map of the Egersund-Ogna massif-type anorthositic body (based on Duchesne & Maquil, 1987 and Marker et al., 2004). There are numerous lakes which are not shown. The Egersund dolerite dyke swarm is not shown. The contacts between the different anorthositic/leuconoritic facies are gradational. Vt = Vettaland dyke; Vb = Varberg dyke; L = Lomland dyke; Va = Vaersland dyke. The minor intrusions at Løyning and Koldal are shown in the foliated southern margin of the Egersund-Ogna anorthosite. Note the thin strips of gneiss squeezed between the intrusions.

A homogeneous, weakly foliated leuconorite constitutes a third important petrographic unit. It is grossly concentric with the core and at equal distance to the margin (Figure 5). A suite of Fe-Ti oxide-rich noritic dykes, with variable grain size (though commonly pegmatitic; Michot 1960), cuts across the anorthosite and Bjerkreim-Sokndal (BKSK) intrusion. The dykes occur everywhere in the anorthosite but are more concentrated towards the margin. Petrographically, they contrast with the noritic material of the anorthosito-noritic complex by the presence of Fe-Ti oxide minerals.

Numerous blocks and slabs of meta-anorthosites and meta-leuconorites occur as inclusions in the central anorthosite, for instance at Ystebröd (Michot 1960).

Figure 6. High-alumina orthopyroxene megacrysts in anorthosite. The hammer handle is 1 m long.

Mineral chemistry

The anorthosite and related leuconorites and norites from the central part of the massif contain plagioclase of monotonous composition: the anorthite content is between 40 and 45 wt.%; Sr 800 - 1000 ppm; Ba 100 - 250 ppm; K_2O 0.5 - 0.8%. The compositions of plagioclase phenocrysts are usually not different from those in the matrix. Some of them, however, namely those associated with megacrysts of orthopyroxene in a sub-ophitic texture, are more calcic (An_{55}), but with similar Sr-contents, but lower K_2O (<0.4%) and Ba (<100 ppm) contents. They typically show labradorescence (Bøggild intergrowths).

The orthopyroxene megacrysts contain numerous exsolution lamellae of calic plagioclase (Emslie 1975; Maquil & Duchesne 1984), a feature which is common to all anorthositic massifs in Rogaland, as well as in most anorthosite massifs elsewhere in the world. For an Al_2O_3 content of about 7-9% (which characterizes the opx from the central part of the massif) estimates of pressures between 10 and 12 kb were suggested by Maquil (1979) and later confirmed by experiments (Fram & Longhi 1992).

Exsolution of plagioclase from opx takes place under decreasing pressure and oxidizing conditions when it is coupled with the exsolution of oxide mineral (Emslie 1975). By contrast, opx in the norite which encloses aggregates of megacrysts has 2-3% Al_2O_3, a value shared by cumulus opx from the neighbouring BKSK intrusion and by granoblastic leuconoritic gneisses from the margin. The Cr-content of the mega-opx from the central part is 600-950 ppm, clearly higher than in the norite opx (<200 ppm).

There are notable differences in the chemical compositions of opx and plagioclase megacrysts from the central and marginal zones of the massif. Undeformed opx megacrysts from the margin contains 3.5 - 6 wt.% Al_2O_3 with Cr between 600 and 1500 ppm. Plagioclases in the margin vary from An_{45} up to An_{75} and have uniformly low Sr-contents (350-450 ppm) and low Ba-contents (< 100 ppm), as was noted by Duchesne (1966) and Duchesne & Demaiffe (1978).

Compared to Cr, other trace elements in opx megacrysts show little variation: $V = 289 \pm 29$ ppm; $Ni = 276 \pm 45$ ppm; $Zn = 133 \pm 22$ ppm; $Co = 103 \pm 7$ ppm; $MnO = 0.24 \pm 0.02$ ppm. This indicates that during mineral-melt equilibrium the bulk partition coefficients of the various elements remained close to unity, which in turn implies cotectic crystallisation of plagioclase and orthopyroxene and precludes olivine and Fe-Ti oxides at the liquidus (Maquil et al. 1980).

Plagioclases from blocky inclusions of leuconoritic and anorthositic gneiss are compositionally similar to those from the foliated margin of the massif. Since these compositional characters are restricted to plagioclases from the margin and the inclusions are texturally similar to the marginal gneisses it can be concluded that they represent fragments broken from the margin of the massif.

Geothermometry

Although clinopyroxene is relatively rare in EGOG, Maquil and Duchesne (1984) selected cpx-bearing samples in various geological occurrences and measured opx-cpx compositions. Application of Wells' (1977) geothermometer and consideration of the Al-content of the pyroxenes give the following main results:

1. Equilibrium temperatures in stretched and recrystallised opx megacrysts from the margin (granoblastic texture) are on the average higher than in metabasites of the granulitic envelope; some samples from the margin indicating temperatures >100°C over that of the envelope;

2. The maximum temperatures measured in the margin are also higher than solidus temperatures in the norites from the centre;

3. Exsolution in opx megacrysts started at higher temperatures and pressures than those that prevailed at completion of crystallisation or during recrystallisation.

Petrogenesis

The generation of huge, uniform masses of anorthosite has been long debated. It is the central question of the so-called "anorthosite problem". The discovery that the opx megacrysts - a common mineral in all massif-type anorthosites - were Ca-tschermakitic has thrown new light on the question. Though experimental data on the plagioclase - Al opx system are still scarce compared to the garnet- or spinel-bearing systems, there is little doubt that the opx megacrysts from the central anorthosite started to crystallise at high PT conditions (around 10-12 kb and 1250°C) and, being interstitial to plagioclase crystals, plagioclase was also stable on the liquidus under those conditions. Accordingly, the PT conditions for crystallisation of opx in the margin were not so high: this opx contains less Al and the plagioclase is more calcic, in agreement with experimental data (Green 1970; Fram & Longhi 1992). The compositions of the minerals from the noritic matrix also points to final consolidation at even shallower depth.

The nature of the parental magma for EGOG is not known. No chilled margin has been unambiguously recognized, although fine-grained noritic rocks occurring locally at the contact with the migmatitic gneiss envelope and septa are potential candidates. The contrast in composition between the plagioclase and opx megacrysts in the central part and the foliated margin is still partly enigmatic. The variation in Sr-content of the plagioclase (low in the margin and high in the center) does not result from a variation in the partition coefficient value between plagioclase and melt with pressure, although pressure significantly increases the partitioning of Cr between opx and melt (Vander Auwera et al. 2000). This opens the possibility that a jotunitic magma could be parental to the central anorthosite and a high-alumina basalt to the foliated margin. This confirms the possible existence of two different parental magmas to account for the Rogaland massifs, as suggested by Duchesne et al. (1985) but now with an important difference: basaltic magma produces the labradorite anorthosite massifs, and a jotunitic magma gives rise to andesine anorthosite, such as that present in the central part of EGOG, the BKSK succession of rocks, the Hidra Massif, etc.

Although many points remain unresolved, a general model for the crystallisation and emplacement of the EGOG massif can be tentatively proposed (Duchesne & Maquil 1981; Maquil & Duchesne 1984). It essentially accounts for the following features:

1. Occurrence in the field of all transitions between igneous and metamorphic textures, particularly coincidence of the foliation plane with the compositional layering, and also between protoclastic and granoblastic structures, points to various degrees of deformation.

2. Indication of progressive deformation in the margin.

3. Evidence that the deformation leading to granoblastic structure was already completed when large parts of the massif were still capable of intrusion (gneissic inclusions, unfoliated noritic dyke in the margin, etc.).

4. Occurrences of different compositions between phenocrysts and matrix minerals (particularly opx megacrysts with different Al- and Cr-contents).

5. Indications from available geothermometers (cpx-opx) and barometers (Al in pyroxenes) of crystallisation (and recrystallisation) processes along a PT gradient.

These points are in favour of an emplacement process in which the anorthosite, in a mushy state, lubricated by a minor amount of interstitial liquids and containing megacrysts or aggregates of megacrysts, formed at depth, rose diapirically in the crust and produced its own deformation along the walls and within the mass. A ballooning process locally led to the foliation of marginal parts and also sufficiently deformed the external metamorphic envelope (syn-emplacement deformation) to achieve parallel structure on both sides of the contact. A final telescopic flattening of the whole system extended the area of the massif by bringing the root of the diapir near to its roof in central areas.

This interpretation of the EGOG body, proposed by Duchesne & Maquil (1981) and Maquil & Duchesne (1984), was consistent with a model of diapiric emplacement suggested by Martignole & Schrijver (1970) for the Morin anorthosite (but later disproved by Martignole 1996). Maquil & Duchesne (1984) showed that the emplacement mechanism was not necessarily linked to regional

deformation, but this could not be proved until accurate age measurements (U - Pb on zircon extracted from megacryst aggregates) yielded an age of 931± 3 Ma (Schärer et al. 1996), some 70 million years younger than the last recognized regional deformation.

The various structural and petrographic characteristics of EGOG, together with thermo-mechanical properties of anorthosite and mid- and lower crustal rocks, were used by Barnichon et al. (1999) to construct a finite element mechanical model of diapiric rise and emplacement. This model confirms that diapirism of an anorthositic mush through the lower crust can indeed take place in the relatively small time interval measured, and gives rise to a strain regime in agreement with field observations.

The other large anorthositic massifs (Åna-Sira and Helleren) also contain the EGOG "trilogy":(1) megacrysts of Al-rich opx; (2) anorthosite-norite complex; (3) large areas of foliated rocks as well as gneissic inclusions. As far as the emplacement mechanism is concerned, the similarities with EGOG are striking and essentially the same diapiric process seems likely. The interaction between the uprising anorthosite diapirs and the surrounding rocks, namely the BKSK layered intrusion and the migmatitic gneiss envelope, has led to gravity-controlled tectonism in which the BKSK intrusion was folded in a doubly-plunging syncline to accommodate the uprise of the EGOG and Helleren massifs to the west and south of the Bjerkreim lobe, and of the Helleren and Åna-Sira massifs on both sides of the Sokndal lobe (Bolle et al. 2000).

The Bjerkreim-Sokndal Layered Intrusion

(by B. Robins and J.R. Wilson)

Introduction

The Bjerkreim-Sokndal Intrusion (BKSK) (Michot 1960; 1965; Duchesne 1987a; Wilson et al. 1996) is a large (40 km long and up to 15 km wide), Late Proterozoic layered intrusionthat occupies an area of about 230 km^2 (Figure 7 and Enclosure 1). Lithologically the intrusion consists of virtually all of the rock types belonging to the anorthosite kindred, i.e. andesine anorthosite, troctolite, leuconorite, norite, gabbronorite, jotunite (hypersthene monzodiorite), mangerite (hypersthene monzonite), quartz mangerite and igneous charnockite (hypersthene granite). Anorthosite, leuconorite and norite are accompanied by ilmenite-rich rocks.

The BKSK is emplaced in granulite-facies quartzo-feldspathic and mafic gneisses as well as anorthosite and leuconorite belonging to the Egersund-Ogna (Michot & Michot 1970; Duchesne & Maquil 1987), Håland-Helleren (Michot 1961) and Åna-Sira (Krause et al. 1985; Duchesne & Michot 1987) massifs, and xenoliths of all these host rocks are common within the intrusion itself (Duchesne 1970).

The BKSK and the various anorthosite massifs are cut by members of a suite of small plutons and wide, laterally-persistent dykes of jotunite, some of which are differentiated (Duchesne et al. 1989; Wilmart et al. 1989). The most voluminous of the jotunites that cut the northern part of the BKSK is the Lomland dyke/sill complex (Duchesne et al. 1989). The BKSK is also cut by members of the Egersund swarm of basaltic dykes.

Shape and internal structure of the Bjerkreim-Sokndal intrusion

The Bjerkreim-Sokndal Intrusion has generally been described as a lopolith, but recent detailed mapping shows it to be a trough-like, discordant intrusion. Modelling of the associated +10-30 mgal gravity anomaly (Smithson & Ramberg 1979) and a seismic reflection profile (Deemer & Hurich 1997) shows that the base of the intrusion lies at a depth of 4 - 5 km in the northern Bjerkreim lobe and ~ 8 km in the centre of the intrusion (Bolle et al. 2002).

Layering within the intrusion is deformed into a deep, doubly-plunging syncline that branches in the south around a dome cored by the Åna-Sira anorthosite massif (Figure 7). The core of the syncline is occupied by quartz mangerite and charnockite, which do not exhibit modal or textural layering, and these are separated in places from the underlying mangerite by a zone with abundant wall-rock xenoliths. The magnitude of the gravity lows over the granitoids suggests a maximum thickness of about 2 km (Smithson & Ramberg 1979). There is no evidence that the roof of the intrusion is preserved anywhere within the confines of the present outcrop.
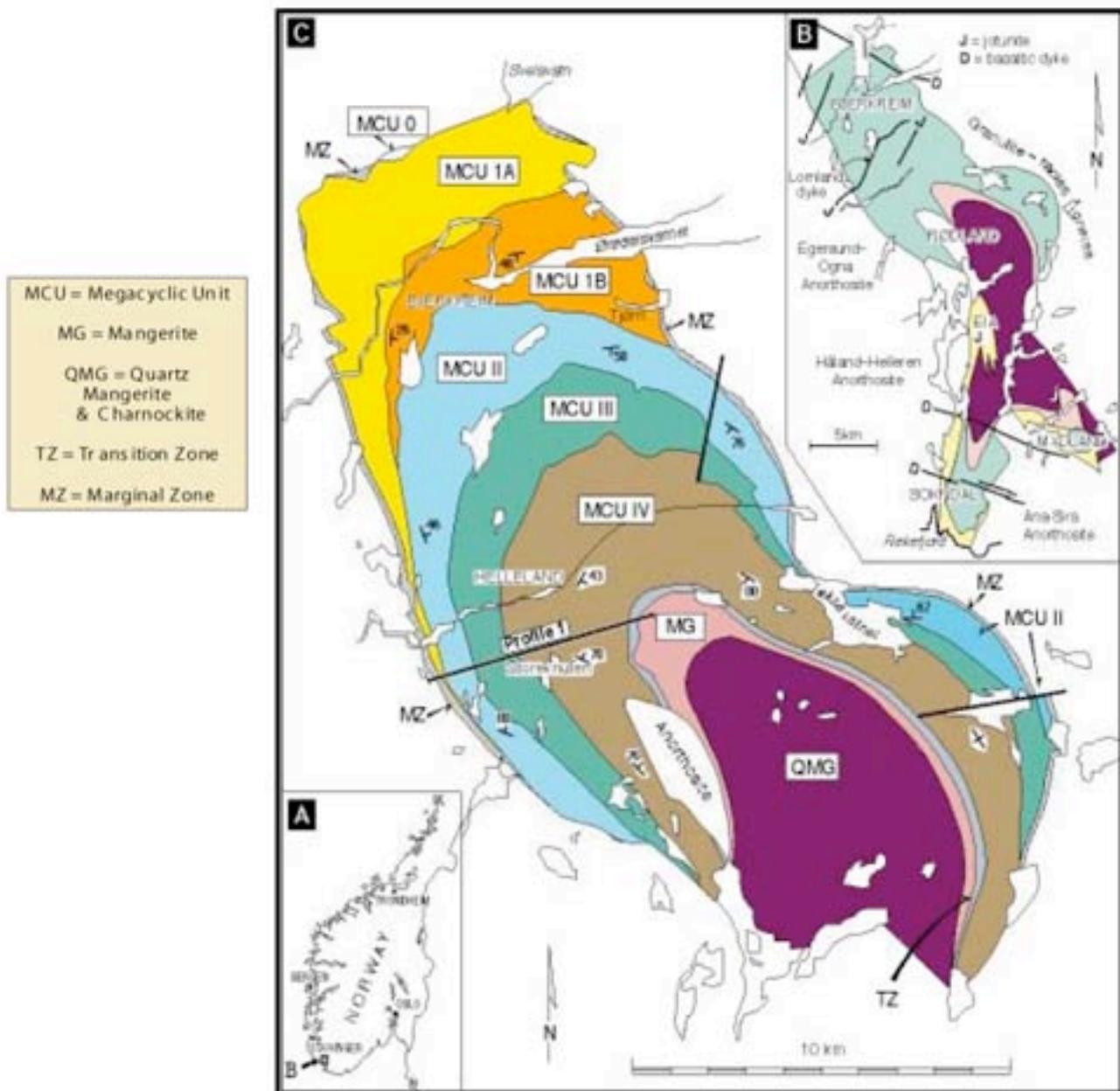
Figure 7. Location (A), sketch map (B), and stratigraphic subdivision of the Bjerkreim lobe (C) of the Bjerkreim-Sokndal Intrusion.

The BKSK consists of three lobes; the Bjerkreim lobe in the northwest, and the smaller Sokndal and Mydland lobes to the south and southeast respectively (Figure 7B). Modal layering and phase contacts in the Bjerkreim lobe are disposed in a syncline that plunges southeast at 20-40°. In the steep limbs of the syncline the cumulates are foliated, generally in the plane of modal layering. In places, cumulus minerals form augen in a foliated matrix, small shear zones are developed, and there is a strong mineral lineation. Linear mineral and magnetic fabrics dominate in the core of the syncline (Paludan et al. 1994; Bolle et al. 2000, 2002). Cumulus plagioclases are strained or recrystallised to shape-oriented polygonal aggregates, whereas prismatic Ca-poor pyroxenes are commonly kinked or bent. Uniform paleomagnetic vectors in different parts of the intrusion (Poorter 1972) suggest that the deformation and development of the synformal disposition of the layering took place at temperatures in excess of the Curie point (550-650°C). The synformal

disposition of the layering is inferred to be due to gravitational foundering (Paludan et al. 1994; Bolle et al. 2000, 2002).

The Layered Series

The Layered Series in the Bjerkreim lobe has a thickness of >7000m in the axial region of the syncline and can be divided into 6 megacyclic units (MCU 0 to IV) which exhibit characteristic sequences of cumulates (Figures 8 and 9). The megacyclic units can be further subdivided into zones a-f, based on assemblages of cumulus minerals (Figures 8 and 9).
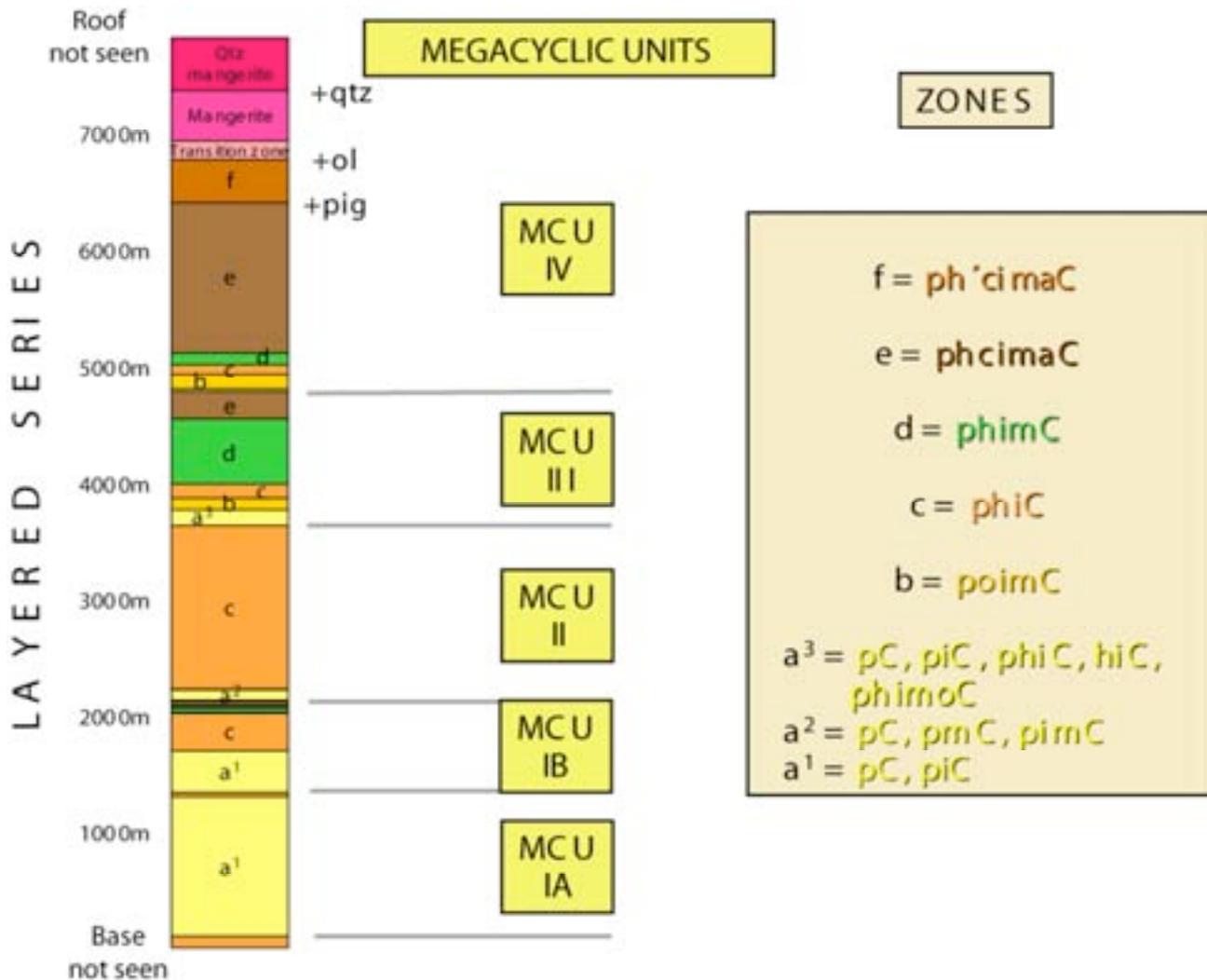
Figure 8. Stratigraphy of the Layered Series of the Bjerkreim-Sokndal Intrusion as developed in the axial region of the Bjerkreim lobe and its subdivision into megacyclic units and cumulate zones.

The megacyclic units vary in stratigraphic thickness, lateral persistence and in the nature of the layer sequences they exhibit (Figure 7C). The lower three megacyclic units, exposed only in the northernmost part of the intrusion, are individually as much as 1300m thick but show a pronounced southward thinning in the western limb of the syncline and are not developed in the southern parts of the Bjerkreim lobe.

The lowermost cumulates are exposed in the northwestern part of the Bjerkreim lobe and consist of plagioclase-hypersthene-ilmenite cumulates (phiC). They are regarded as the top of MCU 0, the rest of which, together with an unknown thickness of cumulates, is hidden. These cumulates are overlain successively by pC, piC and phC belonging to MCU IA (~1300m thick in a profile along the axial trace of the syncline).

This sequence is repeated in MCU IB (~875m thick) which locally also displays more evolved lithologies with the entry of cumulus Ca-rich pyroxene, followed by apatite and magnetite. MCUs 0-IB are characterised by the presence of plagioclase megacrysts (up to 10 cm long) in all rocks with the exception of the most evolved cumulates at the top of MCU IB. MCU II (reaching a thickness of 1600m) consists of a thin layer of magnetite-bearing piC overlain exclusively by phiC. The appearance of cumulus magnetite in the leuconorites at the base of MCU II and its absence in the overlying cumulates suggests affinities with the olivine-bearing zones near the bases of succeeding MCUs. The base of MCU II is characterised by a marked regression in the composition of cumulus plagioclase (Figure 9).
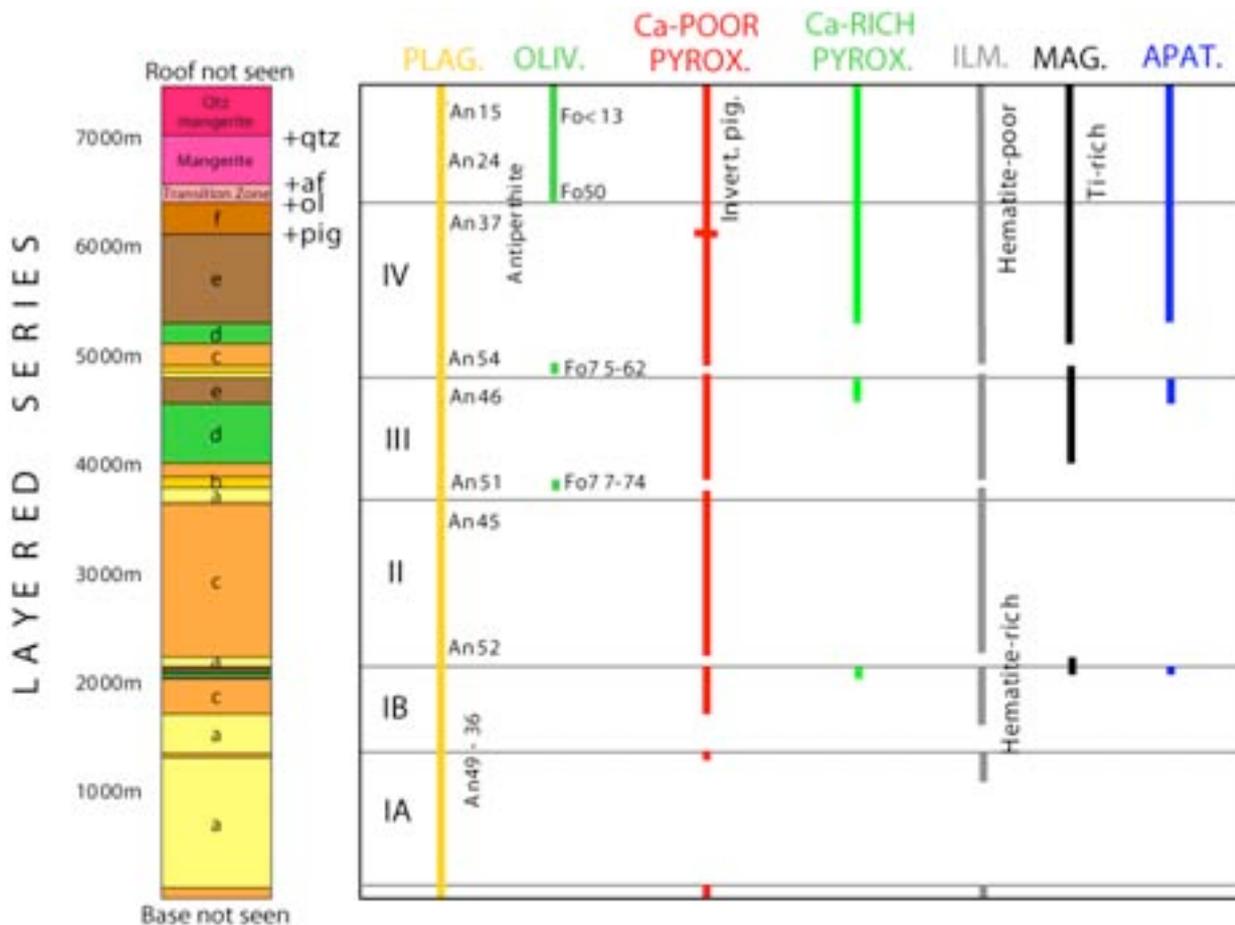
Figure 9. Generalised stratigraphy and cryptic layering of the Bjerkreim-Sokndal Layered Intrusion. After Wilson et al. (1996).

MCU III (maximum ~1100m thick) generally has a lower zone (Zone IIIa in Figure 9) up to 140m thick that consists mainly of pC, but with interlayered iC, phiC and hiC. The base of the zone is marked by a thin (<10m) sulphide-bearing subzone, unique in the Layered Series, that consists of

ilmenite norite, mafic ilmenite norite or massive orthopyroxenite. Zone a is characterised by a stratigraphic regression to higher-temperature mineral compositions. In the axial region of the intrusion and on the southern flank, zone a is overlain by leucotroctolite (zone b) that contains cumulus magnetite in addition to plagioclase, olivine and ilmenite. Together with the similar rocks near the base of MCU IV, the zone IIIb cumulates are the most primitive cumulates in the intrusion.

The leucotroctolite of zone IIIb is in turn overlain by phiC of zone c, followed by magnetite norite (Zone d) and gabbronorite (Zone e) with the successive (re-)entry of cumulus magnetite and then apatite together with Ca-rich pyroxene. In the eastern flank of the intrusion MCU III is relatively condensed and zone b is absent. Zone e is only developed in the flanks of the lobe. In the axial region the base of MCU IV rests on zone d cumulates.

MCU IV (maximum thickness ~1800m) displays a sequence similar to MCU III. MCU IV contains, however, additional, more-evolved cumulates. Michot (1960) recognised the prominent olivine-bearing zone b near the base of MCU IV and referred to it as the "Svalestad horizon". It has a thickness of about 100m and is laterally persistent along strike for about 24km. Olivines in the olivine-bearing zones near the bases of MCU III and IV are partially or completely replaced by orthopyroxene-Fe-Ti oxide symplectites, but the zones are texturally distinctive even where no olivine remains. Small amounts of biotite and hornblende also occur in the olivine-bearing zones. Ca-poor pyroxene is inverted pigeonite in the upper part of MCU IV (Zone f) which grades into overlying mangerite through a jotunitic Transition Zone (TZ) whose base is defined by the re-entry of olivine ($\sim Fo_{50}$), which more or less coincides with the appearance of interstitial alkali feldspar (Duchesne et al. 1987). With the appearance of cumulus mesoperthite the rocks grade upwards from jotunite to mangerite, which in turn passes into massive quartz mangerite and, locally, charnockite. Even in these highly-evolved rocks, hydrous phases are not abundant: Calcic amphibole is generally a minor mineral (except in the uppermost part of the granitoids where it may occur as large oikocrysts) and biotite is generally an accessory mineral. The combined thickness of the mangerite, quartz mangerite and charnockite is >350m (Rietmeijer 1979) and may be as much as 2km (Smithson & Ramberg 1979).

Viewed on a broad scale (Figures 8 and 9), the lower part of the Layered Series is dominated by plagioclase cumulates, the middle part by plagioclase-hypersthene-ilmenite cumulates and the upper part by plagioclase-hypersthene/pigeonite-augite-ilmenite-magnetite-apatite cumulates. Combined with the reversals to relatively primitive mineral assemblages at the bases of the MCUs, this is strong, first-order evidence that the Layered Series crystallised in a continuously fractionating, periodically replenished magma chamber. Replenishment events were few in number and widely spaced in time. The bulk composition of the magma occupying the chamber after each replenishment event can be judged by the relative volumes of the respective types of cumulate that constitute the successive megacyclic units. In the lowermost units the cumulates represented are predominantly high-temperature varieties and the proportion of more-evolved cumulates generally increases in the upper units. This pattern suggests that the bulk composition of the magma occupying the chamber became progressively more evolved with time. The base of MCU IV seems to reflect the last major influx of magma into the BKSK chamber. This replenishment event appears to have involved a large volume of magma and was associated with very significant expansion of the chamber. The regressive layered sequences beneath the most-primitive leucotroctolitic cumulates in MCUs III and IV are up to 120m thick, showing that replenishment of the magma chamber must have taken place over a prolonged period of time. After the influx of magma reflected by the MCU III/IV transition, fractional crystallisation was apparently uninterrupted and

we interpret the stratigraphic transition to mangerite, quartz mangerite and charnockite as reflecting progressive differentiation of the residual magma, probably containing a significant crustal component due to assimilation of country rocks and hybridisation with roof melts.

Fe-Ti oxides in the Bjerkreim-Sokndal intrusion

Ilmenite is an early-crystallising, almost ubiquitous mineral in the Bjerkreim-Sokndal intrusion. Substantial concentrations of ilmenite are restricted, however, to the regressive sequences that occur at the bases of the upper MCUs, especially units III and IV. Ilmenite and plagioclase-ilmenite cumulates are prominent in zone IVa in the axial region of the intrusion, and ilmenite-rich melanorites are found at the base of MCU III to the east of Teksevatnet. This relationship indicates that the generation of ilmenite-rich cumulates was related to replenishment of the Bjerkreim-Sokndal magma chamber and was probably a consequence of turbulent mixing of the resident magma with inflowing more-primitive jotunitic magma.

Ilmenite exhibits a general decrease in hematite content up through the Layered Series, from 16-20% in the lower part of the series where it is the only cumulus Fe-Ti oxide, to about 2% in the mangerite and quartz mangerite (Duchesne 1972a). This pattern is repeated on a smaller scale in the individual MCUs. Ilmenite contains about 0.3% V_2O_3 in the lower part of the Layered Series and shows an identical variation to hematite content. Manganese in ilmenite, however, increases almost continuously up through the Layered Series, from about 0.3% MnO in leuconorites near the base to 1.0% MnO in mangerite; breaks in the trend at contacts between MCUs are slight. Nickel and chromium are enriched in ilmenite at the bases of MCUs where concentrations can be as high as 1000 ppm Ni and 1.4% Cr_2O_3.

Magnetite is a cumulus phase in the upper parts of MCUs IB, III and IV, in the TZ where it occurs in oxide-rich layers, and in the leuconorites and/or leucotroctolites near the bases of MCUs II, III and IV. Its TiO_2 content increases systematically from <2% in zone d of MCU III to as much as 19% (corresponding to Usp58Mt42) in the TZ. As with ilmenite, the Mn-concentrations increase (to ~0.25% MnO at the top of MCU IV) and vanadium decreases upwards through the Layered Series (from ~1.3% to 0.02% V_2O_3 at the top of MCU IV) (Duchesne 1972a). Magnetite in leucotroctolite at the base of MCU IV contains lower V concentrations (1.0-0.75% V_2O_3) than the magnetite in the uppermost part of MCU III and on its reappearance in the upper part of MCU IV, possibly due to the presence in the leucotroctolite of small amounts of amphibole that has a high partition coefficient for V (Jensen et al. 1993). Ni concentrations are generally low (< 40 ppm), except in the leucotroctolites at the bases of MCUs III and IV where concentrations are 900-600 ppm. Nickel decreases with stratigraphic height in the leucotroctolite at the base of MCU IV. Chromium exhibits the same behaviour as Ni, concentrations in the leucotroctolite at the base of MCU IV varying from 1.4-0.4% Cr_2O_3. Chromium contents in magnetite elsewhere in the BKSK are very low.

Parental magma

Fine to medium-grained, granular jotunites are present at several places along the steep, discordant northern margin of the BKSK. They occur along the outer margin of an up to 100m thick Marginal Series that separates cumulates belonging to MCU IA and IB and the high-grade gneisses of the metamorphic envelope (Figure 7). The marginal jotunites are generally sparsely to markedly porphyritic and are considered to be chilled representatives of the magma that was parental to the oldest part of the Layered Series. The jotunites are evolved basic rocks characterised by high FeOt

(11.1-12.9 wt%) and TiO_2, MgO in a narrow range between 3.8 and 5.0 and low CaO (5.4-6.7 wt%) (Figure 10). They exhibit light REE-enriched chondrite-normalised rare-earth patterns with either a small positive Eu-anomaly or none at all, suggesting that previous fractionation or accumulation of plagioclase phenocrysts was very limited. Their compositions are similar to the jotunite trapped between anorthosite blocks enclosed within the plagioclase cumulates of MCU IB at Tjørn that likewise has been claimed to be representative of a parental magma (Duchesne & Hertogen 1988), and also to marginal jotunites of the Hidra Leuconorite (Duchesne et al. 1974).

The marginal jotunites have features that are consistent with a status as the parental magma for the cumulates of MCU IA and IB of the Layered Series of the BKSK. Textures show clearly that plagioclase was the first phase to crystallise from the jotunite magma and was followed by Ca-poor pyroxene and Fe-Ti oxides. The jotunites are rich in TiO_2 and poor in diopside components, compatible with the early crystallisation of cumulus ilmenite and the delayed appearance of cumulus Ca-rich pyroxene. The chemistry of the minerals in the jotunites is also comparable with the BKSK Layered Series: plagioclases in the jotunites are slightly more sodic and the pyroxenes decidedly more iron-rich than the equivalent highest temperature minerals in the BKSK cumulates. The presence of interstitial K-feldspar and quartz in the marginal rocks also demonstrates that the jotunite magma had the potential to produce a significant amount of an acid residual magma, as required by the presence of the granitoids at the top of the BKSK Layered Series.

Dry melting experiments on a jotunite collected from Tjørn show that such melts have plagioclase as the sole liquidus phase to ~7kb at temperatures of 1150-1165°C and oxygen fugacities of between FMQ-2 and FMQ-4 (Vander Auwera & Longhi 1994). Olivine, ilmenite and Ca-poor pyroxene (which crystallises together with olivine) appear successively at lower temperature within ~55°C of the liquidus at pressures up to ~5 kb. Allowing for the low oxygen fugacity in the melting experiments, which stabilises olivine relative to Ca-poor pyroxene and suppresses magnetite saturation, and the lower TiO_2 of the experimental starting material (3.5wt. %) compared with the marginal jotunites, that reduces ilmenite saturation, the experimental crystallisation sequence of the jotunite at moderate pressure (5-7 kb) (plagioclase - hypersthene/olivine - ilmenite) is reasonably similar to that in the lower part of the BKSK Layered Series, that crystallised at 4 - 6 kb based on the contact-metamorphic mineral assemblages (Jansen et al. 1985).

Phase equilibria show that jotunitic magmas have compositions that reside on a thermal divide at pressures where they coexist with plagioclase and two pyroxenes and cannot be decendants of mantle-derived basalts (Longhi et al. 1999). They appear to have originated by melting of lower crustal gabbronorites. Recent investigations of the Re-Os systematics of the Rogaland Igneous Province (Schiellerup et al. 2000) also support a crustal origin.

TYPICAL MARGINAL JOTUNITE (B90)

SiO_2	49.8	Q	6.7
TiO_2	4.2	or	5.3
Al_2O_3	15.0	ab	20.3
FeO^*	14.2	an	27.5
MgO	5.0	di	4.8
CaO	6.7	hy	26.1
Na_2O	2.4	mt	1.6
K_2O	0.9	il	8.0
P_2O_5	0.8	ap	1.8

Figure 10. Major element composition and CIPW norm of a typical chilled jotunite from the northern margin of the Bjerkreim-Sokndal Intrusion. From Robins et al. (1997).

Processes in the Bjerkreim-Sokndal magma chamber

Initial emplacement, subsequent replenishment and expansion

The distribution and contact relationships of the oldest cumulates in the Bjerkreim lobe of the BKSK indicate that the magma chamber during the earliest phases of its evolution was approximately wedge-shaped and relatively limited in horizontal and vertical extent. It is probable that the initial development of the magma chamber was controlled by displacements along a normal fault, space being created by more pronounced subsidence of the hanging wall beneath the floor of the embryonic intrusion than the roof rocks. Thus the cumulates forming MCU 0-IB crystallised at the base of a chamber with the form of a half graben, the deepest part of the chamber being along its steep, fault-controlled, north-eastern margin.

The high frequency of anorthositic xenoliths in the early cumulates suggests that the margins of the early magma chamber were mainly composed of rocks belonging to the Egersund-Ogna anorthosite massif while part consisted of granulite-facies quartzo-feldspathic and mafic gneisses. The incorporation of large numbers of blocks of anorthosite and leuconorite suggests either that extensive stoping took place along the roof and walls of the chamber or that large numbers of xenoliths were transported into the chamber as it was filled.

During the early stages of evolution of the BKSK chamber there were at least two major episodes of magma recharge, represented by the bases of MCUs IA and IB. Each of these was followed by the crystallisation of exceptionally thick sequences of plagioclase-rich, zone a cumulates on the floor of the magma chamber. The cumulus plagioclase in MCUs IA and IB is distinctly more sodic (An_{46-39}) and the orthopyroxene has a lower mg# than in the succeeding units. Plagioclase is commonly antiperthitic and interstitial quartz and apatite occur in some of the plagioclase-rich cumulates, features that are uncommon in the higher-temperature cumulates elsewhere in the Bjerkreim lobe of

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the BKSK. These observations suggest that the early, plagioclase-rich cumulates may have crystallised from lower-temperature, more-differentiated magmas than both those emplaced later in the evolution of the magma chamber and those represented by the jotunite marginal chills. Systematic stratigraphic variations in the composition of plagioclase in these rocks are not conspiquous, despite their considerable thicknesses. These relatively evolved magmas emplaced early in the development of the BKSK must have had densities sufficiently low to permit the settling of leuconorite and anorthosite xenoliths and, by inference, also plagioclase primocrysts. The thicknesses of pC and piC, the inconspiquous cryptic variation and the presence of plagioclase and rarer orthopyroxene megacrysts in MCUs IA and IB suggest that the magmas may have been emplaced with significant amounts of crystals, particularly plagioclase, in suspension.

Crystallisation of the multiphase cumulates at the top of MCU IB was interrupted by emplacement of a voluminous batch of jotunite magma from which the cumulates of MCU II were formed. This influx of magma led to elevation of the roof and substantial lateral enlargement of the chamber. Stratigraphic relations show that the edge of the chamber was displaced by >6 km to the southeast and in the southern part of the Bjerkreim lobe cumulates belonging to MCU II are separated from the floor of the intrusion by only a thin marginal zone of plagioclase-rich rocks. The new stretch of floor produced during lateral enlargement of the chamber was not planar. An elevated ridge existed in the Teksvatnet area, and the MCU II sequence and later cumulates thin markedly over this topographic feature. The ~2m thick sequence of phiC that intervenes between the low-temperature cumulates (phci±m±aC) forming the uppermost part of MCU IB and the higher-temperature zone a cumulates in the lower part of MCU II indicates that the replenishment event was not instantaneous but persisted for a period of time. The regressive stratigraphic sequence that crystallised during the prolonged influx of magma was the result of mixing of some of the resident with the inflowing magma. Subsequent to replenishment, the magma chamber was occupied by a lens of residual magma residing on a floor of earlier cumulates that dipped inwards at low angles to an axial depression (a saucer-shaped floor). Continuous cooling and fractional crystallisation of the magma led to formation of a thick sequence of pimC and phiC (MCU II). The magma did not differentiate sufficiently to re-attain saturation in magnetite, Ca-rich pyroxene or apatite before the emplacement of a further batch of magma.

The replenishment event that terminated the crystallisation of MCU II resulted in further expansion of the magma chamber similar to that accompanying the preceeding magma influx. Judging by the degree of cryptic layering in MCU III, the increase in the depth of the magma occupying the chamber was, however, much less than during the earlier influx and the extent of expansion of the chamber appears to have been more limited. Expansion of the chamber took place by lateral wedging of 1600-3000m towards the south. The edge of the magma chamber in the southernmost part of the Bjerkreim lobe advanced further into the Helleren anorthosite massif, and during this processes numerous blocks of anorthosite and leuconorite were incorporated into the magma chamber.

The final major replenishment event took place after the resident magma had undergone a degree of fractional crystallisation sufficient to stabilise first magnetite, then Ca-rich pyroxene and apatite as liquidus minerals along the more distal (and higher) parts of the floor of the magma chamber while in the axial region of the magma chamber, magnetite-bearing noritic cumulates were still crystallising. This phase of magma influx appears to have been very voluminous and it resulted in a major lateral enlargement of the magma chamber to the south and the development of the Sokndal and Mydland lobes of the BKSK, where only the equivalents of cumulates belonging to MCU IV in

the Bjerkreim lobe are represented. During the lateral migration of the edge of the magma chamber from its previous location near the present southern margin of the Bjerkreim lobe, myriads of large blocks and slabs of anorthositic rocks and quartzo-feldspathic gneisses were stoped from the enlarging roof of the chamber. Whilst new, high-temperature magma flowed into the lowest part of the magma chamber, the less-dense residual magma was probably decanted southwards into the new Sokndal and Mydland lobes. This major replenishment was followed by almost continuous differentation that eventually led to the formation of mangeritic cumulates.

Duchesne and Wilmart (1997) have proposed that the crystallisation of mangerite was terminated by the emplacement of magmas that varied in composition from jotunite to charnockite. They envisage that the thick uppermost unit of quartz mangerite and charnockite in the BKSK crystallised from a viscous, inhomogeneous mixture of residual acid magmas and externally-derived, differentiated magma, possibly with additional admixture of anatectic melts derived from the gneisses that formed part of the roof of the magma chamber. In the Bjerkreim lobe of the intrusion there is, however, an uninterrupted cryptic variation from the TZ into the overlying mangerite and quartz mangerite, suggesting continued cooling and fractional crystallisation of residual magma that had been highly contaminated by assimilation of country rock xenoliths and hybridisation with roof melts. The xenolithic zone located at the mangerite-quartz mangerite boundary may represent an episode of major roof collapse.

Crustal contamination

The BKSK magma chamber was emplaced into quartzo-feldspathic and mafic gneisses as well as massif-type anorthosites. Xenoliths of these country rocks are enclosed in the BKSK cumulates and are exceptionally abundant in places. It is unlikely that the plagioclase-saturated BKSK magmas could have assimilated anorthositic rocks or dry mafic gneisses, but extensive interaction between the magmas occupying the chamber and xenoliths of quartzo-feldspathic gneiss seems very probable. In addition, the granitoids that form the uppermost part of the BKSK may have resulted in part from partial melting of gneisses that formed part of the roof of the magma chamber, and anatectic acid magmas may have mixed with the underlying more basic magmas occupying the bulk of the chamber.

The initial $^{87}Sr/^{86}Sr$ ratios (Sr_0) of cumulates in the Bjerkreim lobe vary substantially and provide robust evidence of extensive assimilation within the magma chamber. Sr_0 shows a general evolution with stratigraphic height in the Bjerkreim Layered Series from 0.705 in MCU II to 0.7086 in the upper part of MCU IV (zone e) (Figure 11). The trend of increasing Sr_0 is interrupted by regressions to values as low as 0.7048 associated with the lower boundaries of MCU III and IV. With the exception of the uppermost part of the Layered Series there is a remarkable antipathetic relation between the cryptic variation as defined by the composition of cumulus minerals (An%, mg# in pyroxenes) and Sr_0.
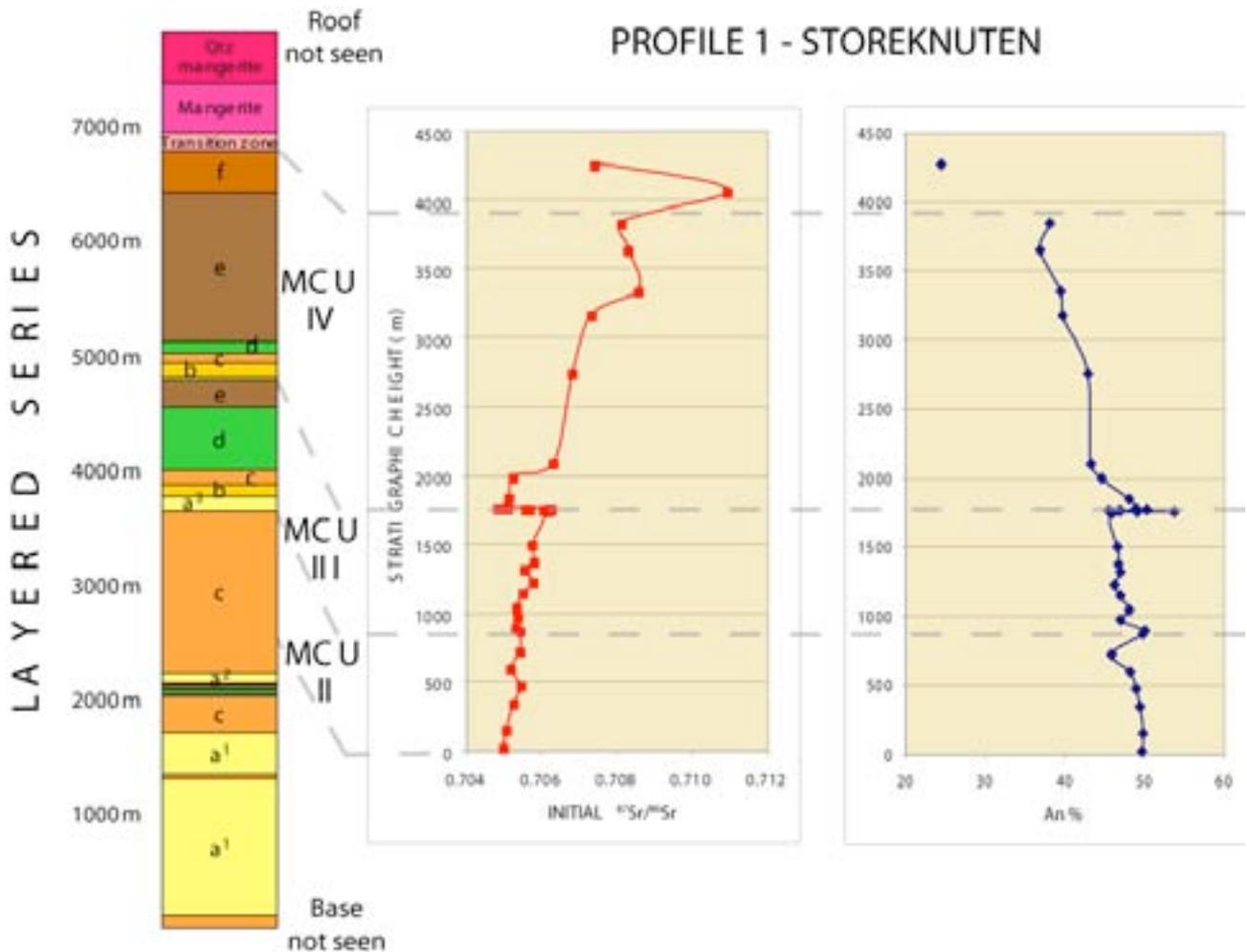
Figure 11. Cryptic variation in plagioclase compositions and initial $^{87}Sr/^{86}Sr$ for bulk-rock samples collected through the Layered Series in the southern flank of the Bjerkreim lobe (after Nielsen et al. 1996). The location of sample profile 1 is given in Figure 7. The stratigraphic column to the left is for the Layered Series as developed in the axial region of the lobe. Note the pronounced cryptic regression associated with the MCU III/IV contact.

There is relatively little isotopic data for the granitoids that form the uppermost part of the BKSK, and certain aspects of it indicates disturbance of the Rb-Sr system. Wielens et al. (1980) calculated an isochron that gave an initial Sr-isotope ratio of 0.7075 ± 0.0028 on the basis of some of the data for these rocks reported by Versteeve (1975). Demaiffe et al. (1986) estimated Sr_0 for the quartz mangerite to be ~0.7085. Both of these values coincide with that in the upper part of MCU IV, eliminating earlier isotopic arguments for a separate origin of the granitoids, and in accordance with an origin as residual, highly-differentiated magmas. Currently, there is no isotopic evidence that supports an origin for all or part of the quartz mangerites and charnockites exclusively through anatexis of country-rock gneiss. The $^{87}Sr/^{86}Sr$ ratios (at 930 – 920 Ma) for the gneisses in the vicinty of the BKSK are extremely variable, but generally higher than that of the quartz mangerite (e.g. 0.7196 for gneisses in Gydalen, a short distance to the east of the margin of the BKSK (Versteeve 1975)).

The variation in Sr_0 in the Bjerkreim Layered Series is open to interpretation in several different ways. Assimilation of country rocks (either in situ or as xenoliths) or incorporation of anatectic melts may have taken place continually during the cooling and fractional crystallisation of magma that was well-mixed on a chamber scale. Alternatively, the degree of contamination may have increased towards the chamber roof in a stratified magma, due to assimilation of increasing numbers of buoyant xenoliths in the upper parts of the magma chamber or variable amounts of physical mixing with a separate, low-density, anatectic roof melt. Additionally, a contaminated isotopic signature may have diffused from the roof downward through a stratified magma column (see below). In view of the evidence in the BKSK for magma stratification during at least part of the evolution of the chamber, it would seem likely that some or all of these processes were operating during the crystallisation of the cumulates at the base of the magma chamber. Assuming simultaneous assimilation and fractional crystallisation (AFC), the available Sr isotope data are consistent with a ratio between the rates of assimilation and fractional crystallisation of ~0.2 (Tegner et al. 2000; Tegner et al 2005).

Compositional stratification of the magma chamber

Several features of the stratigraphic organisation of the cumulates in the Bjerkreim lobe of the BKSK indicate that the magma from which they crystallised was compositionally stratified and that the density stratification was stable over substantial periods of time. Detailed mapping of phase contacts has demonstrated that the zone a cumulates at the base of MCUs IB and II thin dramatically as they are traced from the northeastern margin of the intrusion to the southwest, and both zones eventually pinch out within ilmenite norites. These plagioclase-rich cumulates must be contemporaneous with the lower-temperature cumulates into which they pass along the strike of the modal layering towards the margins of the intrusion. The zone a cumulates at the base of MCUs III and IV exhibit a similar geometrical relationship: They are thickest in the axial region of the intrusion but thin towards both margins, and wedge out completely to the east towards the Teksvatnet ridge. The converse relationship is apparent in the uppermost part of MCU III, where the lowest-temperature cumulates (phcimaC) occur in the more marginal parts of the unit but are absent in the axial region of the Bjerkreim lobe where the basal cumulates of MCU IV rest on higher-temperature phimC. These stratigraphic relationships suggest gradients in magma composition and temperature across the floor of the chamber during fractional crystallisation. We suggest that the magma occupying the chamber was stably stratified with density and temperature decreasing and the degree of magma differentiation increasing upwards through the column of magma, while the cumulate-melt interface was sloping, either uniformly towards the northeast margin of the chamber (during the crystallisation of MCU IB) or generally inwards towards the axis of the chamber (during the crystallisation of MCU III). An exception to this generalisation is the ridge in the chamber floor represented near Teksevatnet that existed during the crystallisation of MCU II and later units. The cumulates of MCU II-IV thin over this feature and certain zones wedge out eastwards towards it (e.g. zone IIIb). Evidently, at the stage in the accumulation of the Layered Series represented by MCUs II and III, higher-temperature cumulates were forming in the adjacent basins than on the ridge itself. During the crystallisation of MCU IV, the Teksevatnet topographic high appears to have been largely eliminated.

The angles of 2-15° that exist between certain of the phase contacts and the boundaries between the megacyclic units in the Bjerkreim lobe provide a reasonable minimum estimate of the original slopes of the temporary floor of the magma chamber beneath a stratified magma. The fact that discordances between cryptic and modal layering exist both near the base and the top of MCU III

suggest that magma stratification was extremely stable. It persisted for at least as long a period of time as the up to 1050m-thick megacyclic unit took to crystallise.

Whether the column of stratified magma in the BKSK chamber was divided into horizontal liquid layers separated by diffusive interfaces is not clear from field relations. A continuously-stratified magma excludes convective mixing. There is, however, clear evidence within the cumulates of the BKSK for convection during their crystallisation, including cross-lamination, erosional unconformities and troughs. We therefore suggest that the magma was discontinuously stratified, and consisted of horizontal, independantly-convecting and internally homogeneous liquid layers separated by relatively-sharp, diffusive interfaces. Several processes that appear to have operated in the BKSK magma chamber could have led to the development of stratification: entrainment of resident magma and hybridisation in turbulent fountains during the emplacement of new, less-differentiated and denser magma (Campbell 1996); repeated emplacement of hot, dense magma along the floor of the chamber, with little mixing with the overlying resident magma (Huppert & Sparks 1980); varying degrees of mixing between the resident magma and anatectic melts generated along the inclined walls and roof of the magma chamber or assimilation of varying amounts of buoyant wall-rock xenoliths (Campbell & Turner 1987); compositional convection driven by density differences arising from crystallisation along inclined surfaces (McBirney et al. 1985).

Hybridisation

The cryptic variation in mineral chemistry and particularly in initial Sr, Nd and Pb isotope ratios exhibited by a section through the sequence of zone a cumulates above the base of MCU IV suggests that the final influx of magma into the Bjerkreim-Sokndal chamber was prolonged and associated with the elevation of the differentiated, contaminated and compositionally-zoned column of resident magma as well as hybridisation of the inflowing and resident magmas (Jensen et al. 1993, Barling et al. 2000). This resulted in a modal regression from phcmiaC to phiC/piC and culminated in the crystallisation of high-temperature, plagioclase (An_{53})-olivine (Fo_{74}) cumulates. The modal regression is accompanied by a reverse cryptic variation in mineral compositions and a systematic variation in initial isotopic ratios (e.g. a steady upward decrease in $^{87}Sr/^{86}Sr$ from 0.7061 to 0.7048), demonstrating that the cumulates crystallised from hybrid magmas with an increasing proportion of the inflowing, more primitive jotunite. Recharge of the magma chamber took place after prolonged fractional crystallisation of magnetite and consequent decrease in the density of the resident magma. Hybridisation is envisaged as taking place in a turbulent fountain with the efficiency of hybridisation of the inflowing magma with the less-dense resident magma decreasing with time.

In contrast, differentiation of the resident magma was arrested at a relatively early stage by the influx of magma marked by the MCU II/III contact. MCU II consists exclusively of a thin basal sequence of plagioclase cumulates and a thick series of phiC. Cumulus magnetite does not make an appearance in MCU II, and it is likely that the resident magma was differentiating with increasing density during its crystallisation. The MCU II/III boundary is characterised by a sulphide-enriched subzone associated with a discontinuous layer of orthopyroxenite or mafic ilmenite norite. This is succeeded by a general regression in mineral compositions that culminates in the zone IIIb troctolitic cumulates in the central and western part of the Bjerkreim lobe. Zone b cumulates are, however, absent in the eastern flank. The stratigraphic relations appear to be consistent with prolonged magma-chamber recharge associated with progressive mixing of the inflowing jotunitic magma and the resident, stratified magma whose basal portion was more dense than the

replenishing magma. The sulphide-enriched orthopyroxenite and related melanocratic ilmenite norite that represent the initial response to the replenishment event are explained by crystallisation of hybrid magmas residing in the pyroxene phase volume. Their chamber-wide distribution is inferred to result from mixing taking place some distance above the floor at a level where the plume formed by the inflowing magma reached a level of neutral buoyancy in the compositionally-stratified magma column and then spread laterally throughout the chamber (Figure 12). As the influx proceeded the resident magma was stripped from the base of the chamber and mixed into the ascending plume as the hybrid layer increased in thickness and became compositionally stratified. Eventually the lower boundary of the hybrid layer reached the floor of the magma chamber. The highest-temperature cumulates (poC, zone IIIb) crystallised from the lowest part of this hybrid layer and were restricted to the central trough on the chamber floor (corresponding to the axial region of the intrusion), while lower-temperature cumulates crystallised simultaneously on the eastern «shelf» from magma higher up in the hybrid layer.
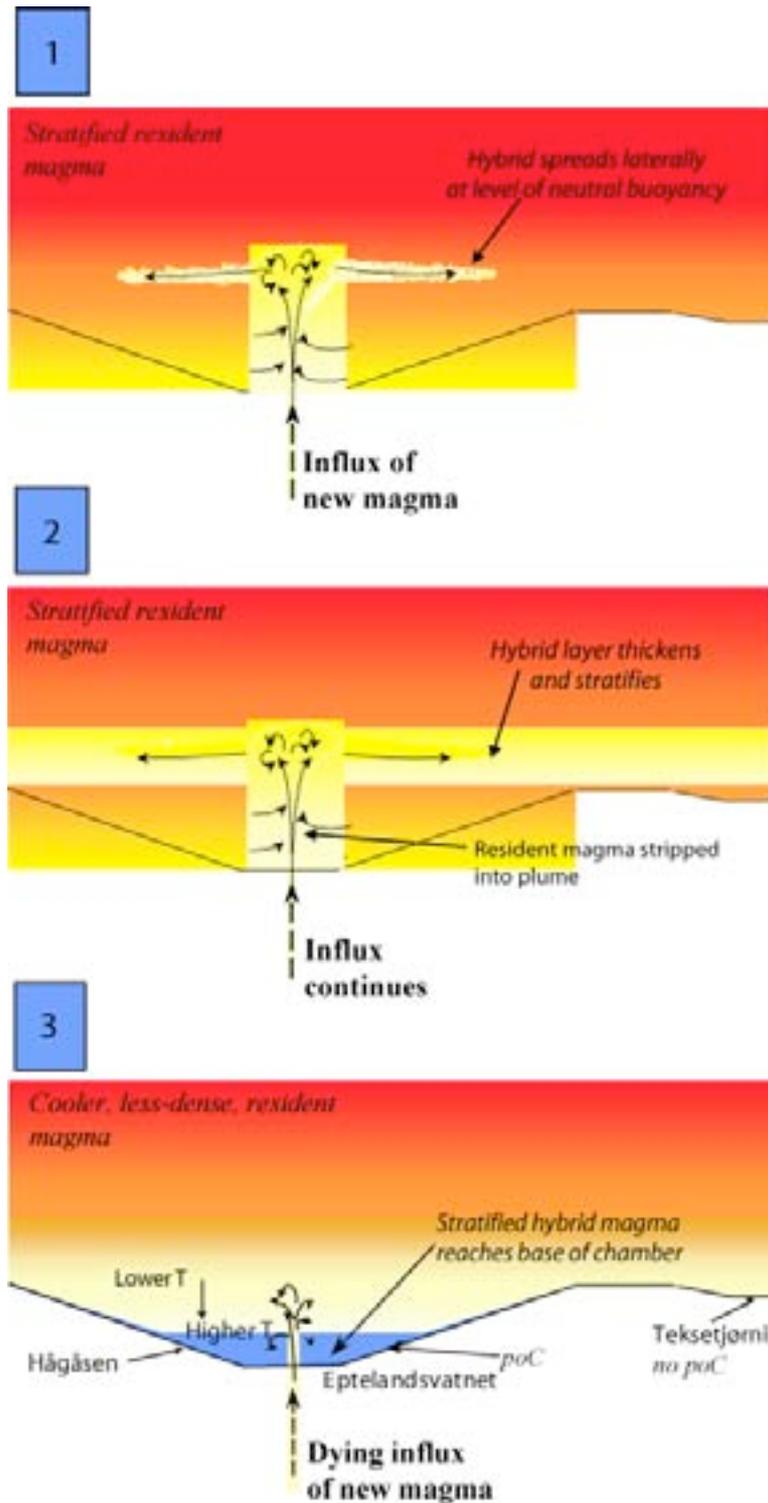
Figure 12. The sequence of events during the influx of magma reflected by zones IIIa and IIIb depicted in schematic W-E sections: 1) Magma flowed in as a turbulent plume and the hybrid spread laterally some distance above the floor of the chamber; 2) The hybrid layer thickened and stratified and its lower boundary sank as resident, denser magma beneath was mixed into the plume. Crystallisation in the hybrid layer resulted in the sulphide-bearing orthopyroxenite and equivalents; 3) The stratified hybrid layer reached the floor of the chamber. Troctolite (zone b) crystallised in the axial trough while more evolved cumulates formed on the eastern shelf.

The Jotunitic and Acidic Igneous Rocks

(by J.V. Auwera, O. Bolle and J.C. Duchesne; modified by J. R. Wilson)

The Jotunite suite

Proterozoic massif anorthosites are usually associated with variable amounts of a characteristic suite of intermediate rocks. The least evolved rocks of this suite are enriched in mafic minerals (low- and high-Ca pyroxenes, Fe-Ti oxides, apatite), and in some cases very high concentrations of these phases give rise to extremely mafic-rich rocks. Different names, including ferrodiorite, monzonorite, jotunite, Fe-Ti-P-rich rocks (FTP) or oxide-apatite gabbronorite, have been used. However, Vander Auwera et al. (1998) referred to them by the collective term jotunite (Fe-Ti-P-rich hypersthene monzodiorite). Evolved rocks of the suite include mangerite (hypersthene monzonite), quartz mangerite (hypersthene quartz monzonite) and charnockite (hypersthene granite). Vander Auwera et al. (1998) accordingly referred to the suite as a whole as the jotunite suite.

The origin of jotunites has been the subject of considerable debate, despite their similar textural and geochemical characteristics from one anorthositic complex to another. Several hypotheses, not mutually exclusive, have been proposed:

(1) jotunites are residual liquids after anorthosite crystallization (Emslie 1978, Morse 1982, Wiebe 1992, Ashwal 1993, Emslie et al. 1994) (evolved jotunites of Vander Auwera et al. 1998);
(2) jotunites are the parental magmas of the andesine anorthosite suite (Duchesne et al. 1974; Duchesne & Demaiffe 1978; Demaiffe & Hertogen 1981) (primitive jotunites of Vander Auwera et al. 1998);
(3) jotunites are products of partial melting of the lower crust with necessary heat produced by anorthosite emplacement (Duchesne et al. 1985b; 1989; Duchesne 1990);
(4) jotunites are transitional rocks in a comagmatic sequence from anorthosite to mangerite (Wilmart et al. 1989; Owens et al. 1993; Mitchell et al. 1996; Duchesne & Wilmart 1997);
(5) jotunites are derived by fractionation of mafic magmas unrelated to the anorthositic suite (Emslie 1978; 1985);
(6) jotunites are immiscible liquids conjugate to mangerites (Philpotts 1981);
(7) primitive jotunites are produced by partial melting of a lower crustal gabbronoritic source (Longhi et al. 1999) and are parental magmas for andesine anorthosites (Vander Auwera et al. 1998).

In the Rogaland intrusive complex (Figure 3; Michot 1960; Michot & Michot 1969), jotunitic rocks and the products of their differentiation are particularly abundant compared to the other anorthositic provinces. Jotunitic rocks mainly occur in a system of dykes and small intrusions (Duchesne et al. 1985a; 1989). Some dykes are petrographically homogeneous along strike, such as the Varberg dyke (jotunitic), the Vaersland and Ørsland dykes (quartz mangerite) and the Vettaland dyke (antiperthite norite). Others show a variation of composition along strike, such as the Lomland dyke (from norite to mangerite) and the Tellnes dyke (from jotunite to charnockite).

The Rogaland jotunites, first briefly described by Michot (1960), were extensively studied by Duchesne, Demaiffe and co-workers in several papers reviewed by Duchesne (1990). Jotunites are typically medium-grained and contain plagioclase (usually antiperthitic), some perthitic to

mesoperthitic (in the evolved facies) K-feldspar, poikilitic inverted pigeonite, augite, Fe-Ti oxides, apatite, and quartz in the evolved facies (Duchesne 1990). They occur mostly as dykes cross-cutting massif-type anorthosites (Figure 3) but those that have been dated have similar absolute ages in the range close to 930 Ma (Schärer et al. 1996). Among them, the Tellnes dyke in the Åna-Sira massif, as well as the Varberg and Lomland dykes in the EGOG massif (Figure 3), have been studied in most detail (Duchesne et al. 1985a; Wilmart et al. 1989). The Tellnes dyke varies continuously from jotunitic to charnockitic lithologies. It has a well-defined Rb-Sr whole rock isochron giving the same age as the U-Pb zircon age and its compositional variation can be explained not by mixing but by a process of fractional crystallization without progressive contamination (Wilmart et al. 1989). Modelling of the fractional crystallization process was achieved in two steps by least square calculation, the mineral compositions of the subtracted assemblages being constrained by Ford et al. (1983) of the olivine composition and for the coexisting minerals by considering the relevant cumulus mineral associations in the BKSK Layered Series.

Whole-rock Rb-Sr isotopic data from other dykes such as Lomland do not fit tightly to isochrons and there is considerable variation in Sr_0 from dyke to dyke (0.704 - 0.710) that does not correlate with other geochemical parameters (Demaiffe et al. 1986, Duchesne et al. 1989). There are also distinct trace element signatures from dyke to dyke: for the same major element contents, significant variations in REE, Zr, Ba and Rb are observed (Duchesne et al. 1989; Bolle 1996). Taken together these data suggest sources with variable mineralogy, degrees of contamination and melting.

Jotunites also form small intrusions (Figure 3) (e.g. Eia-Rekefjord), mingling facies (e.g. in the southern part of the Apophysis: Demaiffe 1972; Wiebe 1984; Bolle 1998), as well as chilled margins to the Hidra and Garsaknatt leuconoritic bodies (Demaiffe & Hertogen 1981) and, locally, to the BKSK layered intrusion (Duchesne & Hertogen 1988; Wilson et al. 1996; Robins et al. 1997). One of these chilled margins, the Tjørn facies (sample 80123a of Duchesne & Hertogen 1988), has been studied experimentally (Vander Auwera & Longhi 1994) and it has been shown that, for this composition, the near liquidus assemblages are plagioclase (An_{49}) + olivine (Fo_{64}) at 5 kb and plagioclase (An_{47}) + low-Ca pyroxene (En_{66}) at 7 kb. Clearly the succession of cumulate rocks in the BKSK intrusion can be reasonably accounted for by fractional crystallization at ~5 kb of a melt similar to the Tjørn chilled liquid, but slightly more An-rich and with a somewhat higher MgO/FeO ratio.

A liquid line of descent (LLD)

Among the Rogaland jotunites, the least differentiated compositions (high MgO, low K_2O) correspond to the chilled margins and, in most variation diagrams (Figure 13), they form a group distinct from the jotunites of the dyke system (Duchesne 1990). Vander Auwera et al. (1998) referred to the chilled margin samples as primitive jotunites and to the least differentiated samples of the dyke trend as evolved jotunites. Using experimental data, these authors showed that the gap between primitive and evolved jotunites only results from a lack of exposure of an early fractionation stage which probably took place below the intrusion level of dykes. Indeed, in variation diagrams, the gap between the primitive and evolved jotunites is filled by experimental liquids residual to the Tjørn primitive jotunite (Vander Auwera & Longhi 1994). Combined experimental and geochemical data have thus enabled these authors to define a complete liquid line of descent (LLD) ranging from primitive jotunites to evolved jotunites and then to charnockites. Modelling of this LLD supports the hypothesis that extensive fractionation of primitive jotunites
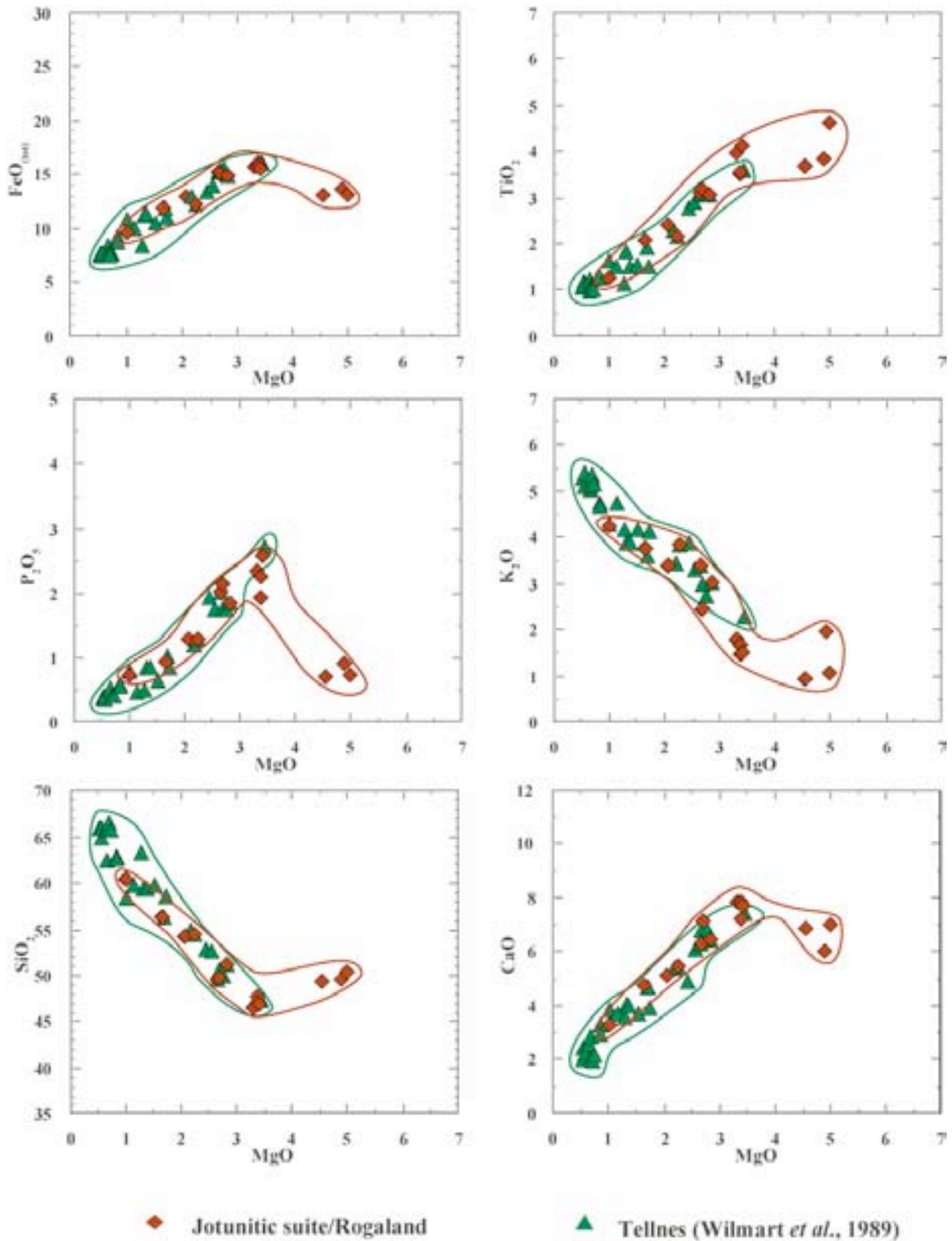
Figure 13. Major element variation diagrams of the jotunitic suite (after Vander Auwera et al. 1998). Data from fine-grained samples (chills) and from the Tellnes dyke (Wilmart 1988; Wilmart et al. 1989).

produces quartz mangerites with REE concentrations in the range of jotunites, strong depletions in U, Th, Sr, Ti, P and smaller to no relative depletions in Hf and Zr. Moreover, experimental and petrographic data indicate that the FTP rocks represent accumulations of a dense oxide-apatite-pigeonite assemblage into coexisting multisaturated jotunitic to mangeritic liquids.

In conclusion, the Rogaland jotunitic-charnockitic trend is the latter part of a multi-stage process of polybaric fractional crystallisation, crystal accumulation, and probably flow differentiation within dykes. The early stage of fractionation passing from primitive jotunite to evolved jotunitic melts is not displayed in the dyke system. It probably took place in agma chamber(s) several kilometers below the intrusion level of dykes to produce andesine anorthosites and layered rocks. Jotunitic dykes, ranging in composition from evolved jotunites to quartz mangerites or charnockites, were probably also spawned by fractionation either within a deeply seated anorthositic intrusion or in a layered mafic body, such as the BKSK intrusion.

Crustal origin of the primitive jotunite

Experimental data on the liquidus equilibria in the range of 1 bar to 13 kbar relevant to anorthosite petrogenesis have brought new constraints on the nature of the source rocks of the jotunite parental magmas (Longhi et al. 1999). Between 10 and 13 kbar, i.e. the pressure conditions of a deep-seated magma chamber where Al-rich opx megacrysts coexist with plagioclase, the phase diagram shows a thermal barrier and the Tjørn jotunite sits close to that barrier. Consequently, the primitive jotunite cannot be derived by fractionation of melt of an olivine-dominated mantle and can only be produced by melting of a source rock whose composition lies on the barrier, i.e. a gabbronorite. These experiments have constrained the composition of the source rocks. Mafic granulites - a major component of the lower crust - have adequate average compositions, although they vary considerably between different tectonic provinces (Rudnick & Fountain 1995). The best candidates are layered intrusions of basaltic kindred such as the Stillwater Complex which have higher mg-numbers than average lower crust. Because of the thermal barrier at high pressure, mixing with silica-rich (crustal) material has no effect on the major element composition of basaltic liquids. Whatever the amount of mixing, these liquids are inexorably brought back to the ol+opx cotectic by decreasing temperature and forced to follow it. Crustal contamination of basaltic magma in deep-seated magma chambers is thus possible, especially at the radiogenic isotope level, but fractionation does not lead to silica-rich liquids.

The acidic igneous rocks

Other main components of the AMCG suite are acidic rocks. They also occur in the Rogaland anorthosite province. They are found in the upper part of the BKSK layered intrusion, in the Apophysis and in the Farsund charnockite as well as in the small Breimyrknuten charnockite. The Lyngdal granodiorite, formerly considered as belonging to the anorthosite province (Falkum 1966; Pasteels et al. 1970), is now preferably connected to the post-collisional plutonism related to the Mandal - Ustaoset Line. The granodiorite contains no opx but hornblende + biotite + titanite and resembles the Svofjell granite, one of the largest plutons related to the Mandal - Ustaoset Line (Vander Auwera et al. 1999; Bogaerts et al. 2001; Vander Auwera et al. 2001).

The BKSK upper part: C-type magmas

The upper part of the BKSK intrusion comprises mangerite, quartz mangerite and charnockite (Duchesne & Wilmart 1997); they form a suite of K_2O-rich alkali-calcic granitoids. Their low mg# and high HFSE contents give them A-type affinities. The agpaicity index varies between 0.87 and 0.94, so the suite is not peralkaline but can be considered as alkaline (Liégeois & Black 1987;

Maniar & Piccoli 1989). The high contents of K_2O, TiO_2, P_2O_5 and low CaO are typical of C-type magmas (Kilpatrick & Ellis 1992).

Mangerites lie stratigraphically above the Layered Series defined by Wilson et al. (1996) (see Figures 8 and 9), more precisely above the jotunitic Transition Zone marked by the appearance of iron-rich olivine (Michot 1960; 1965; Duchesne et al. 1987b). Geochemically they display evidence of mesoperthite accumulation (large positive Eu-anomaly, high Ba contents, low Zr contents). Quartz mangerites and charnockites form the top of the intrusion and its most central part. They are coarse-grained and massive, with a faint foliation (Bolle et al. 2000).

The petrogenesis of this rock suite has long been debated. Michot (1960; 1965) considered they were produced by fractional crystallisation together with the underlying anorthosites, leuconorites and norites, thus giving strong evidence of a continuous evolution from anorthosite to quartz mangerites. This concept was, however, questioned when isotopic evidence of contamination by crustal material became available (see the review by Demaiffe et al. 1986). Moreover the Layered Series was shown to result from repeated influxes of magma (Duchesne 1972; Nielsen & Wilson 1991) and assimilation was recognized as a constantly operating mechanism during fractional crystallisation, the contaminant being anatectic melts from country rock gneisses at the roof of the intrusion (Nielsen et al. 1996). The granitoid rocks from the upper part were therefore considered either as the contaminated residual liquid of the cumulate pile (Nielsen et al. 1996) or, following a suggestion of Wiebe (1984), as the melted roof itself.

Detailed work in the Ørsland area has suggested another scenario (Duchesne & Wilmart 1997): the transition from mangerite cumulates to quartz mangerites takes place in a zone of enclaves crowded with jotunite microgranular inclusions, pods and rafts of leucogranitic material and countless gneiss xenoliths. This zone was identified by Michot (1960; 1965) as a discontinuous "xenolithic septum" at the same level of the stratigraphic column. This enclave zone also marks a minor discontinuity in the evolution (Duchesne & Wilmart 1997). Wilson & Overgaard (2005) studied a series of profiles from the upper part of the BKSK Layered Series into the overlying evolved rocks. They found that the minerals became continuously more evolved with no sign of a compositional reversal, concluding that: a) the minor reversal at Ørsland is not chamber-wide and does not reflect a major magma replenishment event; b) the sequence studied in the profiles represents aevolution of the Layered Series into the evolved, overlying jotunitic Transition Zone, mangerites, quatz mangerites and charnockites.

Two series of liquids

Petrographic and geochemical features studied by Duchesne & Wilmart (1997) indicate that the the evolved rocks at the top of BKSK fall into two distinct series: the main LLD (mg# ~0.15), which passes from jotunites through two-pyroxene quartz mangerites to amphibole charnockites, and the olivine trend (mg# ~0.06), which encompasses olivine-bearing quartz mangerites and charnockites,

and represents the evolved differentiation products of the magma parental to BKSK. The samples studied by Wilson & Overgaard (2005) belong to the olivine trend. These two series are intimately mixed in the field. They evolve through fractional crystallisation with assimilation of a crustal leucogranitic component, which has been identified in fine-grained leucogranitic enclaves that are particularly abundant in the uppermost part of the massif, close to the now eroded roof. These enclaves display very irregular shapes with long dyke-like fingers. They have a very peculiar geochemical signature: they are strongly depleted in REE with the exception of Eu which shows a huge positive anomaly. Similar characteristics have been described in leucosomes from migmatites (Barbey et al. 1989; Sawyer 1991; Fourcade et al. 1992; Vander Auwera 1993), which corroborates the origin of these enclaves as migmatitic melts from the gneissic envelope.

The main LLD is similar in major elements to the Tellnes evolution up to the charnockites. Then, due to a higher water activity of 0.3, it moves to amphibole charnockites representing a granitic eutectic with a high SiO_2 content (Wendlandt 1981; Ebadi & Johannes 1991). Some trace elements are, however, quite different from the Tellnes trend. Rb, Cs and Th increase much quicker here, and zircon saturates at 60-62% SiO_2, earlier than at Tellnes. These differences may be related to the higher water fugacity and/or to the assimilation process. The olivine trend displays an evolution similar to that of the main LLD, with contamination by the same leucogranitic material.

Zircons from both series reveal complex structures (Duchesne et al. 1987a). U-mapping unravels U-rich cores or U-poor cores rimmed by a U-rich envelope, both within U-poor outer shells. These point to hybridization processes and/or heritage from the source rock.

The Apophysis

In the southern part of the Apophysis, as near Fidsel, mingling and mixing relationships between primitive jotunitic magma (similar to the Hidra chilled margin) and mangeritic melt are conspicuous (Duchesne 1989; Bolle, 1998). In the northern part, detailed mapping (Bolle 1996; 1998) has shown that (quartz) mangerites dominate and contain a network of elongate lenses of mafic-rich jotunite. The contact zone between the Åna-Sira massif and the envelope was therefore intruded by various magmas. These magmas cut across the noritic to mangeritic cumulates of the Mydland lobe, confirming an intrusive event after formation of most of the BKSK.

The Apophysis (quartz) mangeritic magma defines a short trend, from 58 to 66.5% SiO_2, plotting close to or between the main LLD and the olivine-trend defined in the upper part of BKSK. This may indicate that the Apophysis could have acted as an escape conduit for the acidic magmas that mingled at the top of the BKSK, rather than as a feeder conduit. The Apophysis (quartz) mangeritic magma may then have resulted from complete mixing of the other two magmas. However, the intermediate geochemical character of the Apophysis (quartz) mangeritic magma does not systematically lie between the two trends defined in the BKSK acidic rocks, and, moreover, preliminary Sr-Nd isotope data obtained on quartz mangerites from the BKSK and the Apophysis preclude that the latter may have formed by mixing of the former without simultaneous, unsupported, crustal contamination. The Apophysis (quartz) mangerite is therefore best seen as resulting from the crystallisation of a third acidic magma, preferentially intruded along the eastern contact of the Åna-Sira massif.

The Farsund charnockite

The Farsund charnockite is still imperfectly known. It is compositionally rather homogeneous. More data are required to decide whether it is a differentiate of a jotunitic melt or a product of charnockitic anatexis. Isotopic signatures are currently ambiguous (Demaiffe et al. 1986).

Conclusions

Rogaland jotunites have proved decisive in filling the Daly Gap between basic and acidic rocks. A continuous LLD - the Tellnes trend - has been identified with chilled melts. This is a rare example of fractional crystallization of dry magma in a closed system. Modelling by various methods was confirmed by experimental petrology. The Tellnes trend thus appears to be an excellent reference for the definition of C-type granite LLD (a typology that we now prefer to "A-type" used by Duchesne & Wilmart (1997)).

Starting from this relatively simple case (dry system, no contamination), we can now better decipher the influence of assimilation and low water activity on the position of the LLD and on the behaviour of trace elements. The identification of leucogranitic (leucosome) material, unexpectedly depleted in incompatible elements, as a possible contaminant can also question classical views on the effect of contamination.

The origin of the jotunite parental to andesine anorthosite at mid-crust pressures, as proposed by Duchesne & Demaiffe (1978), is now confirmed by experiments and modelling. This view can now be extended to massif-type andesine anorthosites at the pressure of the deep-seated magma chamber (10 - 13 kb). Moreover, experimental data now show that jotunites lie on thermal highs in the relevant phase diagrams at 10 - 13 kbar, indicating that these magmas cannot be derived by fractionation of peridotitic mantle melts but by melting of gabbronoritic sources in the lower crust at depths of 40-50 km. One can now question the capability of the underplating process to yield intermediate magma through crustal contamination of mantle-derived magmas.

The Iron-Titanium Deposits

(by J.C. Duchesne and H. Schiellerup; modified by J. R. Wilson and B. Robins)

Introduction

Numerous Fe-Ti deposits of economic or sub-economic grade occur in the Rogaland Anorthosite Province. They include the famous world-class deposit of Tellnes, discovered in 1954 and operative since 1960, which is the second most important ilmenite deposit in crystalline rocks after the Lake Tio deposit, Allard Lake district, Quebec. The Storgangen deposit, which closed in 1964, is another famous mining site. Total production at the two deposits exceeds 20 million tons of ilmenite (Force 1991). The old Blåfjell mine, active from 1863 to 1876, produced some 90,000 tons of high quality ore. Apart from these economic deposits, numerous smaller occurrences are located in the anorthosite massifs. Krause et al. (1985) tabulated 23 small mines or prospects in the Åna-Sira anorthosite massif, 7 in the Sokndal lobe of the Bjerkreim-Sokndal intrusion, and 39 in the Håland-Helleren anorthosite (Figure 14). There are also disseminated ilmenite + magnetite ± apatite occurrences in banded norite units of the Bjerkreim-Sokndal layered intrusion and in numerous jotunitic (Fe-, Ti-, P-rich hypersthene monzodiorite) dykes and intrusions (e.g. in the Eia-Rekefjord massif and the Lomland dyke).

Mining activity in the Rogaland province began at Koldal, east of Egersund, in 1785 and reached a maximum between 1861 and 1881 in that region. After a 20-year break in Fe-Ti oxide ore exploitation, activity moved definitively to Sokndal which became the mining center for the Blåfjell, Storgangen and Tellnes ore bodies (Figure 15).

Exceptional exposure, lack of a metamorphic overprint (that typically affects the North American deposits), and a great variety of concordant and discordant occurrences, large compositional variations and a beautiful varieties of microstructures are features of considerable interest in the Rogaland mineralizations. It is thus not surprising that the ore-bodies are cited in numerous papers and text books (e.g. Vogt 1893; Foslie 1928; Ramdohr 1960).

Hubaux (1956; 1960) described a large number of occurrences in the Egersund district. He was able to distinguish variation in microtextures in the various deposits. However, his conclusions on the genesis of Rogaland Fe-Ti deposits were strongly influenced by Michot's (1955; 1956) interpretation of the Norito-Granitic Zone (NGZ) located between the Egersund-Ogna and the Håland-Helleren massifs (Figure 14b). Michot (1956) suggested a metasomatic origin for the Fe-Ti ore-bodies, which were considered to represent a mafic front in the complex transformation of a norite. Duchesne (1970, 1973) showed that the microtextures and the compositions of ilmenite and magnetite from the "metasomatic" bodies were quite similar to those in the Bjerkreim-Sokndal layered rocks, as well as in other, smaller deposits far away from the NGZ. Duchesne (1972) used trace elements to classify the deposits in a simple magmatic sequence. He further suggested that the metasomatic hypothesis was not necessary to account for the data. Later, new trace element data, including REE on apatite, led Roelandts & Duchesne (1979) to propose an origin for the deposits by segregation of Fe-Ti oxide minerals from comparable magmas at various stages of differentiation.

Krause and co-workers have documented the Blåfjell (Krause & Zeino-Mahmalat 1970), Storgangen (Krause & Pape 1975) and Tellnes (Gierth & Krause 1973) deposits in great detail (Figure 14). Although they were rather reluctant to propose detailed models for the formation of the
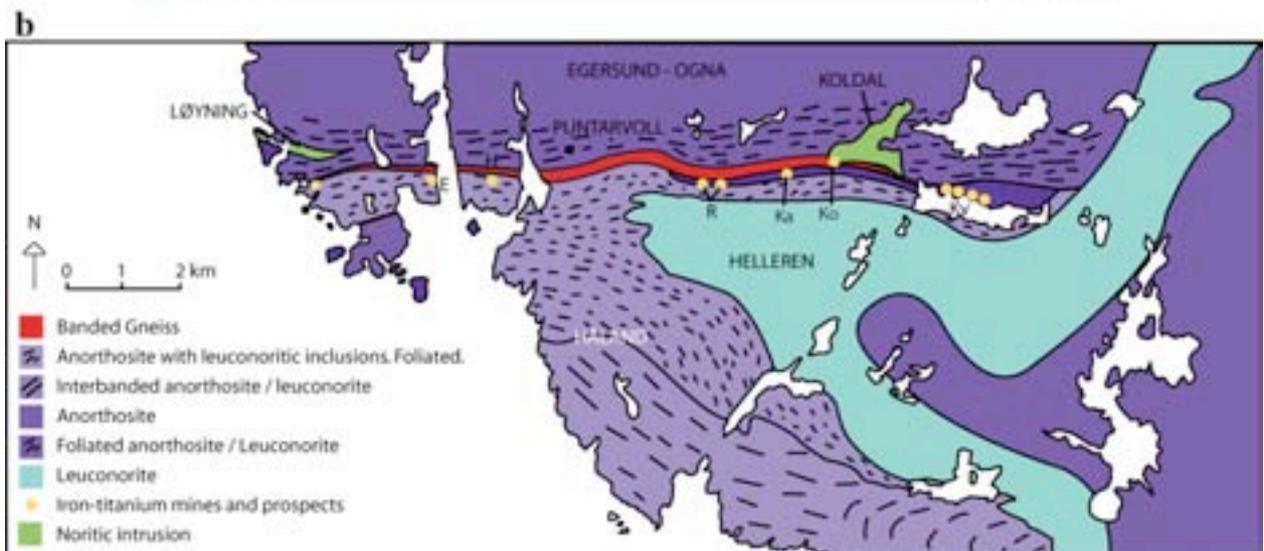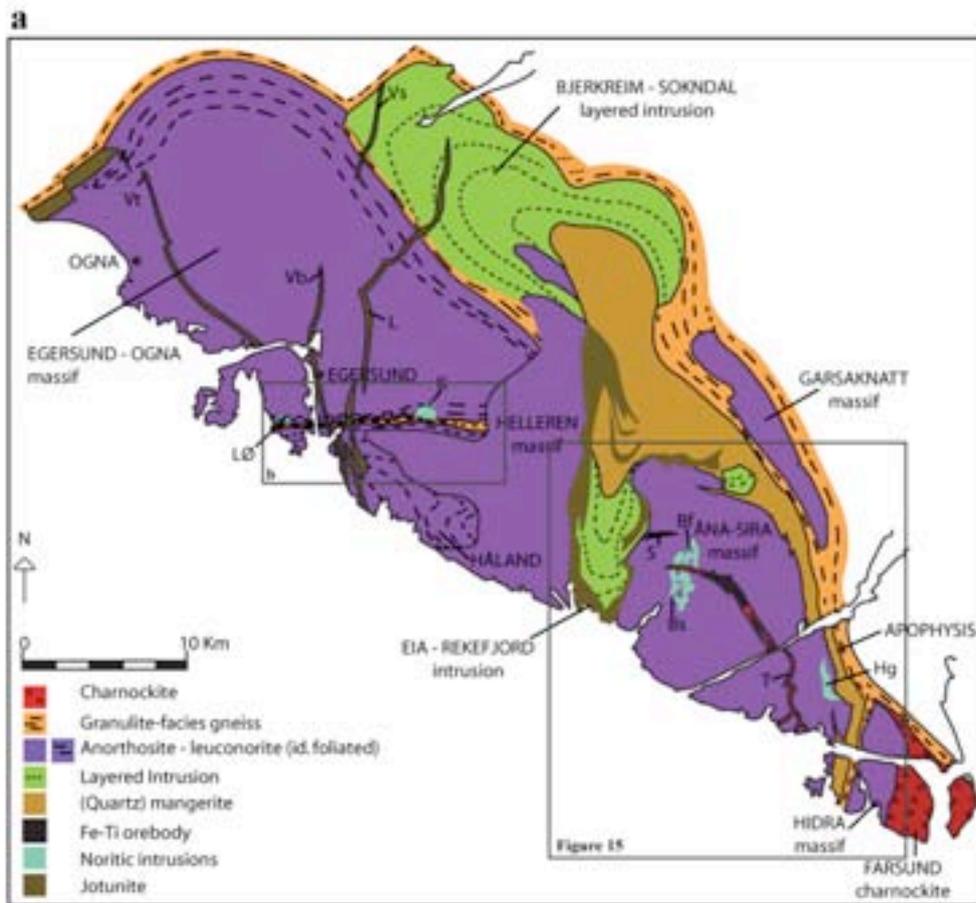
Figure 14a. Location of Figures 14b and 15. b. Simplified geological map of the western part of the Håland-Helleren anorthosite. Jotunitic and basaltic dykes are not shown. Many small lakes are omitted. The minor intrusions at Løyning and Koldal are developed in the southern foliated margin of the Egersund-Ogna anorthosite. A thin strip of banded gneiss between the anorthosite bodies was called the Puntevoll – Lien zone by Michot (1955a). The spelling of these names has been changed to Puntarvoll and Lia (at Liavatnet or lake). The following Fe-Ti ore deposits are shown: E = Eigerøy; H = Hestnes; R = Rødmyr; Ka = Kagnuden; Ko = Koldal; Kv = Kydlandsvatnet. A total of 31 old mines and prospects are shown in this ore-rich zone by Krause et al. (1985).
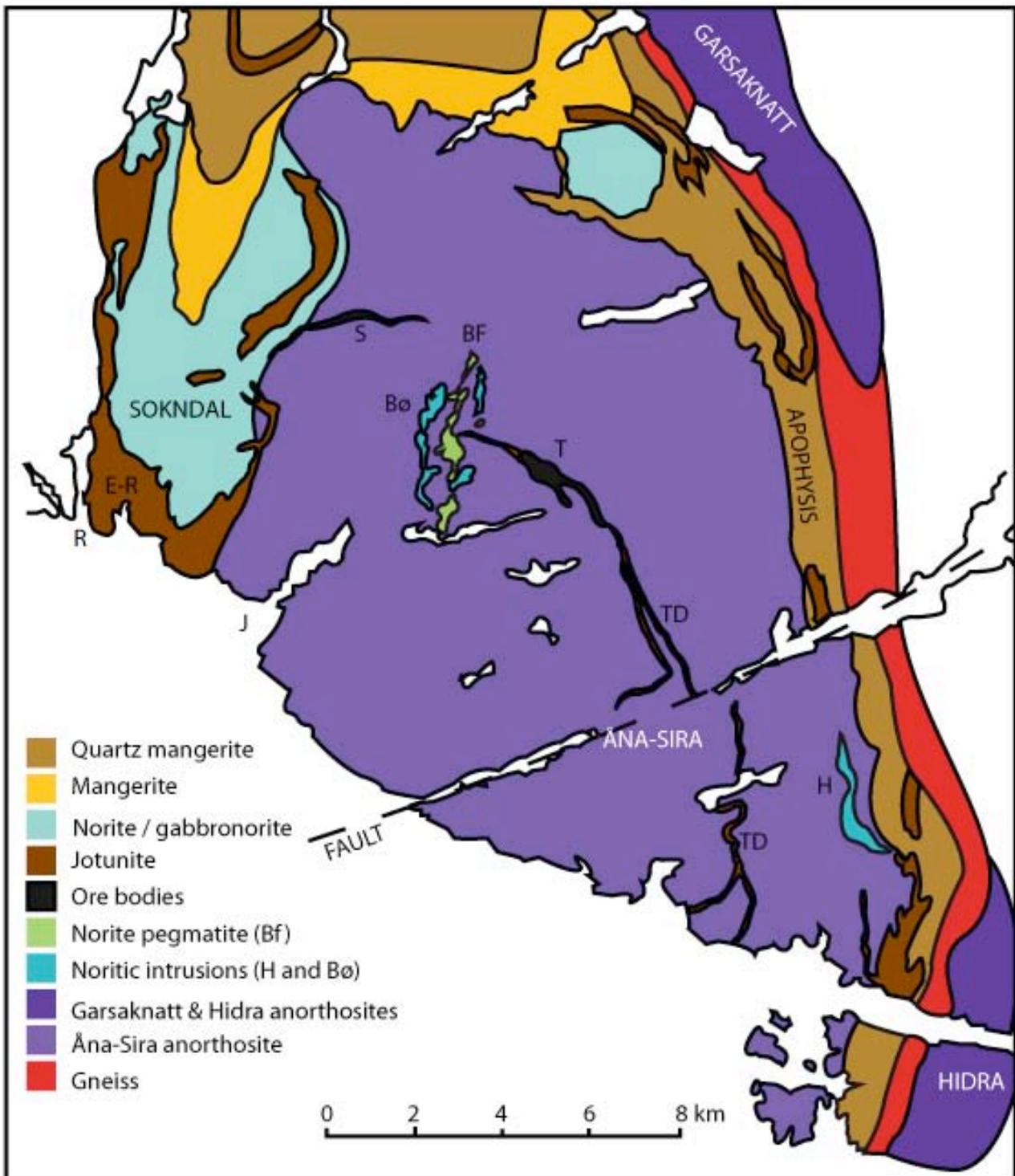
Figure 15. Simplified geological map of the Åna-Sira anorthosite and related rocks. Many small lakes omitted. Many small jotunitic dykes and the Egersund basaltic dyke swarm are not shown. T = Tellnes ore body; TD = Tellnes dyke; Bø = Bøstølen; BF = Blåfjell; S = Storgangen; H = Hogstad intrusion; M = Mydland; J = Jøssingfjord; R = Rekefjord; E-R = Eia-Rekefjord intrusion.

ore-bodies, they did suggest a relationship between all the ore-bodies and the Bjerkreim-Sokndal intrusion. They also invoked a complex fractional crystallization process to give rise to the anorthositic series of rocks and ore-bodies (Krause & Pedall 1980; Krause et al. 1985). Wilmart et al. (1989) showed that the relationship between the Tellnes deposit and the associated jotunite dyke system (see below) was more complex than formerly suspected, and ruled out a strictly comagmatic origin (without contamination).

New studies have recently been devoted to the deposits: Schärer et al. (1996) determined the U-Pb age of the Tellnes ore-body; Duchesne (1999) revisited some of the typical ore-bodies; Schiellerup et al. (2000) investigated the Re-Os isotopes in several deposits and the related anorthosites; Kullerud et al. (in prep.) produced a first interpretation of the Titania A/S data base of the Tellnes deposit (2000 analyses for major elements and S, Cr, V, Zr, Sr, Ni, Cu, Co, Nb, and Pb); Diot et al. (1999) studied the anisotropy of magnetic susceptibility of the Tellnes deposit in order to better constrain its structure; many aspects of the origin of the deposits have also been resolved by experimental petrology (Vander Auwera & Longhi 1994; Vander Auwera et al. 1998) and theoretical considerations (Duchesne 1996).

The various Fe-Ti deposits have been described by Duchesne & Schiellerup (2001). Here we concentrate on those to be encountered on the excursion (Koldal, Blåfjell and Tellnes) that are described in more detail in the appropriate place.

The various Fe-Ti deposits

A first classification of the deposits into low-grade and high-grade types based on the oxide mineral content is convenient to circumscribe the petrological problem of formation. The low-grade type (or disseminated type) is found in BKSK and the jotunite dyke system. Accumulation in a magma chamber or direct crystallisation from a jotunitic melt can account for their formation. TiO_2 and P_2O_5 concentrations of 13% and 5% respectively are employed to separate high-grade from low-grade deposits. All high-grade deposits are of magmatic origin and are discordant; they form dykes, pods, veins or stockworks into enclosing rocks.

Irrespective of their relationship with enclosing rocks, the high-grade deposits can be conveniently classified on the basis of their mineralogy and particularly their oxide association. Three types have been defined (Duchesne 1973, 1999):

Type 1 oxide assemblage (hemo-ilmenite as the only oxide), rich in Cr, Ni, Co, Mg, is found in Blåfjell (as well as Jerneld, Flordalen, Vatland, and Svånes).

Type 2 oxide assemblage (hemo-ilmenite + magnetite) characterizes Storgangen and Tellnes (as well as Bøstølen, Vardåsen, Kydlandsvatn and Rødemyr I).

Type 3 oxide assemblage (ilmenite + Ti-magnetite + apatite) is found in Hestnes, Eigerøy, Kagnuden and Rødemyr II, with lower Cr, Ni, Co and higher Zn contents in the oxides as well as high REE contents in the apatite.

As pointed out by Duchesne (1973; 1999), the variations in the nature of the oxide assemblage and in the trace element composition are quite similar to the evolution in BKSK. The three types of

oxide assemblages correspond to three successive stages of evolution in the BKSK cumulates. Moreover, evidence of layering is found in several deposits (Svånes, Flordalen, Vardåsen, Storgangen, Bøstølen and Kydlandsvatn). In BKSK, hemo-ilmenite is the second mineral to appear on the liquidus, subsequent only to plagioclase. Similarly, layers of pure hemo-ilmenite in anorthosite occur in the Kydlandsvatn deposits, and a cumulate origin involving magmas, in which ilmenite was the first mafic mineral to crystallise, is plausible. The trace element evolution, particularly the Mg and Cr content of ilmenite, also mimics the BKSK-trend. The similarities point to a fractional crystallisation process, with accumulation of Fe-Ti oxides as the main controlling mechanism, to explain the variety of deposits.

However, there are compositional, morphological and textural differences between BKSK and the high-grade deposits: (1) some deposits contain several mineral assemblages side by side: Tellnes, Laksedal and Kydlandsvatn have types 1 and 2 and, in the latter, apatite can be also present in type 2; (2) the trace element content in the deposits is usually much higher than in BKSK: type 3 has a magnetite with much higher Cr contents (200 to 1300 ppm) than in BKSK (< 50 ppm).

The discrepancies between the deposits and BKSK might result from the more complex evolution of the massive anorthosites compared to BKSK. The latter represents a magma chamber that evolved at a roughly constant pressure of c. 5 kb. In contrast, the massive anorthosites crystallised over a large pressure interval with deformation starting in the magmatic stage and continuing in the solid stage. Igneous textures and mineral compositions may therefore have been modified in the solid stage (annealing texture, Ostwald ripening) at relatively high temperature (500-1000°C). Because crystallisation and deformation were synchronous, filter press mechanisms could have expelled magmatic liquids, crystal-laden liquids, or even crystal mushes from more rigid crystal matrixes. Hence, typical intrusive contacts, as observed in dykes or pods, do not necessarily imply that the intruded material was liquid. It could equally well represent an injected crystal mush or a crystal-laden liquid.

Although many ambiguities remain, fractional crystallisation with accumulation of Fe-Ti oxides satisfactorily account for the Tellnes, Storgangen, Kydlandsvatn, Flordalen, Frøytlog, Vatland, and Svånes deposits. The Blåfjell and Laksedal ilmenite deposits are integral parts of a large mass of norite pegmatite and most likely represent concentration of cumulus minerals in the noritic parental magma. Due to its wetting properties and ability to recrystallise, ilmenite could have migrated in the solid state during deformation to form veins. Considering the usually high contents of Cr and MgO in ilmenite, the parental magmas of all these deposits were probably more primitive than that of BKSK, but they belonged to the same kindred, with early ilmenite crystallisation. Immiscibility cannot be rejected as an alternative enrichment mechanism, although supporting experimental evidence is currently lacking (see the discussion in Duchesne 1999), it is a convenient mechanism to generate vein deposits of almost pure material.

Tellnes (T)

The Tellnes deposit is a sickle-shaped ilmenite-rich noritic body more than 2700 m long and, in the central part, more than 400 m wide. It is intrusive into the Åna-Sira anorthosite, as evidenced by sharp contacts, apophyses cutting the surrounding anorthosite, intrusive breccias, and xenoliths of anorthosite (Gierth & Krause 1973; Krause et al. 1985). Extensive drilling has shown that the orebody is trough shaped and plunges to the south-east beneath a roof of anorthosite (Figure 16).

The ilmenite norite ore body extends at both ends into a jotunite dyke (called the main dyke), that is 5 to 10 m wide and ranges in composition from jotunite to quartz mangerite. At the south-eastern end, a zone of interfingering leuconoritic and mangeritic dykes forms the transition with the main dyke. The latter cuts across the Åna-Sira anorthosite for more than 4 km in the northwest and for more than 10 km in the southeast. U-Pb zircon and baddeleyite ages from the ilmenite orebody are 920 ± 3 Ma, slightly younger than the jotunite dyke (931 ± 5 Ma) (Schärer et al. 1996). However, Charlier et al. (2007) regard the ages from the orebody as being related to the exsolution of ZrO_2 from ilmenite rather than its primary crystallisation.

The ilmenite norite is medium grained and generally massive. Modal layering is rare. The norite consists of sub- to euhedral plagioclase (An_{49}- An_{39}), often slightly deformed and recrystallised, orthopyroxene (En_{76}- En_{65}), in places minor olivine (Fo_{80}) and abundant interstitial hemo-ilmenite (Hem_{10-14}). Fe-Ni-Co-Cu sulphides and Ti-biotite are present in minor amounts. Magnetite with lamellae of zinciferous spinel occurs in small amounts in the uppermost parts of the orebody. It is rich in Cr, V and Zn with the highest Cr/V ratio (1.6) and ZnO content (0.16%) in the area. Small amounts of apatite occur along the margins of the intrusion.

Wilmart et al. (1989) suggested that the ore deposit and the related plagioclase-rich rocks, could be explained as cumulates, injected as a crystal mush lubricated by 3 to 10% of interstitial melt. The ilmenite norite locally exhibits a plagioclase lamination and the study of anisotropy of magnetic susceptibility (Diot et al. 2003) has revealed a trough-like internal fabric and a magnetic lineation that generally plunges to the south-east, parallel to the synclinal axis. The mineral orientations have been related to the lateral emplacement of a noritic crystal mush (Diot et al. 2003) during transcurrent dilation. On the contrary, Charlier et al. (2006, 2007) recognised that the orebody displayed a cryptic internal layering and compositional variations that could only be due to the in situ accumulation of ilmenite and plagioclase (in the Lower Central Zone) and ilmenite, plagioclase, orthopyroxene and olivine (in the Upper Central Zone), together with trapped jotunite melt increasing in amount from 20 to 80% at the margins of the body. The abundance of ilmenite in the orebody (40-50 wt. %,) is much higher than the inferred cotectic proportion of ilmenite that crystallised from the parental magma (~17.5 wt. %). This is explained by the preferential accumulation of ilmenite on the floor of the magma chamber while much of the plagioclase floated. According to Charlier et al. (2006, 2007) the orebody represents 40% crystallisation of the parental magma, of which 26 wt. % is plagioclase that is not represented in the body and must have been transported elsewhere.
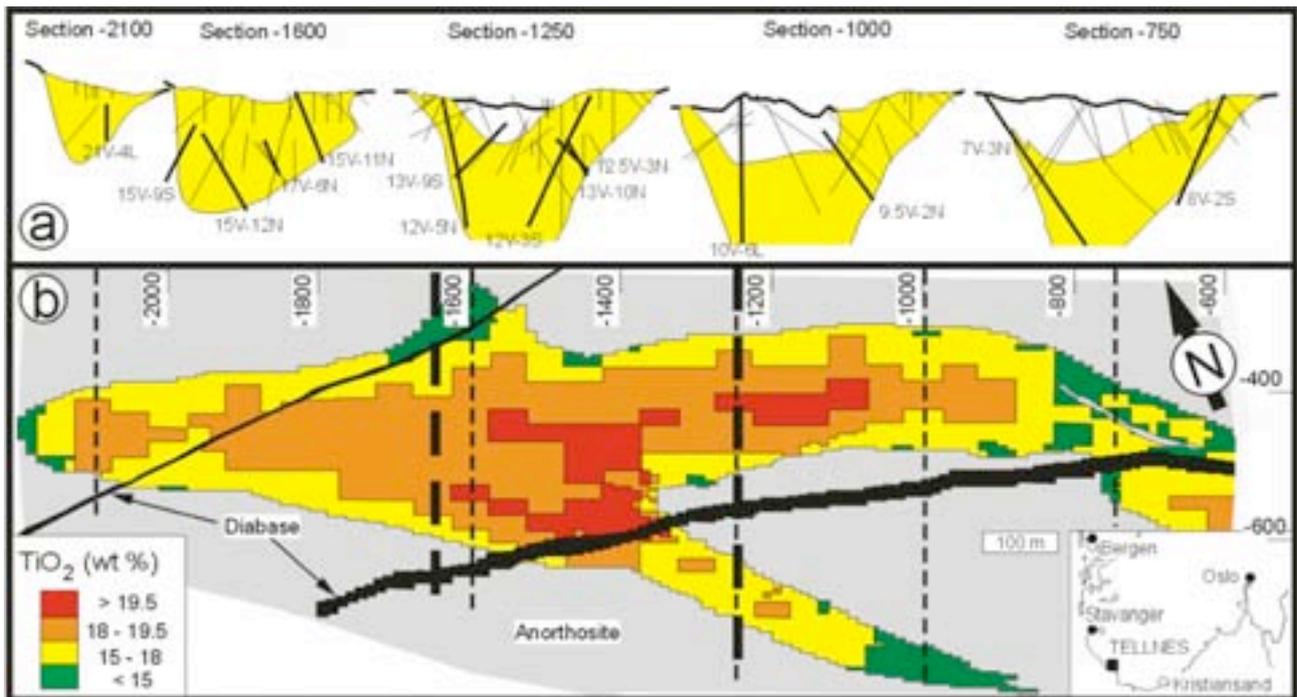
Figure 16. A three-dimensional block model of the Tellnes one compiled on the bassis of approximately 4900 analyses of ore, using DATAMINE®.a) Vertical sections showing the sampling density of drill cores; b) Horizontal section showing the variations in the TiO₂ content of the ore. Light dotted lines show the position of vertical sections in a) (Kullerud et al in prep.).

Blåfjell (B) and Laksedal (L)

In the Blåfjell deposit, massive bodies of hemo-ilmenite (Hem$_{20}$, 0.25% Cr$_2$O$_3$, 3.22% MgO; Krause & Zeino-Mahmalat 1970) occur in a pegmatitic norite close to its contact with the enclosing Åna Sira anorthosite. The norite pegmatite shows two oxide assemblages (Krause & Zeino-Mahmalat 1970). In the first, hemo-ilmenite is the only oxide mineral (>2100 ppm Cr); in the second, magnetite is present together with ilmenite and apatite (Cr contents are very low in ilmenite and magnetite). Duchesne (1973) proposed that these assemblages represented two stages in the fractional crystallisation of noritic liquids. The Laksedal deposit occurs in the same pegmatite body and also shows type 1 and 2 oxide parageneses. When hemo-ilmenite is the only Fe-Ti oxide, it is rich in Cr and V, but when accompanied by magnetite, hemo-ilmenite is distinctly lower in Cr and V, and magnetite is richer in both elements.

Storgangen (S)

The Storgangen orebody forms a sheet in the Åna Sira massif, 4 km long, up to 50 m thick, with numerous offshoots (Figure 15). The anorthosite, which constitutes the hanging wall of the dyke, is always foliated concordantly with the contact. Strong foliation in the westernmost part of the intrusion, close to the ÅS margin, is also evident, and accompanied by deformation and granulation of plagioclase grains. The observations imply that the Storgangen dyke had intruded and solidified prior to the final deformation of ÅS, which was possibly related to the gravitationally induced subsidence of the neighboring Bjerkreim-Sokndal intrusion (Paludan et al. 1994; Bolle et al. 2000). The orebody is strongly modally layered on a cm to m scale, locally with some irregularities. The layering generally dips in a northerly direction at an angle of 40-60°, and is conspicuously

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isomodal. In the westernmost outcrops, modal layering strikes almost parallel to the layering in the adjacent parts of the BKSK but recent mapping suggests that Storgangen is cut out obliquely by the contact of the younger BKSK. The BKSK cumulates crystallised from a much larger magma chamber, where modal layering developed sub-horizontally. The concordant and parallel layering in the BKSK and Storgangen seem to indicate that the latter originated as a sill-like body. The mineralogy comprises plagioclase, Ca-poor and Ca-rich pyroxene, apatite, Fe-Ti oxides, green chromian spinel and a variety of minor sulfides, as well as baddeleyite. Cumulus Ca-rich pyroxene is rare and only seems to be present in the uppermost part of the layered sequence. Late entry of Ca-rich pyroxene is in accordance with up-section being equivalent to stratigraphic up, and the hanging wall thus represents the roof of the Storgangen magma chamber. Apatite is an accessory phase but does not seem to be stratigraphically confined. The complete section is generally rich in oxides, but the most extensive oxide-rich zones occur in the lower half of the stratigraphy. At the footwall, the norite contains a hemo-ilmenite (Hem_{13}) associated with magnetite and pleonastc spinel. The mafic mineral content decreases somewhat upwards, and there is a systematic decrease in An content of plagioclase (An_{55} to An_{43}) and En content of Ca-poor pyroxene (En_{75} to En_{66}), though distinct lateral variation exists (Krause et al. 1985, and current contribution). The MgO content of ilmenite is strongly correlated with the En content of coexisting Ca-poor pyroxene, and ilmenite in Storgangen evolves from 3-3.5% MgO to around 2% MgO. Strong upward decreases in Cr, Ni and Cu in the Storgangen cumulates reflect fractionation of oxides and, apparently, fractional segregation of sulfides. In addition, Gierth (1983) observed a distinct decline in V and Zn concentrations, the Ni/Co ratio, as well as an increase in Mn in both oxides from the base to the top of the dyke.

Kydlandsvatn (Ky)

The Kydlandsvatn deposits belong to the Kolldal-Liåsen type defined by Michot (1956). Lenticular orebodies (1 to 2 m-thick) in anorthosite are elongated parallel to the contact between the HH and EGOG anorthosite massifs, and to the norito-granitic septum (NGZ), which is itself intercalated between the two massifs (Figure 14a). In Liåsen, the orebodies are made up of bundles of parallel layers (up to 20 cm-thick) of massive ore, interbedded with anorthosite, leuconorite or norite layers. All gradations between a very pure oxide ore and noritic varieties exist. Similarly, the accompanying "gangue" rocks pass progressively from norite to anorthosite by decreasing the amount of mafic minerals.

Although these features were interpreted by Michot (1956) as bunches of veins emplaced in anorthosite, the layered character calls for a different explanation: the orebodies and associated rocks accumulated from a fractionally crystallising melt that intruded as a concordant sill in the contact zone between the two anorthosite massifs. The strongly dipping lamination plane (70°S), together with the frequent lenticular structures and overall granulation and recrystallisation of the plagioclase indicate that the layered sill was also involved in the same syn-emplacement deformation as the surrounding anorthosite massif. In the westernmost contact zone between the EGOG and HH massifs, the occurrence of a layered sill - the Løyning sill (Figure 14a) should also be noted. The Løyning sill was injected and deformed concordantly with the foliation of the EGOG margin (Ernst & Duchesne 1991). These occurrences may suggest that the marginal zones of the diapiric anorthosite massifs contained a number of small mafic magma chambers, in which layering could develop.

The Kydlandsvatn deposits are made up of hemo-ilmenite (Hem_{20}) with or without Ti-poor magnetite. When hemo-ilmenite is the only oxide mineral (sample 66-182) it shows Cr, V and Mg contents comparable to the Svånes deposit. A variety of ore contains abundant apatite (up to 26 vol. %) with relatively low REE content.

Excursion Stops

The locations of stops 1-15 are shown in Map 1.

Map 1. Locations of stops 1 – 15 in Rogaland.

Day 1. Egersund-Ogna Anorthosite and the Koldal Intrusion

Introduction

The Egersund-Ogna Anorthosite (EgOg; Figure 5), like the other anorthosite massifs, gives rise to a characteristic landscape that is dominated by bare, rounded, rocky hills. We will see the coarse-grained, homogeneous nature of the anorthosite in central regions, as well as megacrysts of plagioclase and orthopyroxene. Labradorescence is locally developed in plagioclase and such rocks are extracted as dimension stone. Norite pegmatite dykes cut the anorthosite on Eigerøy and seem to have acted as feeders for magma that brecciated the anorthosite. The foliated margin of EgOg, which was produced during diapiric uplift, was intruded by small broadly noritic intrusions, such as at Koldal.

Stop No 1. Eigerøya lighthouse geotour

Location

This trip starts and finishes at the car park on Eigerøy signposted "Eigerøy fyr" (= lighthouse) (Figure 17).

Figure 17. Eigerøy lighthouse is located on massive anorthosite.

Introduction
Many features typical of the Egersund-Ogna anorthosite can be studied on this tour. Special features include norite pegmatite dykes and extensive brecciation of the anorthosite by coarse grained norite.

Description
This tour is described in detail in Enclosure 2.

Stop No 2. Piggstein

Location
Park in the layby on route 44, at the sign "Hå kommune 500m" (~15 km west of Egersund at 031634 648647). Walk ~100m along the road to the west. Pass through silver birch trees to a field with a large split block. From here follow the rough track up hill to the north. Cotinue north along the western side of the lake Piggsteintjørna. The dimension stone quarry at Sørskog (Stop 3) comes into view. There are good outcrops between the two lakes on ther left side of the valley.

Introduction
The coarse-grained anorthosite with the rounded, bare, rocky hills is typical for most of the central part of the Egersungd-Ogna massif. Here we will also see lenses of leuconorite, megacrysts of orthopyroxene and plagioclase as well as veinlets of hemo-ilmenite.

Description
On the western side of the valley between the two small lakes (Piggsteintjørni and Auratjørni), the outcrops beautifully display several features. Aggregates of megacrysts of labradorescent, granulated plagioclase (up to 30 cm in length) forming anorthositic lenses, and of megacrysts of Al-rich orthopyroxene and plagioclases with sub-ophitic texture (leuconoritic lenses) are embedded in a matrix of finer-grained leuconorite (without opaque minerals), in which the orthopyroxene displays an interstitial "cuspate" structure. The aggregates (2 to 10 m in size) are elongated parallel to a plane which corresponds to the rough orientation of the plagioclase network in the matrix. Rapid variation in grain size of the matrix leuconorite can be observed locally. Some of the leuconoritic aggregates display a recrystallised medium-grained sugar-like texture with granulated and stretched orthopyroxene. Such texture is transitional to that of leuconoritic gneisses of the marginal zone of the massif. A large opx megacryst can be seen close to the fence between Hå and Egersund municipalities at 031634 648702.

This outcrop beautifully illustrates the polybaric evolution of the anorthosite. The megacryst aggregates were formed at high pressure (the high Al content of the orthopyroxene megacrysts indicate 11 to 13 kb) and rose diapirically in a leuconorite to anorthosite crystal mush lubricated by some leuconorite melt (with Al- and Cr-poor orthopyroxene). The occurrence of deformed and recrystallised inclusions suggests that the deformation took place before the end of the intrusive process.

A short walk SW leads to a small body of brownish leuconorite with a typical fine-grained granular texture and some layering (orthopyroxene layers), outcropping on the western flank of a small hill. At the roof of the intrusion, several mushrooms of leuconorite penetrate the anorthosite (gravity instabilities) with an ill-defined gneissic texture; clusters of plagioclases constitute small inclusions in the norite.

Walk back to the starting point (parking place). The road cuts display typical coarse-grained, granulated, locally labradorescent anorthosite in which some interstitial orthopyroxene megacrysts can be observed. Good samples can be found in the embankment of the road. Proceed along road 40 to the north.

Stop No 3. Sørskog dimension stone quarry

Location
This large active quarry is reached via a wide gravel road northeast of Sørskog (entrance at 031506 648956).

Introduction
The massive anorthosite here displays conspicuous labradorescence. It is quarried in blocks and transported to Larvik where it is cut and polished. The polished product is marketed as "Labrador Antique" (www.granit.no).

Description
About 100 m past the entrance to the quarry on the right there is a ~10m wide, fine-grained basaltic dyke. This belongs to the Egersund basaltic swarm of dykes that all trend WNW – ESE and were intruded at 616 ± 3 Ma (Bingen et al. 1998b). There are beautiful exposures of anorthosite and leuconorite with 3-5 cm-sized iridescent, zoned plagioclases with blue and green colors (An_{55}). Small orthopyroxene megacrysts are present.

Stop No 4. The Koldal Intrusion

Location
This small noritic intrusion is located about 5 km east of Egersund. Take the turn off the RV44 in Egersund town signposted to Koldal. Park near the bus shelter at the "Ferist" sign (033065 648016).

Introduction
The ~1.8 km^2 Koldal intrusion (Andersen, 2004) is a broad, V-shaped body which lies on its side and is open to the east (Figure 18). It sharply cuts the foliated margin of the Egersund-Ogna anorthosite and the banded gneiss unit to the south and contains inclusions of these lithologies. The "base" of the V in the west (Koldal area) consists of gabbronorite with local modal layering that strikes ~64° and dips ~56° to the north. The eastern limbs (Høgåsen in the north and Forefjellet in the south) consist mainly of coarse grained (leuco)norite which is also sporadically layered (strike ~90°, dip ~28°N in Høgåsen; ~110°, ~25°S in Forefjellet). The Høgåsen (leuco)norites are separated from the Koldal gabbronorites by a mangeritic unit that was intruded into these pre-existing rocks. The Høgåsen (plagioclase An_{40}; orthopyroxene En_{59}) and Forefjellet (An_{43}; En_{65}) areas contain the most primitive rocks and crystallised first, possibly in two small chambers since their modal layering has different orientations. Slightly more evolved magma was subsequently
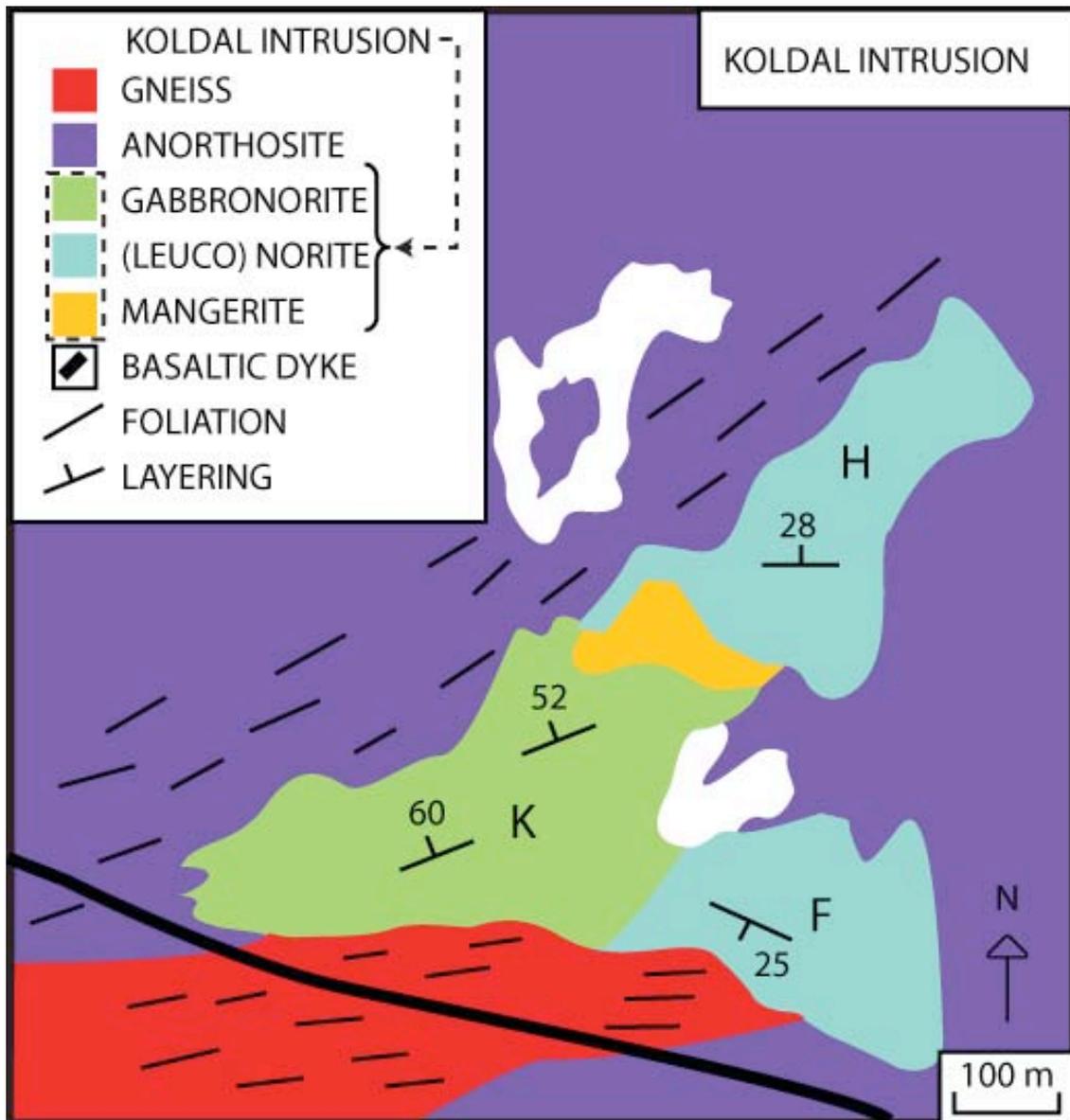
Figure 18. Geological map of the Koldal layered intrusion. K = Koldal; H = Høgåsen; F = Forefjellet. The gneiss and anorthositic country rocks are foliated.

emplaced into a nearby chamber to the west to form the Koldal gabbronorites (An_{41}; En_{55}). Assuming that the layering formed more or less horizontally, its different orientation in the (leuco)noritic and gabbronoritic units implies that local tilting took place between their crystallisation. The mangerites (An_{26}; En_{48}) were derived from an underlying chamber slightly later, and were intruded between the Koldal and Høgåsen units. Jotunitic dykes cut across all the lithologies of the Koldal intrusion and the mangeritic unit is cut by many thin charnockitic veins.

Description
Locality 1
Just through the gate west of the bus stop is an outcrop of fine-grained basalt. This is one of the dykes belonging to the Egersund swarm (see also Stop 2, Day 1). From here, walk along the fence for ~100m to the east and then up hill to the south to the old ilmenite mines (near 033068 648000). The flooded mine entrances are obvious, and the old tips contain many ilmenite-rich samples. The

mines are in the northern margin of the Håland anorthosite body. Country rock gneisses belonging to the "Puntevoll-Lien" zone can be seen just north of the mines. The ilmenite mines here were among the first in the area and date from 1875. A railway was constructed to transport the ore to the coast. Horses were transported down to the coast in the last wagon together with the ore. They were then faced with the task of hauling the empty trucks back up hill to Koldal. The course of this railway track can be seen ~15m south of the fence at, for example, 033072 868014.

Locality 2
Drive to the north through into Koldal farm and take the road to the left up to the top of the hill at 033034 648063. You are now in the marginal zone of the Egersund-Ogna anorthosite. The foliated nature of the (leuco)norites is obvious. This foliation is parallel with the country rock margin all around the body and was formed during diapiric rise of the anorthosite under granulite facies conditions.

Locality 3
Drive back to Koldal farm and continue to the east. Leave the car by a small lake at 033124 648055. You are now in the country rocks anorthositess at the closure of the "V" in the Koldal intrusion. Anorthosites form the small peninsula jutting into the lake here. The three main lithological varieties of the Koldal intrusion can be seen within a small area: coarse grained, layered, ilmenite norites (in the Høgåsen limb); gabbronorites of the Koldal unit (033096 648064); and intervening mangerites (033115 6480). Charnockitic veins are quite prominent in the mangerites and a jotunitic dyke can be followed for some distance (033126 648076) in the Høgåsen ilmenite norites. The extremely sharp, strongly discordant, northern contact between the Koldal intrusion and the foliated margin of the Egersund-Ogna anorthosite is also very well exposed at, for example, 033105 648079

This small magma chamber developed after deformation of the Egersund-Ogna anorthosite and bears witness to the availability of noritic (or jotunitic) magma over a long period of time in Rogaland.

Day 2. Bjerkreim-Sokndal Layered Series

Introduction
On Day 2 we focus on the largest layered intrusion in Western Europe. This intrusion is compositionally unusual and important since it contains all the lithologies found in the Rogaland Anorthosite Province, linking anorthosites at the primitive end of the scale to charnockites at the evolved end. Features that will be examined include modal layering and a variety of xenoliths as well as evidence for magma replenishment, magma mixing and magma current activity.

Stop No 5. Storeknuten; the Basal Contact of MCU IV

Location
Storeknuten is a rounded hill (summit at 306 m) which is located ~1km south of Helleland (Figure 19). From the main road (E39) take the turn off south towards Drange and Eia. Follow the winding road up hill and take the road towards Drange. Leave the car where a road (Dybingsveien) goes up hill to the right (0334983 648985). Walk up Dybingsveien and proceed to the right of the concrete-based farm building and through a green gate. Follow the gravel road (covered with "white anorthosite" chippings) up hill to the northwest towards Storeknuten.
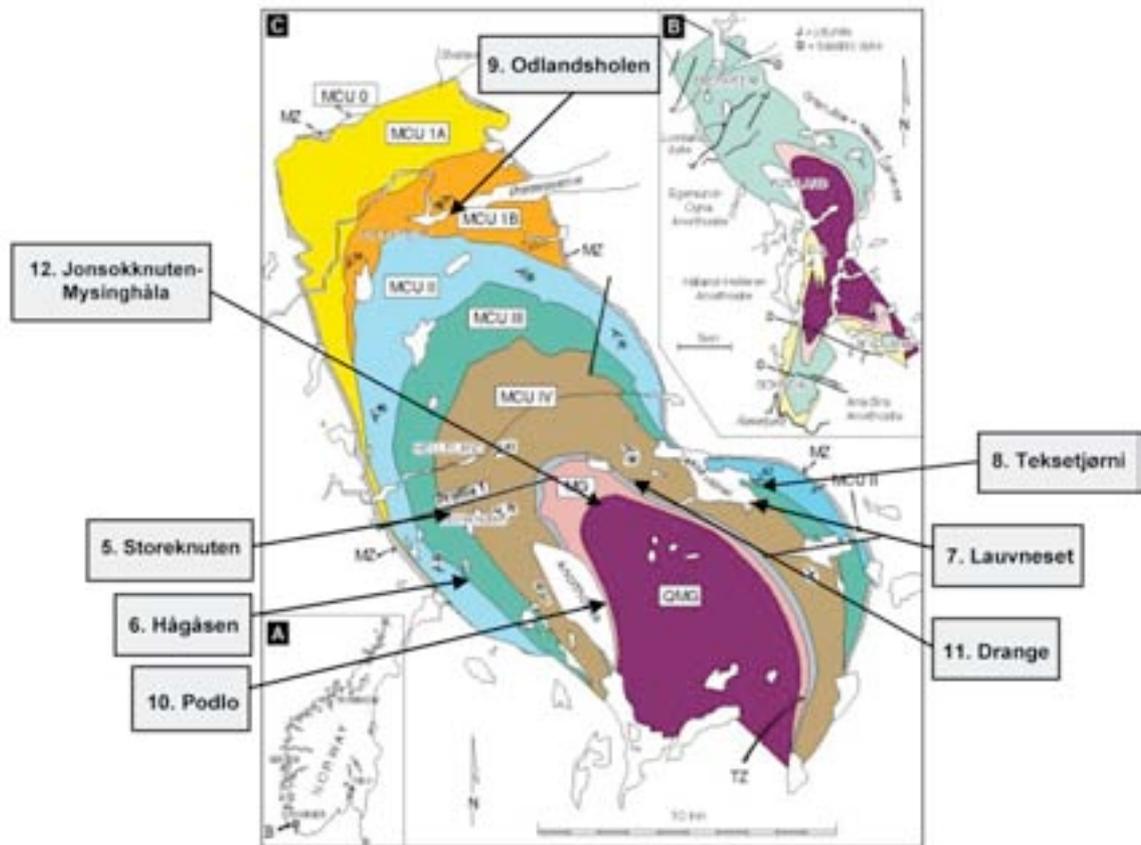
Figure 19. Locations and stop-numbers of places in the Bjerkreim-Sokndal Intrusion described in this excursion guide.

Introduction

The boundary between Megacyclic Units III and IV has been studied in detail at Storeknuten (Jensen et al. 1993, Nielsen et al. 1996, Barling et al. 2000). There is a good view of the Bjerkreim lobe from the summit. The strike of the layering here is NW-SE and the dip is about 50-60° NE into the core of the Bjerkreim synform. Olivine-bearing rocks in the Layered Series are restricted to two zones just above the bases of MCUs III and IV and form pronounced topographic ridges. Storeknuten belongs to the uppermost olivine-bearing zone which Paul Michot called the Svalestad unit (referred to as zone IVb here).

Description

Locality 1

There are sporadic exposures of gabbronorite (phcimaC) belonging to the uppermost part of MCU III (zone e) in the fields on either side of the track. On the left of the track (~100m past a fenced-in field to the right of the track and ~10m south of the track, at 033450 649012) is a particularly instructive exposure of modally-layered gabbronorite in which several gneissic xenoliths are embedded. The modal layering here strikes NW-SE and dips ~60°NE; stratigraphic up is to the NE. Structures due to blocks of gneiss impacting and slicing into partly-crystallised cumulates are preserved and allow discussion of layering-forming processes (Figure 20).

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Figure 20. Modally-graded layering in MCUIII, Storeknuten section. Stratigraphic up is to the left.

Locality 2

Follow the track to the WNW. When you reach a green gate, Storeknuten is straight ahead across a fenced-in field. Do NOT cross this field. Skirt around the outside of the field to the left. Locality 2 is the view of Storeknuten from the south when it becomes visible (from, e.g. 033419 649037). The basal part of Storeknuten consists of moss-covered rocks. These belong to MCU IIIe, similar to those seen at Locality 1 (Figure 20). They are relatively rich in mafic minerals and contain apatite (which is phosphorus-bearing) so that soil produced from their breakdown is quite fertile. The contact between the moss-covered rocks and the bare rocks of MCU IVa is very sharp. MCU IVa (~30 m thick) consists dominantly of anorthosite ± ilmenite and its breakdown products are very infertile. A characteristic feature of MCU IVa is the presence of thin ilmenite and pyroxene-rich layers, many of which are discontinuous and deformed by slump folds. These ilmenite-rich layers, particularly abundant in the axial region of the intrusion at this stratigraphic level, suggest that magma-chamber replenishment and magma mixing were a prerequisite for ilmenite concentration. MCU IVa is overlain by olivine-bearing cumulates of MCU IVb which dominate Storeknuten.

Locality 3

Proceed to the western side of Storeknuten and take the path up a grassy slope to the top. The path goes round to the left and then up to the top of the hill. MCU IVa cannot be studied along this path and the first accessible outcrops are of troctolite of MCU IVb in which olivine forms brown-weathering patches. These troctolites continue to the top of the hill. MCU IVb consists dominantly

of massive leucotroctolite containing oikocrysts of Ca-poor pyroxene (Figure 21). MCU IVb is about 100m thick here and contains sporadic cumulus magnetite (and possibly ilmenite and Ca-poor pyroxene), as well as small quantities of biotite and brown hornblende. Most olivines are partly or completely replaced by orthopyroxene-oxide symplectites. The summit of Storeknuten is composed entirely of rocks belonging to MCU IVb. The disappearance of olivine and magnetite, and the entrance of cumulus Ca-poor pyroxene in the slopes to the north define the base of MCU IVc (phiC). This phase contact is accompanied by the development of an igneous lamination and modal layering. Modal layering becomes increasingly well developed up through MCU IVc.

The view from the top of Storeknuten is impressive. The relatively massive, resistant rocks of MCU IVa and b form an arcuate ridge that can be followed northwards through Kråknuten and Liaknuten. This outlines the synclinal form of the intrusion (Figure 19).

Mineral compositions and Sr-isotope ratios. There is a cryptic regression in mineral compositions through the uppermost part of zone IIIe that continues through zone IVa (Figure 22). The upper part of MCU IIIe has Ca-poor pyroxene with En_{68}- En_{70}, plagioclase with An_{44}- An_{46} and an initial Sr-isotope ratio of 0.7061; the base of MCU IVb has En_{76}, An_{53} and Sr_0 0.7049, together with olivine Fo_{74}. There is an extremely systematic upward decrease in Sr-isotope ratios through the upper part of MCU IVa (Figure 23). The decrease in initial Sr isotope ratio appears to be delayed relative to the regression in mineral compositions.
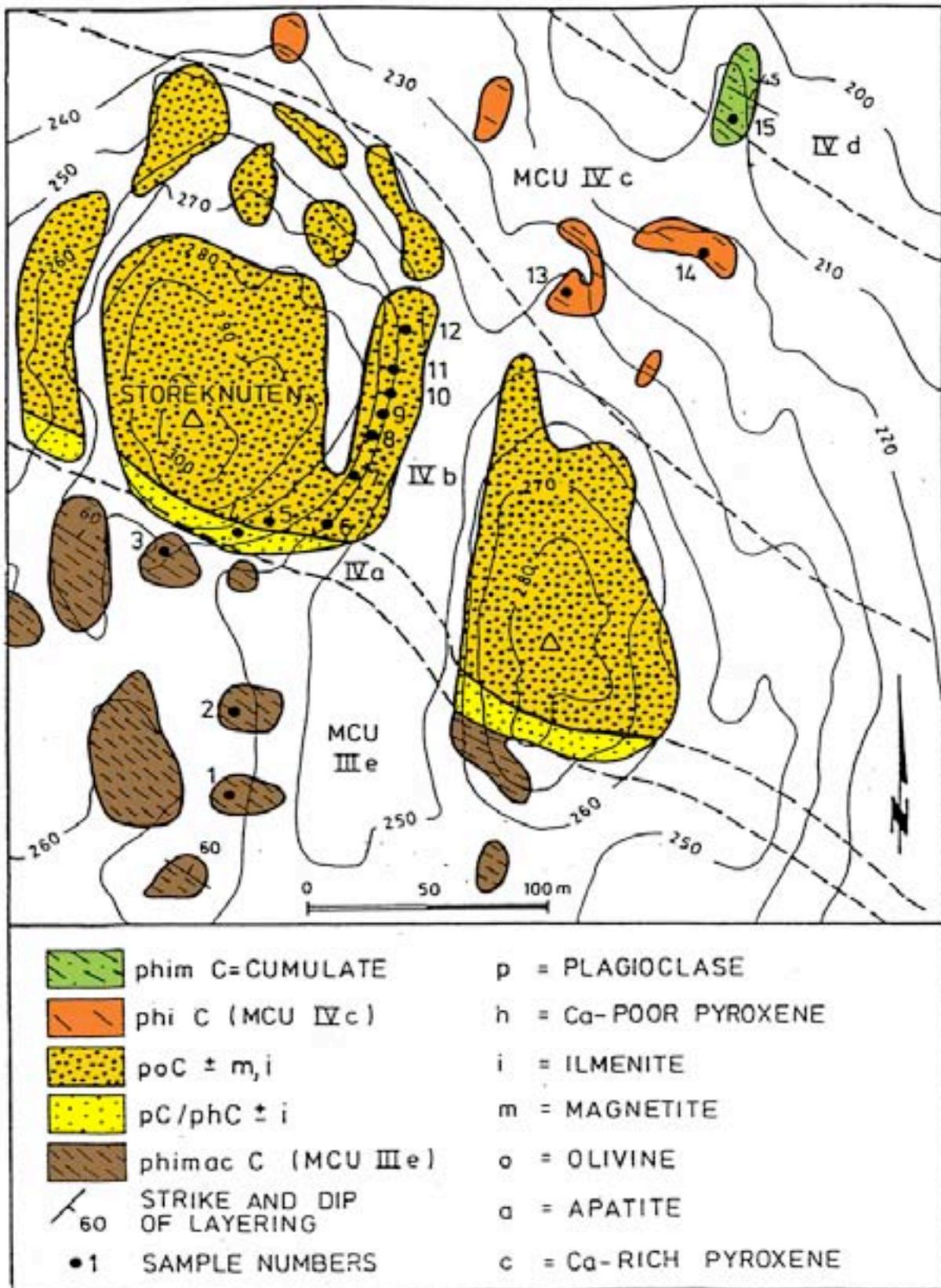
Figure 21. Geological map of the Storeknuten area showing the distribution of major outcrops, lithologies, strike and dip of layering, and sample locations. The legend explains the abbreviations used for the cumulate nomenclature. From Jensen et al. (1993).
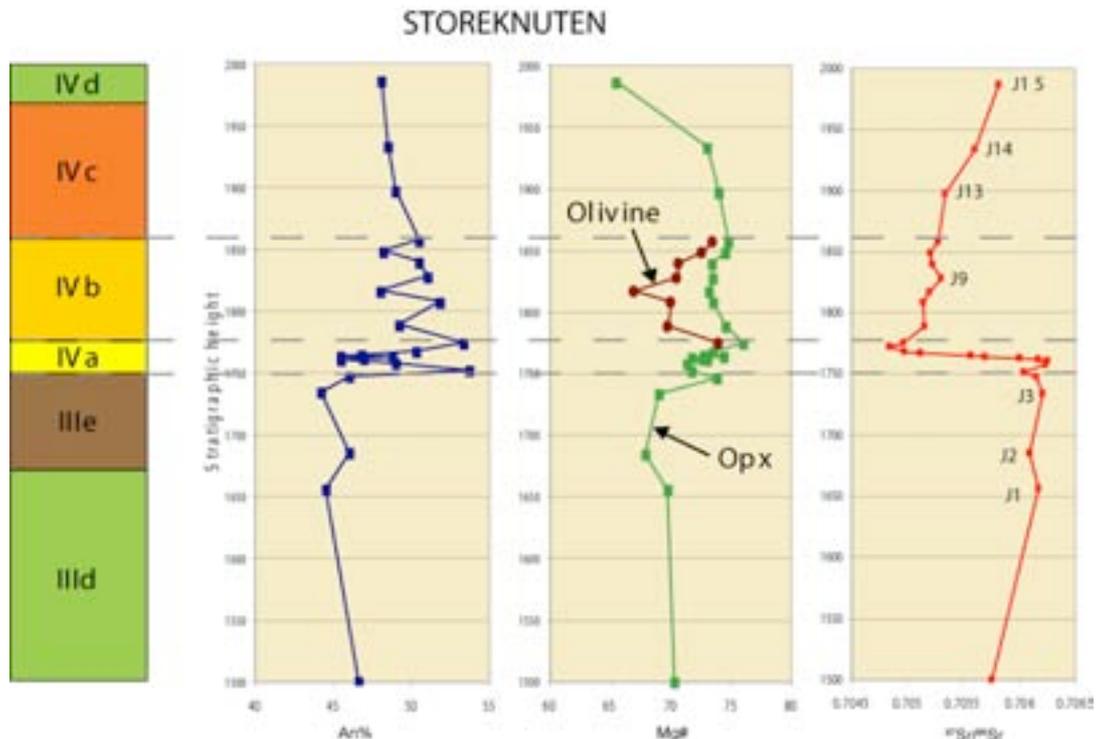
STOREKNUTEN

Figure 22. Cryptic variation through the upper part of MCU III and the lower part of MCU IV at Storeknuten. The sample numbers (J1-15) correspond to those marked in Figure 21. Based on data from Jensen et al (1993) and Nielsen et al. (1996).

Plagioclases show a rather erratic trend to more evolved compositions upwards through MCU IVb, while olivines first become more Fe-rich and then more Mg-rich (Figure 22). The olivine trends may have been influenced by trapped-liquid shift. Sr-isotope ratios increase systematically from 0.7049 at the base of zone IVb to 0.7053 at its top, reach 0.7058 in zone IVd and returns to 0.7061 in zone IVe (Figures 22 and 23).

The significance of the MCU III/IV boundary for magma mixing. The cryptic variations across the boundary between MCUs III and IV clearly indicate the operation and importance of magma mixing during magma-chamber replenishment. The magma residing in the chamber when the influx marked by the base of MCU IV took place was compositionally zoned (Figure 24), and assimilation of gneissic country rock at the roof had resulted in an elevated Sr-isotope ratio that may have increased upwards through the magma column. The inflowing magma had a Sr-isotope ratio of about 0.7049 while the resident magma had a ratio of 0.7061 at the floor in the Storeknuten area. The inflowing magma mixed with the basal layer(s) of the resident magma as a result of the new magma fountaining into the chamber. A decreasing degree of mixing between the inflowing and resident magma with time led to hybrid magmas with decreasing Sr-isotope ratios. Crystallisation of these hybrid magmas during replenishment produced the isotopic regression in the upper part of MCU IVa. Initially, influx led to elevation of the zoned magma column, exposing the base of the chamber in the Storeknuten area, located some distance up the inwardly-sloping floor, to progressively more primitive magma. It took some time before the hybrid magma flooded this point on the floor, causing the delay in the regression in isotope ratios relative to that defined by the mineral compositions. When the magma inflow ceased, olivine-bearing rocks of MCU IVb began to

crystallise at the base of the chamber. The leucotroctolites at the base of MCU IVb are amongst the most primitive rocks in the entire intrusion.
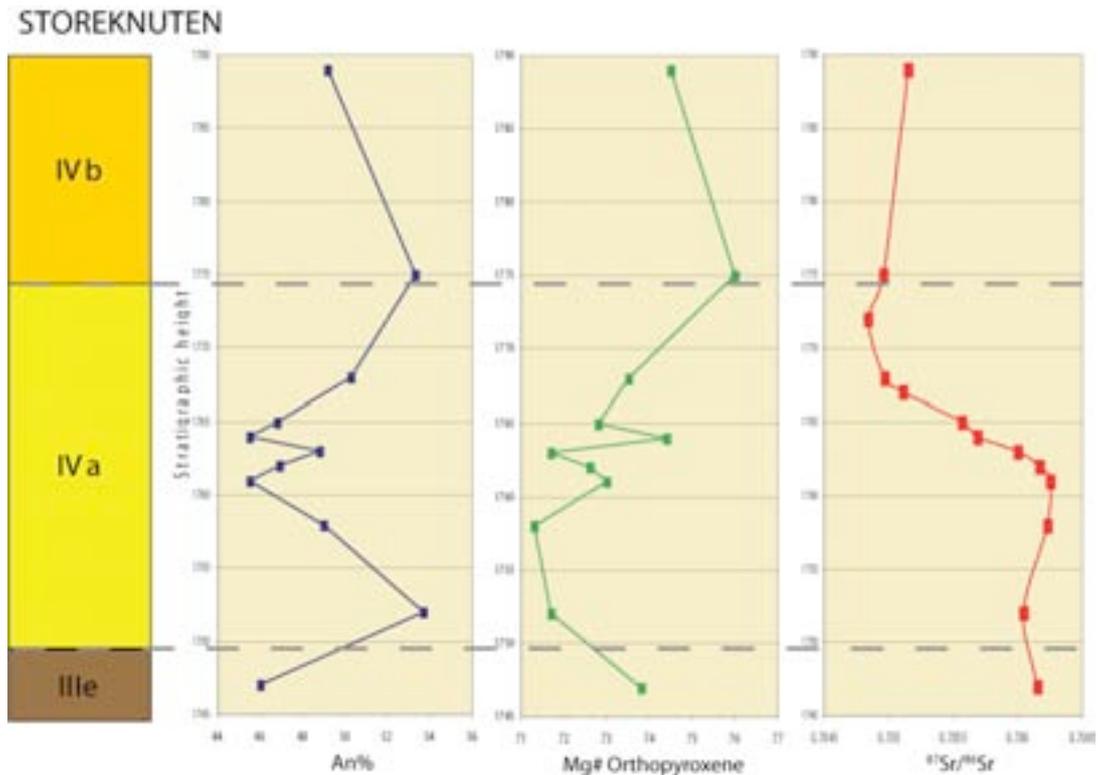
Figure 23. Cryptic variation through the basal, regressive zone of MCU IV at Storeknuten.From Nielsen et al. (1996).

Calculations based on geochemical modelling, the thickness of cumulate stratigraphy repeated (from the top of zone IIIe to the appropriate part of zone IVe) and Sr-isotope ratios indicate that the layer of hybrid magma generated during replenishment had a thickness of 350-500m in the Storeknuten area and that the leucotroctolites of MCU IVb represent about 20-30% crystallisation of this layer.
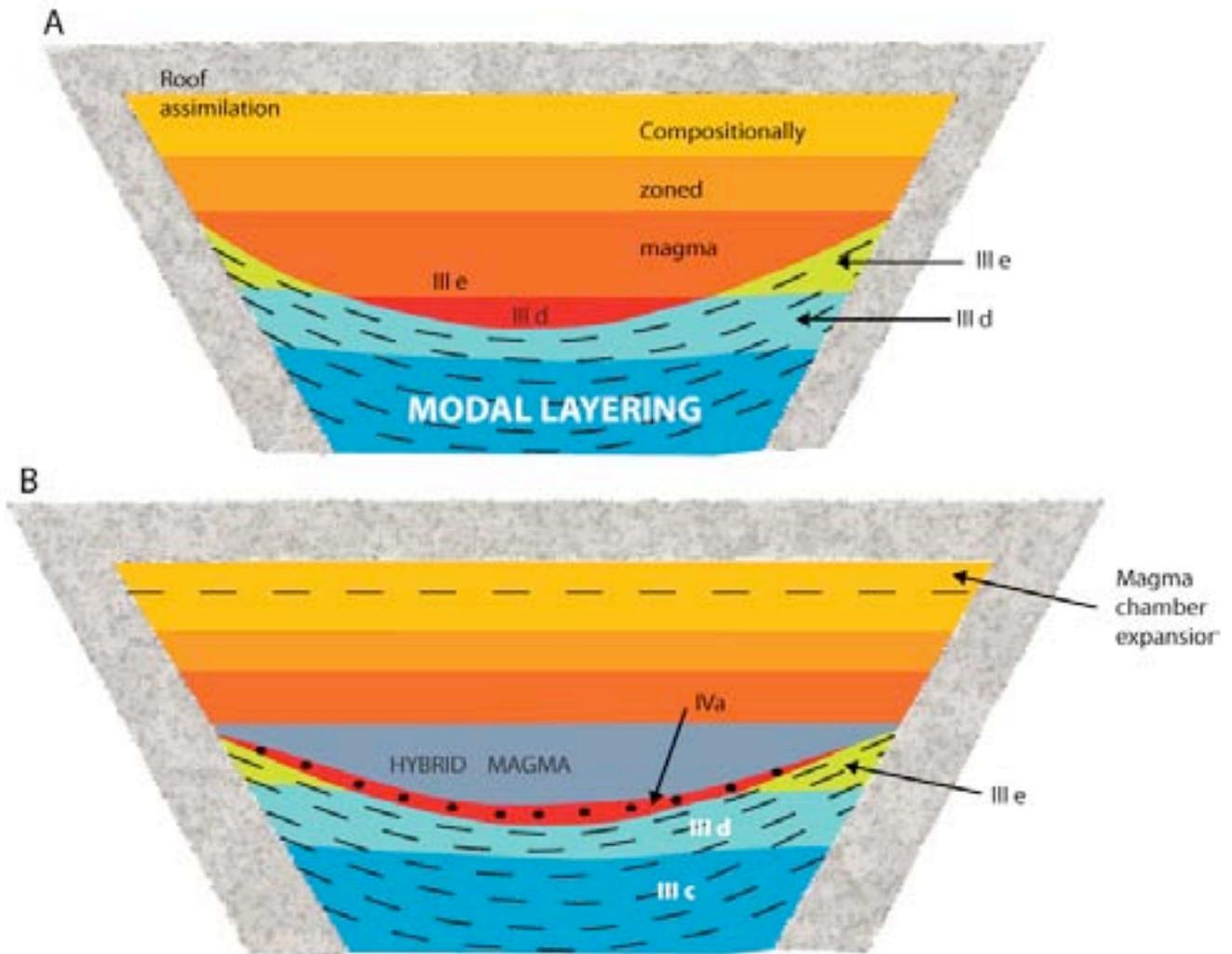
Figure 24. Sketches of the Bjerkreim-Sokndal magma chamber during formation of the MCU III/IV boundary. From Jensen et al. (1993). A. Crystallisation of the upper part of MCU III. The magma layer parental to zone IIId is only present in the central, lowest part of the saucer-shaped chamber. Zone IIIe is crystallising from the overlying magma layer(s) towards the margins. The Storeknuten profile is located near the margin, where zone IIIe cumulates are present. B. Magma replenishment elevated the residual magma and produced a hybrid magma layer at the floor. Zone IIIa crystallised during influx to produce a modal and cryptic regression. Note that the vertical scale has been greatly exaggerated in these sketches.

Stop No 6. Hågåsen

Location

Hågåsen is located ca. 2.5km SE of Storeknuten. Follow the road from Helleland to Drange and turn left at the T-junction at Drange. Drive through the farm buildings along Gløbstadveien. The narrow, winding road passes over a bridge across a stream and past a lake on the right. Leave the car on a grass-covered area (033553 648820) beside the road, ~100m past an outcrop in which a telegraph pole is embedded.

Introduction

Hågåsen is a hill located on the southern flank of the Bjerkreim lobe of the Bjerkreim Sokndal intrusion, on which the layered sequence across the boundary between MCUs II and III is well exposed. We shall walk from the road northeastwards up through the layered sequence to the top of Hågåsen.

Description

The stratigraphically-lowest cumulates exposed along the traverse are massive to weakly modally-layered ilmenite leuconorites (phiC) forming the uppermost part of MCU II. In places these enclose large slabs of anorthosite and leuconorite. They are succeeded by 20cm of intensely modally-layered melanorite and a massive layer of sulphide-bearing pyroxenite up to 2m thick that mark the base of MCU III (at, for example, 033553 648856). The orthopyroxenite is exceptionally thick here and as it thins in both directions along strike it appears to occupy a shallow and >200m broad trough. The orthopyroxenite is overlain by phiC with laterally-persistent and remarkably rythmic modal layering that gradually dies away upwards into massive phiC about 15-20m above the orthopyroxenite. The base of the succeeding massive poC (MCU IIIb) is encountered a few metres further up the sequence (25-30m above the orthopyroxenite). Proceeding to the NE, olivine disappears as you enter ilmenite norites of MCU IIIc; these rocks form the top of Hågåsen in the vicinity of a glacial erratic of gneiss. Some ~200 m further to the NE the rocks develop a brownish, rusty weathering surface; this reflects the presence of magnetite as you reach MCU IIId.

Mineral compositions. Mg#s of orthopyroxenes in the upper part of MCU II are ~74, decreasing rather abruptly to 70 immediately beneath the orthopyroxenite. The orthopyroxenite itself contains pyroxene with a mg# of 72.5 and in the overlying phiC the mg# shows a slight regressive trend from 72 to 74. The poC contains olivine of Fo_{74}- Fo_{76}. Plagioclase exhibits no systematic variations in composition. PhiC in the upper part of MCU II contains plagioclase of fairly constant composition (An_{47}) while in the sequence above the orthopyroxenite plagioclase compositions vary irregularly between An_{46} and An_{49}.

Stop No 7. Lauvneset

Location

Take the turn off the E39 to the north signposted "Bjørnemoen". The locality is on the shore of the eastern end of Teksevatnet (LK428-931).

Introduction

Cumulates containing apatite together with magnetite, ilmenite and Ca-rich pyroxene occur in the upper parts of MCUs IB, III and IV. Apatite in the Bjerkreim-Sokndal Intrusion generally makes its entry as a cumulus mineral at about the same stratigraphic level as Ca-rich pyroxene but may preceed or postdate it stratigraphically by some tens of metres. The late appearance of Ca-rich pyroxene is a reflection of the unusually Ca-poor composition of the parental jotunite magmas. Apatite is most abundant immediately after its appearance as a cumulus mineral when it may constitute as much as 10% of the rocks.
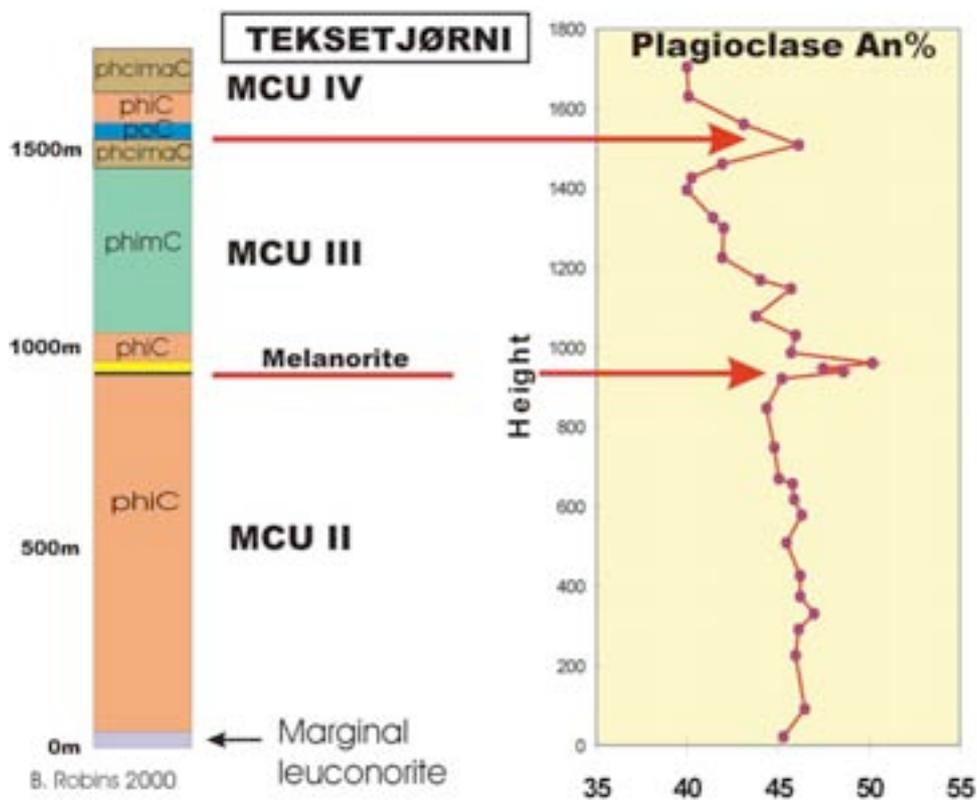
Figure 25. Cryptic variation in plagioclase through MCU II, III and the lower part of IV in the eastern flank of the Bjerkreim lobe as displayed in a series of samples collected along a traverse from the margin of the intrusion, near Lauvneset (Figure 19).

Description

This locality exhibits apatite- and oxide-rich gabbronoritic cumulates with pronounced modal layering immediately above the apatite-in phase contact within MCU IV. The sequence of MCU IV cumulates in this area is different from the axial region of the intrusion: The thickness of zone c (phiC) is reduced and zone d (phimC) seems to be absent (Figure 25).

Mineral compositions. In keeping with the evolved cumulus assemblage, the minerals in this part of the Layered Series have relatively low-temperature compositions: Plagioclase is ~An_{40}; Ca-poor and Ca-rich pyroxene have Mg#s of ~63 and ~70 respectively.

Stop No 8. Teksetjørni

Location

Leave the car where a tractor track turns off to the right from the road to Bjørnemoen (034311 649327).

Introduction

This locality lies on the eastern flank of the Bjerkreim lobe of the Bjerkreim-Sokndal intrusion, to the east of the Teksevatnet ridge. Cumulates in this part of the intrusion are believed to have crystallised on an elevated portion of the floor of the magma chamber and as a result the Layered Series is condensed relative to the axial regions of the intrusion and certain stratigraphic zones are absent. The cumulates present along a short N-S traverse at this locality can be compared with those present at Hågåsen, illustrating some of the lateral stratigraphic variations that occur in the Layered

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Series. The locality also demonstrates the relationship that exists between ilmenite-rich cumulates and replenishment of the magma chamber.

Description

The traverse starts from the track leading to Teksetjørni in ilmenite norites (phiC) belonging to the upper part of MCU II. These cumulates exhibit steeply-dipping to overturned small-scale modal layering, minor unconformities and abundant, generally tabular xenoliths. They are succeeded by ~5m of ilmenite-rich melanorite with sulphides and sparse olivine at the base of MCU III, then rather massive leuconorite containing thin, discontinuous ilmenite-rich layers and a sequence of strongly modally-layered, ilmenite-rich norite. The latter are overlain successively by ilmenite leuconorite and magnetite-bearing norite enclosing numerous blocks and slabs up to 100m across of massive norite or leuconorite. Note that the prominent poC seen at Hågåsen is absent here. The unit of olivine-bearing melanorite is the lateral equivalent of the layer of sulphide-bearing orthopyroxenite developed locally elsewhere.
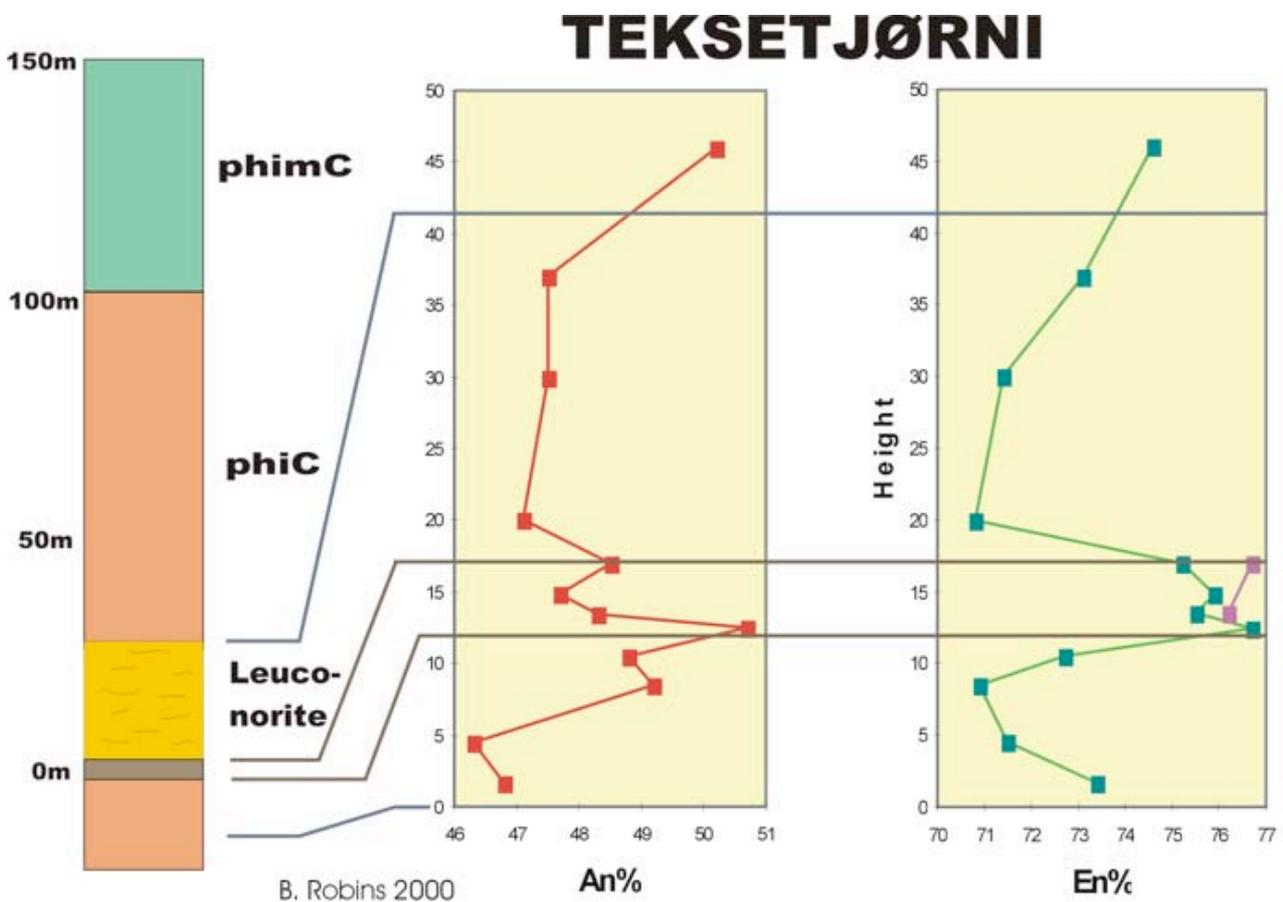
Figure 26. Cryptic variation in plagioclase, orthopyroxene (green) and olivine (violet) across the MCU II/III boundary att Teksetjørni.

Mineral compositions. The compositional variations in plagioclase, orthopyroxene and olivine in the sequence developed at this locality are illustrated in Figure 26. Note the cryptic regression through the uppermost 5m of MCU II as well as the presence of more calcic plagioclase, more magnesian orthopyroxene and magnesian olivine in the melanorite, all suggesting that the formation

of the melanorite was a response to magma-chamber replenishment. Orthopyroxene (and to a lesser degree plagioclase) near the base of the overlying leuconorite returns to compositions similar to those in the upper part of MCU II, and it exhibits a slight but consistent cryptic regression through the leuconorite into the phiC. This trend does not persist further upwards in the sequence, the majority of MCU III in this region being characterised by a normal cryptic variation (Figure 26).

Interpretation. Recently we have studied the lithostratigraphic relationships and cryptic layering in a series of sections across the boundary between MCUs II and III spaced over a distance of 25km along strike. This boundary is particularly instructive with respect to processes during replenishment since lateral variations in the thicknesses of MCU II and III are pronounced and reflect the topography that existed on the chamber floor at the time of magma replenishment. In the central region of the BKSK, around the hinge of the deep syncline defined by the layering, MCU III has a thickness of 900-1050m while in the SW limb of the syncline its thickness is reduced but fairly constant at ~800m. To the east of the axial region MCU III decreases to <350m in thickness over a ridge of gneiss in the substrate, then increases slightly to ~450m before thinning and wedging out further to the SE against the base of the intrusion. The thickness of MCU II varies in a similar but even more dramatic way. These variations are considered to be due to crystallisation of the megacyclic units in a central trough on the magma-chamber floor and on an elevated "shelf" or shallow trough to the east. In addition, differentiation of the resident magma was arrested at a relatively early stage by the influx of magma marked by the MCU II/III transition. MCU II consists of a thin basal sequence of plagioclase cumulates and a thick series of phiC. Cumulus magnetite does not make an appearance in MCU II, and it is likely that the resident jotunitic magma was differentiating with increasing density during its crystallisation. The stratigraphically lowest cumulates in MCU III are a thin sequence of strongly-layered melanocratic, orthopyroxene- and ilmenite-rich norite (phiC), or a discontinuous layer of orthopyroxenite up to 3m thick, all characterised by elevated amounts of disseminated sulphides (pyrrhotite, pentlandite, chalcopyrite and pyrite). The layer of orthopyroxenite is unique in the Bjerkreim Layered Series. Although it shows considerable lateral variations both in thickness and modal composition, this sequence can be recognised everywhere at the base of MCU III. A distinctive feature of the sequence as developed on the "shelf" is the local occurrence of sparse cumulus olivine in melanocratic ilmenite norite and the correlative layer of orthopyroxenite. The basal sulphide-bearing cumulates are succeeded in the majority of the Bjerkreim lobe by 25-130m of massive to strongly-layered phiC (zone a cumulates), then a massive unit of troctolite (pomC, zone b) up to 100m thick, that constitute the highest-temperature cumulates in MCU III. The troctolites reside beneath lower-temperature phiC, phimC and eventually phcmiaC that form the remainder of MCU III. In the eastern part of the lobe the sequence immediately above the basal cumulates of MCU III is much thinner (25- 45m) and consists of either rather massive leuconorite with discontinuous thin layers of ihC (resembling zone a cumulates elsewhere in the intrusion), or modally-layered, melanocratic ilmenite norite. With the exception of a locally-developed up to 12m-thick layer, troctolite (zone b) is conspicuously absent in this shelf region and the leuconorite or melanocratic norite is succeeded by "normal" phiC.

The cryptic variation across the MCU II/III boundary is characterised by a regression in mineral compositions (and 87Sr/86Sr) from the phiC forming the upper part of MCU II to the most primitive compositions that are found either in the troctolites forming the zone b cumulates of MCU III in the central and western part of the lobe or in the ilmenite-rich norites in the eastern, "shelf" area. This is consistent with prolonged magma-chamber replenishment associated with progressive mixing of the inflowing and resident jotunitic magmas. The sulphide-enriched orthopyroxenite and related melanocratic ilmenite norite are explained by crystallisation of hybrid magmas residing in

the pyroxene phase volume during the initial stages of replenishment. Their "global" distribution is inferred to result from mixing taking place some distance above the chamber floor at a level where the plume formed by the inflowing magma reached a level of neutral buoyancy in the compositionally-stratified magma column and spread laterally throughout the chamber. As the influx proceeded the resident magma was stripped from the base of the chamber and mixed into the ascending plume as the hybrid layer increased in thickness and became compositionally stratified. Eventually the lower boundary of the hybrid layer reached the floor of the magma chamber. The highest-temperature cumulates (poC, zone b) crystallised from the lowest part of this hybrid layer and were restricted to the central trough on the chamber floor, while lower-temperature cumulates crystallised simultaneously on the eastern "shelf" from magma higher up in the hybrid layer.

Stop No 9. Odlandsholen

Location
Turn off the E39 to Bjerkreim. Cross the bridge and follow the sigs to Lauperak and Tjørn. At the junction go straight ahead towards Odlandstø. The locality is 1.3km NE of this cross roads at the NE end of a fenced-in field (033231 649839).

Introduction
Large xenoliths of anorthosite in the lower part of the Bjerkreim-Sokndal layered intrusion.

Decription
In this recently excavated surface numerous large blocks and slabs of anorthosite and leuconorite are clearly visible within leuconorite (pC) belonging to the lowermost part of MCU IB. The margins of the xenoliths are generally outlined by concentrations of orthopyroxene and ilmenite. These xenoliths appear to have been derived from the adjacent Egersund-Ogna Anorthosite Massif, and are particularly abundant in the lowermost parts of MCUs IA & IB.

Day 3. Bjerkreim-Sokndal Evolved Rocks.

Introduction
We now concentrate on the upper, evolved rocks in the layered intrusion. In the upper part of the final megacyclic unit (MCU IV), apatite ilmenite magnetite gabbronorites (with inverted pigeonite; MCU IVf) are overlain by olivine-bearing rocks in which plagioclase is commonly antiperthitic and there is interstitial K-feldspar. This form the so-called "jotunitic Transition Zone". This passes into mangerites (with cumulus K-feldspar), quartz mangerites (with up to 5% quartz) and locally charnockites (with abundant quartz). Country rock xenoliths are locally abundant and are concentrated in a thick interval near the mangerite/quartz mangerite boundary. It has emerged that these BKSK fractionation products are cut by a series of quartz mangerites and related rocks that cannot be distinguished in the field.

 Stop No 10. Pollo

Location
Take the road from Helleland towards Eia. Turn off where signposted "Skeipstad". Leave the car at the junction (~150m past a deserted house at 033865 648941. Follow the main road NNE to Pollo. Go through the farm buildings and cross the concrete bridge over a stream.

We see the Transition Zone (poorly exposed) and the overlying mangerites and quarz mangerites as well as a wide variety of xenoliths. Place names on Norwegain maps have been revised in recent years. On the 1:50.000 map (1312 III; Ørsdalsvatnet) from 2006 this farm is named Pollo. On the 1971 version it is Podlo, and on the 1:5000 "Økonomisk Kartverk" map it is Podlå.

Decription

The jotunitic Transition Zone (TZ) is a thin sequence of notoriously poorly-exposed cumulates. Mafic TZ cumulates here form the floor of the farmyard. The sharp boundary between the TZ and the mangerite forms a marked topographic step on the edge of the farmyard, and the bare slopes to the north are of mangerite and quartz mangerite.

Some 200m east of the farm, modally-layered mangerite at the base of the unit is exposed in a field on the north side of the tarn (Podlohölen). Walking then northwards around the edge of the Kvednamyra marsh and following a well-marked path into a side valley (the path is starts close to the stream at 033922 648975) to the east of the river, the appearance and gradual increase in the amount of interstitial quartz can be noted in the generally massive mangerite. The path takes one into a small NW-SE valley with an idyllic tarn. This valley follows the zone with abundant xenolithic blocks of country rocks that is located stratigraphically above the gradational boundary between the mangerite and quartz mangerite. Recent mapping has shown that the xenolith zone is laterally persistent and stratigraphycally discordant. In the axial region of the intrusion it is situated entirely within the mangerite. Many of the xenoliths here are large parallel-orientated slabs and consist of amphibolite, banded gneiss, leucogranite and breccia consisting of blocks of amphibolite cemented by leucogranite. To the north of the valley there is massive quartz mangerite almost devoid of xenoliths. The latter contains 8-15% quartz and 63-65 wt% SiO_2. Further north, in the inferred core of the syncline, there are patches of charnockite within the quartz mangerite.

Mineral compositions: The compositional evolution through the upper part of BKSK is shown in Figure 27. Olivine occurs only sporadically in the mangerite and quartz mangerite in the Podlo sequence and is fayalite with Fo_5 - Fo_4. Inverted pigeonite is more common (possibly due to subsolidus replacement of original olivine) and maintains a composition of En_{13}- En_{16} through most of the mangerite and quartz mangerite in this section. The Ca-rich pyroxene shows a similar pattern and has a mg# of 25-18 in most of the section. However, the content of *Or* in the normative feldspar appears to increase systematically upwards through the sequence from 36% to ~46% and reaches ~49% in the most evolved rocks (charnockite) while *An* decreases from 10.5% to 7% (~4% in charnockite).

Interpretation: The mangerites were earlier suggested to be flotation cumulates that crystallised under the roof of the Bjerkreim-Sokndal magma chamber, and the quartz mangerites have been regarded as a later intrusion and to have essentially liquid compositions (Duchesne et al. 1987). We view both the mangerites and quartz mangerites as bottom cumulates, mesoperthite being the principal cumulus mineral while quartz is regarded as an intercumulus phase. The charnockites represent the final differentiates of the Bjerkreim-Sokndal magma chamber.
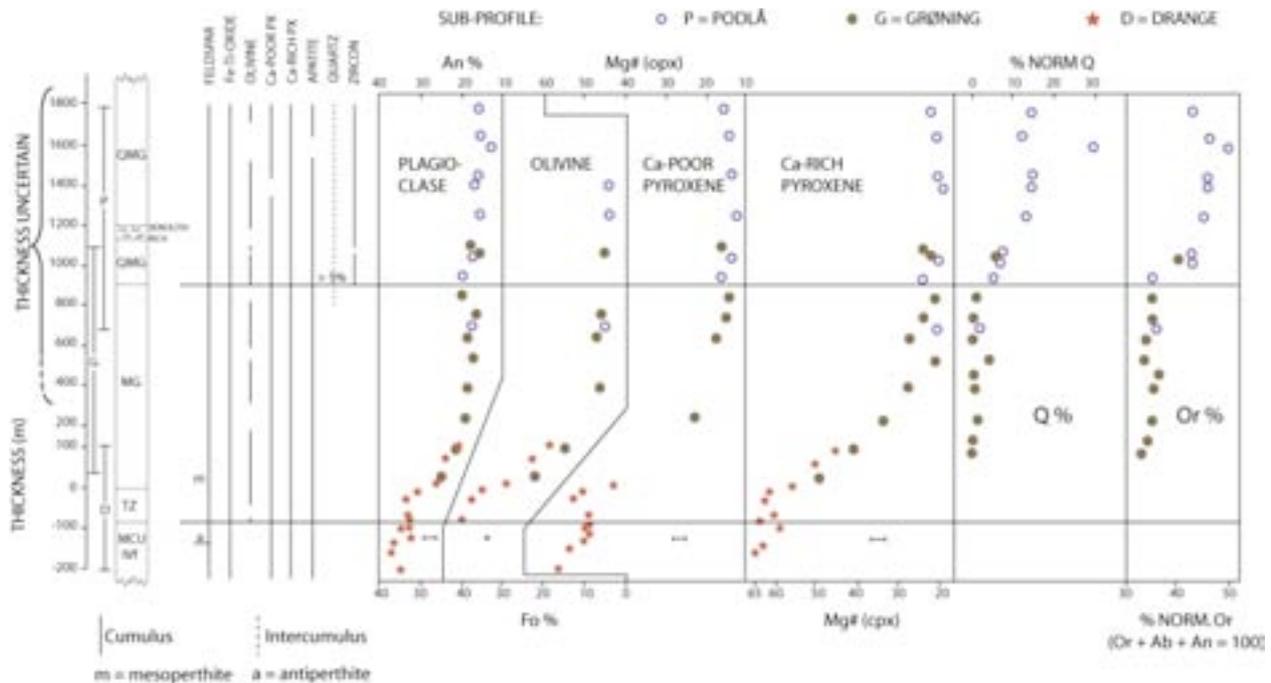
Figure 27. Compiled profile from the upper part of the Layered Series to the quartz mangerites in the Bjerkreim-Sokndal layered intrusion. From left to right: stratigraphic thickness (uncertain above ca. 400m, note change of scale between 100m and 200m); identification of sub-profiles from which the figure is compiled (D = Drange; G = Grøning (~1km NW of Podlo); P = Podlo); zonal subdivision; cumulate stratigraphy; variation in An% of plagioclase, Fo% in olivine, Mg# (=100 Mg/Mg+Fetot) in Ca-poor and Ca-rich pyroxenes; CIPW-normative quartz; CIPW-normative orthoclase (calculated as Or + Ab + An = 100). Error bars in the lower parts of the plots are at the two standard deviation level. Plagioclase analyses up to the TZ-MG boundary represent cumulus grains. In the MG and QMG they are of granular plagioclases that have probably exsolved from mesoperthite. Modified after fig.4 in Wilson and Overgarrd (2005).

Stop No 11. Drange

Location
Leave the car in the layby on othe E39 by the lake Kleivatjørna at 033918 649252. Walk west along the E39 for ~100m. Outcrops on the right (signpost Sørlandsveien 1220-1224) are of MCU IVf. Take the path on the opposite side of the E39 (at 033904 649262). Turn south off this path (at 0338932 64925) and follow a winding track that passes up through the jotunitic Transition Zone.

Introduction
This is one of the most accessible and best exposd sections through the Transition Zone.

Description
This north-south traverse along the west side of Kleivatjørni starts in gabbronorites with modal layering dipping ~65° south. These cumulates are characterised by inverted pigeonite and form the uppermost part of MCU IV (Zone f cumulates). The base of the 100m-thick "Transition Zone" (TZ), marked by the (re-)appearance of cumulus olivine, is located close to the junction between the main road (E39) and the side road to Drange. The TZ cumulates contain antiperthitic plagioclase together with Ca-rich pyroxene, Fe-rich olivine, inverted pigeonite, Fe-Ti oxides, K-feldspar and

apatite. Through the TZ olivine exhibits a rapid and systematic change in composition from Fo_{39} to Fo_{29} while plagioclase simultaneously changes from An_{32} to An_{26} (Figure 28). This smooth cryptic variation continues into the mangerite that is exposed to the south of the main road. The mangerites are generally leucocratic, massive, coarse-grained rocks characterised by cumulus mesoperthite. Locally, particularly in its lowest part, the mangerite exhibits crude modal layering. Partial recrystallisation of the mesoperthite commonly results in the appearance of separate crystals of plagioclase and alkali feldspar. The mangerite at the southern end of the traverse contains olivine with Fo_{23}- Fo_{19} and the plagioclase has a composition of An_{24}- An_{21}.
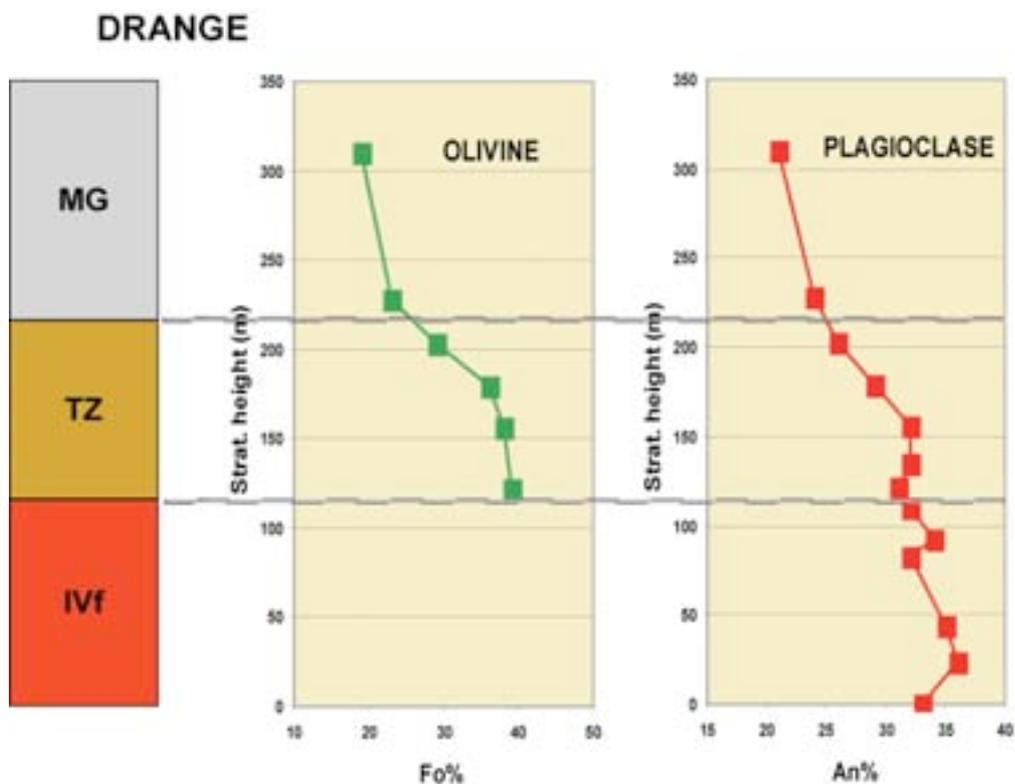
Figure 28. Cryptic variation through the upper part of Zone IVf, the Transition Zone and the lowest part of the mangerite at Kleivatjørni (Drange).

Interpretation: The continuous cryptic variation in mineral compositions from the Zone f cumulates into the base of the mangerite indicates that the sequence reflects progressive fractional crystallisation, with the single cumulus feldspar changing gradually towards more ab- and or-rich compositions. The single cumulus feldspar is an unusual and notable feature of the Layered Series of the BKSK.

Stop No 12. Jonsokknuten-Mysinghålå Round Trip

Location
Turn off the E39 to the south towards Mysinghålå (at LK375-922). Drive to the car park at the end of the road.

This walk passes across mangerites, quartz mangerites and charnockites that form the most evolved rocks in BKSK. The size and structure of the layered intrusion can appreciated in a view from the top (Figure 29).

Description

This trip is described in detail the "GeoTur" guide "Jonsokknuten – Eigersund" (Enclosure 3).

Figure 29. View to the northeast from the top of Jonsokknuten.

Day 4. Åna Sira and Fe-Ti Ore Deposits

Introduction

There is a long history of mining in the Geopark area, mostly for titanium which is extracted from ilmenite. Mining of ilmenite ore started in 1785 in the Koldal area, ~6 km east of Egersund. The ore was initially used to extract iron, and about 3.000 tons of ore were mined up to 1796 by Moss Jernverk (iron company). This mining activity soon ceased, however, since there were smelting problems; there was too much titanium in the iron! In 1861 a new attempt was made by the Egersund Mining Company, this time for titanium. This continued until 1881. Mining also took place at Blåfjell from 1863 to 1876 and a total of 90.000 tons of ore were exported, mainly to Italy and Hungary. There were up to eight active mines at Blåfjell, employing 72 men, but even more (up to 200) were engaged in building a railway. The ore-laden wagons here ran down from 106 m above sea level to the coast at Rekefjord about 8 km away. The last wagon carried two English brewery horses that hauled the empty wagons back to Blåfjell.

There was no further mining of Fe-Ti ores for the next 20 years. The Norwegian company Titania A/S was founded in 1902 and started mining at Storgangen, using the ore mainly for Ti-pigment. In 1958 there were 450 employees at Storgangen, producing 720.000 tons of ore. The world-class deposit at Tellnes was discovered in 1954 and has been mined since 1960. Mining at Storgangen ceased in 1964 since extraction was easier at Tellnes. Production from Tellnes reached a maximum of 930.000 tons of ilmenite concentrate (with 44.5% TiO_2) in 1989.

The mineral ilmenite ($FeTiO_3$) is an important raw material for the production of titanium dioxide (TiO_2). While ilmenite is black, titanium dioxide is white. It is mainly used as pigment in paint, plastic and paper, but also as an ingredient in cosmetic products including suntan lotion and make up, as well as in medicine (where it is used in many pills) and in some food. In this context the titanium pigment is referred to as E171. Only a small proportion of titanium production (~5%) is converted to titanium metal.

Stop No 13. Blåfjell

Location
Blåfjell is reached along a road that follows the old railway track from Hauge i Dalane. Turn north off the RV44 in Hauge on the road to Mydland and Moi. Turn right to Blåfjell after ~150m. Drive to the car park at Blåfjell at the end of the road (at 469 717).

Introduction
The ilmenite ore at Blåfjell is associated with very coarse-grained norite which extends as far south as the lake Måkevatnet. The Blåfjell-Måkevatnet pegmatite was intruded into the Åna Sira anorthosite. The pegmatite body has a very irregular shape and extends for about 5 km, from Blåfjell in the north to Måkevatn in the south. Crystals of plagioclase and orthopyroxene are generally about 10 cm across, but larger crystals occur locally. Ilmenite is very unevenly distributed and economic concentrations occur in layers and lenses that cannot be followed very far. Ilmenite associated with the pegmatite body was mined at several places in addition to Blåfjell (Bryns, Dalens Gang, Laksedalen, Sletthei).

In the Blåfjell area the most ilmenite-rich portions of the Blåfjell-Måkevatn pegmatite are located close to its contact with the enclosing anorthosite. The pegmatite body has a very irregular shape on a large scale and the ore-rich portions are also unevenly distributed and discontinuous. Some of the ore is, however, extremely ilmenite-rich. The locally high concentrations of ore and its uneven distribution meant that ilmenite was extracted from at least 8 mines in the Blåfjell area. Four of these, the Platform, Under, Over and Top mines, are described here.

The entrances to these four mines are located on the northern slope of Blåfjell. The entrance to the lowest mine (Platform) is at 110 m, at the same level as the lake and the road. The present road is located along the course of the railway built to transport ore to the coast. This mine can be followed into the hillside for ~63 m and has a breadth of 3-15 m and a height of 10-12 m near the entrance, decreasing to ~2 m furthest in. This excavated volume represents the size of the ore-body which has almost been completely removed.

The entrance to Under mine is at 138 m, almost directly above Platform mine. The excavated portion extends ~100 m into the hillside, has a breadth of 3-40 m and a height of 2-12 m. The entrance to Over mine is at 152 m. It extends ~52 m to the south, is up to 20 m wide and 2-6 m

high. The Under and Over mines are in the same ore-body and were, to some extent, excavated jointly.

Top mine is the most instructive in the Blåfjell area. The ore-body is exposed at the surface at ~228 m. The ore here is extremely rich; it locally reaches 100% ilmenite. This ore-body has a relatively simple, sheet-like form that dips to the north with a thickness of 2-6 m. There are several entrances at ~200 m and excavations extend inwards and upwards for ~55 m where they reach the surface. When the sheet of ore was excavated, several columns were left to support the roof. Much very high quality ore remains in the Blåfjell area, but in too small concentrations to make it of economic value today. So much ore remains that it appears that the mine was abandoned quite rapidly.

Description
Locality 1
Platform mine was probably one of the first mines at Blåfjell. It is easy to see why they mined here where the ilmenite ore is exposed and accessible. Signs of drilling can also be seen. The mine is essentially a large cavern where the ore was excavated and it has been used for, amongst other purposes, concerts and church services.

Locality 2
Towards the top of Blåfjell there is a prominent ilmenite layer (Figure 30) which was mined at Top mine (and elsewhere). This ~50 cm-thick black layer consists of almost 100% ilmenite. Many layers of this type can be seen on the way up towards the top of Blåfjell.

Locality 3
We go into Top mine at its lower entrance and go up through three levels. Evidence of drilling can be seen, as well as some old rail tracks and a rusty wagon. The columns consist of ilmenite ore and were left to support the roof; the shape of the ore body can readily be envisaged. When we come out of the mine we pass around and up the hill to the right where the mined ilmenite layer is well exposed at the surface. The black layer is 1-2 m thick and produced very good quality ore.

Locality 4
A steep outcrop some 100m to the SW of Top Mine has an unusual pattern of deep joints. From here there is a good view of the valley (Lille Beinsdalen) which contains many glacial erratics.

Locality 5
On the way back down to the road you pass the old explosives store and can follow the old mine path. Explosive (including nitroglycerine) materials for use in the mines were stored here.

Figure 30. Ilmenite layer at Blåfjell.

Stop No 14. Tellnes

Location
This stop is at the active mine ~8km east of Hauge i Dalane. It is reached via a turn off the RV44 ~3km east of Hauge. You need to have permission to enter the mine area.

Introduction
Tellnes is described in detail elsewhere in this guide.

Description
The shape of the open pit follows that of the orebody. The walls consist of anorthosite belonging to the Åna Sira massif. The orebody is cut by two major basaltic dykes.

Stop No 15. Hellersheia geotur

Location
This round trip starts and finishes at Helleren at the end of Jøssingfjord.

Introduction
This walk gives a good impression of the nature of the Åna Sira anorthosite massif. The view of Jøssingfjord from the top is excellent.

Description
This is described in detail the "GeoTur" guide "Hellersheia"" (Enclosure 4).

Figure. 31. View of Jøssingfjord from Hellersheia.

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