Origin of plagioclase-megacrystic, orthopyroxene amphibolites within a Precambrian banded gneiss suite, Flekkefjord area, Vest-Agder, South Norway

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Within a banded gneiss suite belonging to the high-grade Mesoproterozoic Flekkefjord complex in southern Norway, thin lenses of orthopyroxene amphibolites with medium- to large-size plagioclase megacrysts are located at roughly the same stratigraphic level in an area covering more than 200 km^2. The big feldspars are either more or less altered, single plagioclase megacrysts up to decimetre size or anorthositic aggregates measuring almost 1 metre across. The rock has suffered several phases of deformation and high-grade metamorphism during the Sveconorwegian orogeny, obscuring the primary origin of this unusual rock-type. Most rocks in the area have retained their granulite-facies mineral assemblage, whereas some zones within the southwestern area have been retrograded to amphibolite facies. Although several alternative modes of origin are possible for these big-feldspar rocks, a sill-like emplacement of jotunitic magma bearing plagioclase megacrysts which had previously crystallized in a deep-seated magma chamber is favoured. Intrusion of the big-feldspar amphibolites as sills took place before 1.16 Ga. Geochemical similarities with jotunitic rocks in the Rogaland anorthosite complex, emplaced at around 932 Ma, and the Hunnedalen dykes, which were intruded 100 million years later, suggest that similar magma-producing processes were in operation sporadically over a period of more than 325 million years.

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Introduction

In the northeastern part of the Flekkefjord area of SW Norway, a dark orthopyroxene amphibolite (pyribolite) containing numerous, large, white plagioclase crystals of varying size was originally discovered within the Mesoproterozoic banded gneiss suite on the plateau to the north of Leirvika and south of the intrusive Homme granitic gneiss (Fig. 1). This area is located in the eastern limb of a complicated double-folded synclinorium. When this highly characteristic rock-type was eventually detected in the western limb, 5 km west of the first locality, a more detailed investigation of this stratigraphic level was carried out. This revealed three more localities in the hinge-zone 5 km south of the first locality, to the north of Leirvika in the inner part of Fedafjorden (Fig. 1). This distinctive rock-type was also found at several localities covering a 2 km-wide zone to the south of Fedafjorden, southwest of Åsen. It also turned up to the north of Fedafjorden, in the western part of Fig. 1, suggesting that this rock-type was stratabound over an area covering more than 200 km^2 (Falkum 1998). A similar rock type has also been observed in the Lyngdal area to the southeast of Fig. 1 (Y. Ohta, pers. comm. 1998).

The presence of large plagioclase crystals suggested some link with the Rogaland anorthosite complex to the west, where plagioclase and orthopyroxene crystals may reach several metres in size (Barth 1935). A crucial point, however, is that the plagioclase-megacryst amphibolite was metamorphosed under high-grade conditions and subjected to several phases of deformation long before emplacement of the anorthosite massifs farther west, and consequently must represent a much older event of anorthositic magmatism.

Field occurrence

The 'big-feldspar rock' usually occurs as strongly deformed lensoid bodies (1-30 metres wide) with conformable contacts against the surrounding banded gneisses. These lenses inevitably wedge out along strike and can never be followed for more than about 100 m, normally considerably less.

The matrix of this big-feldspar rock ranges from a dark, orthopyroxene amphibolite to a slightly lighter, biotite amphibolite with some variation in the biotite content. There is also a huge variation in the number and size of plagioclase crystals or aggregates in the different localities, and the inhomogeneity is pronounced even within single outcrops. At some localities the feldspar megacrysts constitute up to 90% of the rock, and there are gradual transitions towards an almost megacryst-free amphibolite.

The size of individual crystals varies from 2-3 mm to almost 40 cm and irregular-shaped aggregates composed of several crystals may reach up to almost one metre across. The variation in size between individual crystals or aggregates within a single outcrop may be small. For example, one locality in the southwestern part of the area has crystals where the longest and shortest axes are all in the range 9-11 cm and 5-7 cm, respectively. A locality nearby has smaller,

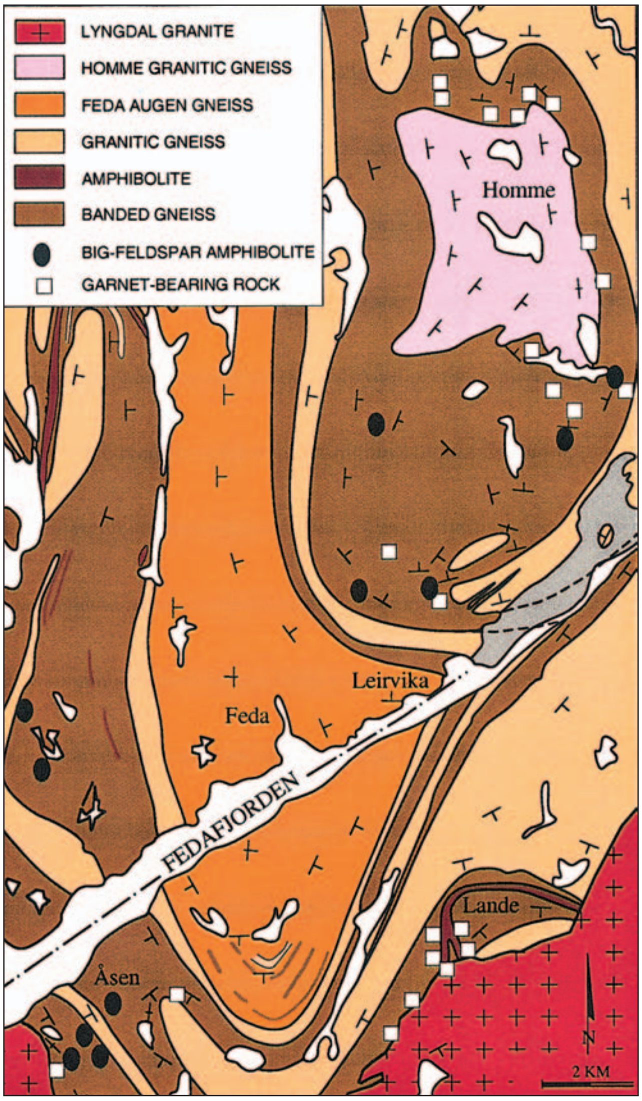

Fig. 1. Geological map of the Flekkefjord area with the recorded localities of the big-feldspar amphibolites. The mafic country rocks are generally in granulite facies, except in the southwesternmost area.

Fig. 2. The least deformed zones within the big-feldspar amphibolite exhibit sub-rectangular crystals mixed with crystals which are slightly more rounded. The scale (tape) is in centimetres. Locality A23 - 3.

rectangular crystals in the 4 x 2 cm range. Other localities expose relatively large crystals in the 30-40 cm range.

There is also a large variation in megacryst shape. The least deformed zones exhibit almost perfect rectangular crystals (Fig. 2), whereas the megacrysts become more and more ovoid in shape with increasing deformation and both the shape and the size are dependent on the degree of deformation (Fig. 3). Ductile deformation has affected all exposures of this rock-type, but to varying degrees. The least-deformed parts of some outcrops comprise 60 to 90% plagioclase megacrysts with relatively angular crystals (Fig. 2). These megacrysts are commonly somewhat elongate and there is no preferred orientation. The best preserved occurrences occur to the north of Leirvika and to the south of Homme, where several lenses of big-feldspar amphibolite are located roughly along strike over more than a kilometre (sample A23-3). Asymmetric folds with long, N-S-trending limbs and short, E-W-striking limbs dominate the structure. The least deformed big-feldspar amphibolites are commonly located in the E-W limbs of these folds.

With slightly stronger deformation, feldspars become more ovoid in shape and parallel oriented with their longest axes parallel to the foliation. Further deformation created thin lenses from the terminations of the longest axes of the ovoids, producing a still more pronounced foliation and banding (Figs. 3 & 4). The foliation and banding became more and more pronounced as the intensity of deformation increased, and this also resulted in a gradually decreasing crystal size. Local shear zones are almost devoid of crystals larger than a few mm, while the surrounding rock contains large crystals. In the most intensely deformed zones, individual plagioclases are totally recrystallized, leaving irregular bands of white feldspar as the only traces remaining of the mega-feldspar texture. The degree of deformation increased northwards, where extreme ductile deformation and local anatexis accompanied the forceful intrusion of the Homme granite (Falkum 1976). An agmatitic amphibolite (Fig. 5) without any obvious resemblance to the original rock occurs along strike from the big-feldspar amphibolite; this may represent the ultimate fate of this special rock-type within the migmatite region.

Mineralogy

The large, white megacrysts in the amphibolite matrix are mostly single plagioclase crystals (Fig. 2). Most of them are larger than a thin-section and crystals in the 10-40 cm range are common in many localities. The plagioclase crystals are rarely fresh, and even relatively fresh ones have suffered partial pseudomorphic replacement by fine-grained white mica or sericite. Sericite is generally aligned parallel to twin lamellae or cleavage traces, reflecting zones of weakness along which fluids had easier access through the feldspar lattice. Other plagioclase grains are even more altered as saussuritization has produced epidote, zoisite and/or clinozoisite. In these cases it may be difficult to find any remaining twin lamellae. In addition, there are irregular zones of a semi-opaque, brownish substance which remains unidentified,

Fig. 3. With increased deformation the plagioclases have been rounded and rotated, and their longest axes lie within the foliation. Furthermore, metamorphic recrystallizations in connection with the intense deformation produced thin lenses from their longest axes, accentuating the foliation. The scale (tape) is in centimetres.

Fig. 4. The extreme ovoid shape and lensoid form of the plagioclases illustrate the strong ductile deformation that has affected these rocks, particularly those in the southwesternmost area which have been retrograded to amphibolite facies. The length of the compass is 20 cm. Locality M29 - 9.

Fig. 5. Agmatitic amphibolite with zones of white plagioclase crystals. This type of rock is found along strike near the typical big-feldspar amphibolites.

possibly an iron-rich mineral. Rarely, but especially along contacts between adjacent grains, smaller areas of the larger grains may be replaced by granular aggregates of finer-grained plagioclases. The least altered of the larger plagioclases are commonly in the labradorite range (An_{60-65}), measured by the Michel-Lévy method on albite twins. Smaller grains of andesine (An_{35-40}) probably recrystallized from the larger grains during metamorphic recrystallization in amphibolite facies.

The matrix of the big-feldspar rock is commonly a dark, homogeneous or faintly banded amphibolite (pyribolite) with a nematoblastic texture, dominated by the granulite-facies assemblage hornblende-hypersthene-augite-plagioclase.

The main mineral assemblage in the southwestern part of the area is composed of hornblende, biotite and plagioclase (amphibolite facies). This area is dominated by structures of the fourth phase of deformation which formed the Feda fold with the fold closure southeast of Åsen (Falkum 1998). The tectonism responsible for this large structure has thoroughly reworked the older complex, and the most deformed rocks in the Flekkefjord area are situated in the fold closure immediately to the south of these big-feldspar localities.

Biotite in the biotite amphibolite in the southwest has a pale yellow to red-brown pleochroism, indicating a high titanium content. It formed late since it always replaces hornblende. The small plagioclase grains (An_{30}) in the biotite amphibolite are commonly fresh, but some have been altered from the centre and outwards. This type of alteration becomes more common approaching the larger mega-plagioclases which are always strongly altered in the biotite amphibolites. Many small apatite grains and a few opaque minerals are also encountered, together with secondary sericite, epidote, zoisite and/or clinozoisite.

In granulite facies, the rock contains orthopyroxene with a pink to grey or very pale green pleochroism indicating a rather Fe-rich hypersthene, although it is somewhat altered. The clinopyroxene has a colourless or greyish to pale green pleochroism, typical of augite in granulite facies. The plagioclase in these granulite-facies rocks is typically andesine (An_{40}) and thus more calcic than in the biotite amphibolites, probably reflecting the higher metamorphic grade. Within both types, a few larger plagioclase crystals situated close to the mega-plagioclases have even higher An contents (An_{48-50}). The alteration of the mega-size plagioclases compared with that of most of the smaller fresh grains within the amphibolite could suggest an original disequilibrium between them, although it is more likely that the smaller grains recrystallized more easily in response to the metamorphism and deformation during the last metamorphic event.

Geochemistry

Two, relatively large, plagioclase crystals were selected for chemical analysis. Sample A is from the orthopyroxene amphibolite in the northeastern part of the area (A23-3), while sample B is from the biotite amphibolite in the southwest (M29-9 in Table 1). It was impossible to avoid areas with sericite and saussurite in the samples, as these alterations are only revealed under the microscope. The calculated An content shows a clear difference between plagioclase from the high-grade area (An_{63}, Table 2) and from the dyke-like body in the amphibolite-facies rocks to the southeast (An_{52}, Table 2). These compositions are in good agreement with the optical determinations and suggest that plagioclases in the high-grade rocks retained their original compositions more closely than those in the amphibolite-facies parageneses.

High potassium contents in the plagioclase megacrysts (2.7 and 3.3 w% K_2O, Table 1) could reflect an original composition or have been introduced during the metamorphic episodes, causing the later sericitization. High potassium contents are also found in plagioclases in a type of anorthosite classified as alkalic by Herz (1969), who found that the Roseland alkalic anorthosite massif in Virginia has 2.1% - 3.2% K_2O with an antiperthitic plagioclase (andesine) of 3.9% K_2O. The first published analysis ever of an anorthosite from the Bergen district in western Norway (Kjerulf 1862) shows a K_2O content of 2.7%. This is a whole-rock analysis but as anorthosites are commonly monomineralic so the differences between the whole-rock composition and single crystals are relatively small. Whole-rock analyses from the oldest known anorthosites in the world, in Australia, show 2.6 - 3.8% K_2O (Myers 1988). Although the present analyses are of mineral separates, they compare with the average of 104 analyses from massif anorthosites (Le Maitre 1976), so from a chemical point of view the pre-

Table 1. Chemical analyses and CIPW-norms (calculated from water-free analyses recalculated to 100) of two plagioclase crystals. A is from the granulite-facies area (sample A23 - 3) and B from the amphibolite-facies area (M29 - 9).

Sample	A (A23-3)	B (M29-9)
SiO_2	50.00	51.11
TiO_2	0.08	0.11
Al_2O_3	28.36	27.81
Fe_2O_3	0.92	0.60
FeO	0.33	0.47
MnO	0.04	0.04
MgO	0.41	0.38
CaO	10.49	9.80
Na_2O	3.35	4.08
K_2O	3.33	2.74
P_2O_5	0.01	0.02
Volatiles	2.04	2.12
Sum	99.36	99.28
FeO^{tot}/MgO	2.8	2.7
CIPW-norm		
C	0.18	0.37
Or	20.23	16.69
Ab	18.00	25.63
An	53.50	49.95
Ne	6.00	5.34
Ol	0.66	0.89
Mt	1.00	0.88
Il	0.15	0.21
Hm	0.26	0
Ap	0.02	0.04
Total	100.00	100.00

Table 2. Microprobe analyses of single grains of plagioclase megacrysts. Analysis A23 - 3a (from granulite-facies area) represents the average of five different analyses (no. = 5), while b to e are single analyses from the same grain. Recalculation to plagioclase composition gives an anorthite content of $An63_{\pm 3}$. Sample L7 - 11a is from the amphibolite-facies area and represents the average of 5 analyses, while b is the average of 15. Recalculation to plagioclase composition gives $An52_{\pm 2}$.

Sample	A23-3a	A23-3b	A23-3c	A23-3d	A23-3e	L7-11a	L7-11b
n	5	1	1	1	1	5	15
SiO_2	53.32	53.55	53.10	52.97	52.85	55.25	56.38
Al_2O_3	30.22	30.38	30.13	29.95	29.85	28.67	27.91
CaO	12.58	12.68	12.73	12.79	12.63	10.86	10.26
Na_2O	4.17	4.19	4.11	4.15	4.23	5.09	5.40
K_2O	0.17	0.12	0.14	0.18	0.19	0.10	0.16
Sum	100.46	100.92	100.22	100.04	99.76	99.97	100.11
An	$63_{\pm 3}$					$52_{\pm 2}$	

Table 3. Chemical analyses of the amphibolitic matrix of two samples from the granulite-facies area (A23-1 & 3) and 4 analyses of matrix from the amphibolite-facies rocks (M29-1, 2, 3, 9). Sample L7-11 is from a dyke-like body approximately 30 km to the southeast of the area represented in Fig. 1.

Sample no.	**A23-1**	**A23-3**	**M29-1**	**M29-2**	**M29-3**	**M29-9**	**L7-11**
SiO_2	49.12	49.08	43.26	43.23	43.15	43.15	46.77
TiO_2	3.10	3.10	2.13	2.03	2.07	2.07	3.58
Al_2O_3	12.42	12.41	16.65	16.77	16.48	16.50	16.37
Fe_2O_3	3.16	2.68	3.04	2.88	3.06	2.52	4.59
FeO	11.49	11.98	10.68	10.39	10.50	10.97	9.74
MnO	0.28	0.25	0.23	0.22	0.23	0.21	0.15
MgO	4.32	4.28	7.56	7.75	7.77	7.70	5.30
CaO	7.87	7.81	9.91	9.84	9.74	9.69	7.71
Na_2O	1.77	1.83	2.73	2.82	2.82	2.87	3.17
K_2O	2.14	2.19	1.72	1.57	1.51	1.53	1.18
P_2O_5	1.15	1.16	0.25	0.25	0.25	0.25	0.44
Volatiles	2.63	2.50	1.69	1.71	1.83	1.83	0.73
Sum	99.45	99.27	99.83	99.74	99.40	99.29	99.83
$\frac{FeO^{tot}}{MgO}$	3.3	3.4	1.8	1.7	1.7	1.7	2.6
CIPW-norm							
Q	7.06	6.13	0	0	0	0	0
Or	13.07	13.38	10.34	9.46	9.16	9.34	7.09
Ab	15.54	16.02	9.25	10.55	10.96	10.08	27.11
An	20.32	19.86	28.65	29.11	28.52	28.31	27.20
Ne	0	0	7.73	7.48	7.31	8.06	0
Di	10.25	10.34	16.20	15.61	15.77	15.86	6.84
Hy	20.36	21.52	0	0	0	0	13.72
Ol	0	0	18.65	19.10	19.13	20.01	3.52
Mt	4.73	4.03	4.49	4.26	4.55	3.74	6.70
Il	6.07	6.10	4.12	3.86	4.03	4.03	6.84
Ap	2.60	2.62	0.57	0.5	0.57	0.57	0.98
Total	100	100	100	100	100	100	100

Table 4. The FeO^{tot} contents and FeO^{tot}/MgO ratios from samples of the big-feldspar amphibolite matrix compared with samples from the Rogaland anorthosite complex.

Sample	**FeO^{tot}**	**FeO^{tot}/MgO**	**References**
A23 - 1	14.33	3.3	This paper
A23 - 3	14.39	3.4	"
M29 - 1	13.42	1.8	"
M29 - 2	12.98	1.7	"
M29 - 3	13.25	1.7	"
M29 - 9	13.24	1.7	"
L7 - 11	13.87	2.6	
B-90	12.6	2.5	Wilson et al. (1996)
B-93	12.1	2.4	Jotunites from (BKSK)
B-95	12.5	2.8	Bjerkreim Sogndal
Hunnedalen	12.18	3.1	Maijer & Verschure (1998) (average of 20 analyses)
Jotunite from Tjørn	12.87	2.9	Duchesne & Hertogen (1988) Duchesne (1999)
179 LN	14.70	2.7	Wiebe (1984) LN=Leuconorite
7234 Hidra	13.68	2.8	Duchesne et al. (1974)
7020 massif	14.90	3.2	"
66125 Eia-Rekefjord intr.	14.70	3.9	"
HITJ	14.09	2.9	" average of 7 monzonorites, Hidra (HI) and Tjørn (TJ)

sent plagioclases are similar to single crystals from massif-type anorthosites in terms of their K_2O content.

In order to check if unaltered parts of plagioclase grains have high potassium contents, microprobe analyses were carried out on several plagioclase grains from the high-grade rocks (A23-3) and from the dyke-like body to the south (L7-11). The unaltered areas of these plagioclases have low potassium contents (less than 0.2% K_2O) relative to bulk rock analyses (Table 2). It is therefore apparent that K_2O is concentrated in the altered sericite-saussurite areas of the grains. The question is whether the high potassium content was an original feature of the rock or whether some of the potassium was introduced at a later stage during the several metamorphic overprints that have affected these rocks.

Situated immediately to the west of the Flekkefjord area is the Rogaland anorthosite complex with its numerous plutons that reveal a complicated history of diapiric emplacement, magmatic replenishment and differentiation, further complicated by assimilation (Wiebe 1984, Wilson et al. 1996). In the northern part of the Bjerkreim-Sokndal layered intrusion, some dykes of jotunitic composition are considered to represent a possible parental magma to this intrusive complex (Wilson et al. 1996). This jotunite is compositionally similar to the amphibolitic matrix of the big-feldspar hypersthene amphibolites from the Flekkefjord area, apart from having somewhat higher TiO_2 and slightly lower CaO and

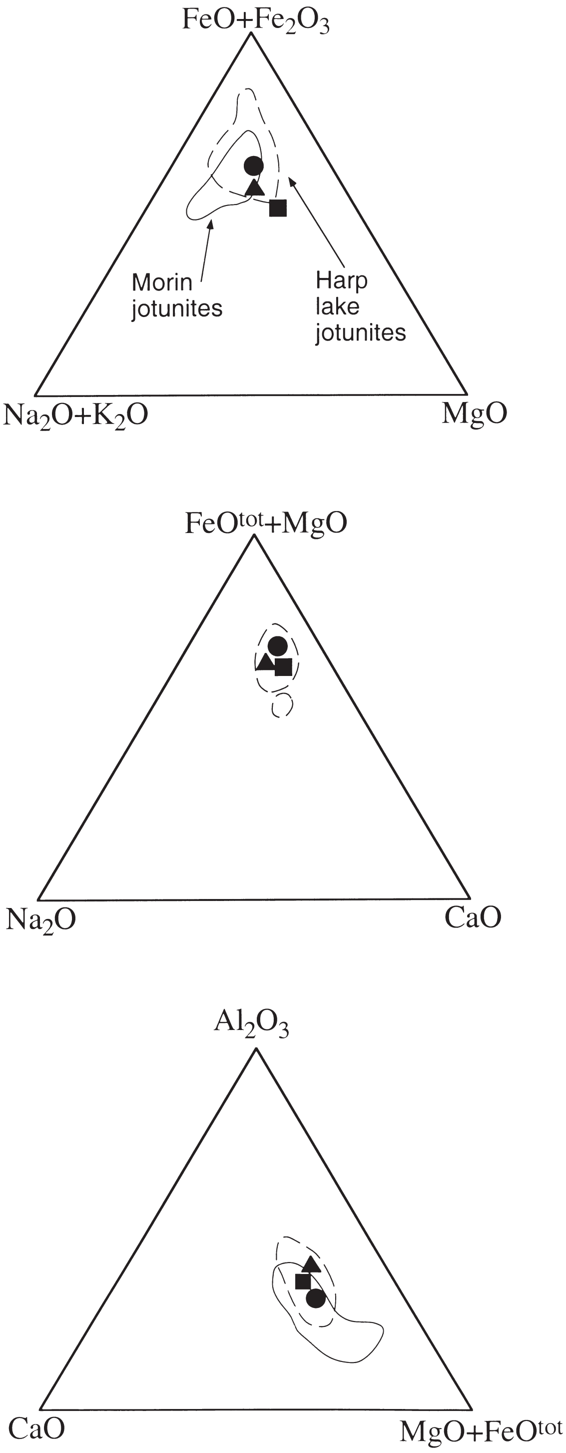

Fig. 6. AMF, (FeO^{tot}+MgO)-CaO-Na_2O and (FeO^{tot}+MgO)-Al_2O_3-CaO diagrams with the solid line enclosing 17 jotunites from Morin and the stippled line enclosing 17 ferrodiorites from Harp Lake (Emslie 1975,1980). The filled square represents sample A23 - 3, the triangle L7 - 11 and the circle M29 - 9.

K_2O contents (Tables 3 & 4). Farther to the south in this complex is the Eia-Rekefjord monzonorite (= jotunite) (Duchesne et al. 1974) which, geochemically, compares even better with the amphibolites, especially the most primitive Eia-Rekefjord samples (Wiebe 1984). The biotite amphibolite

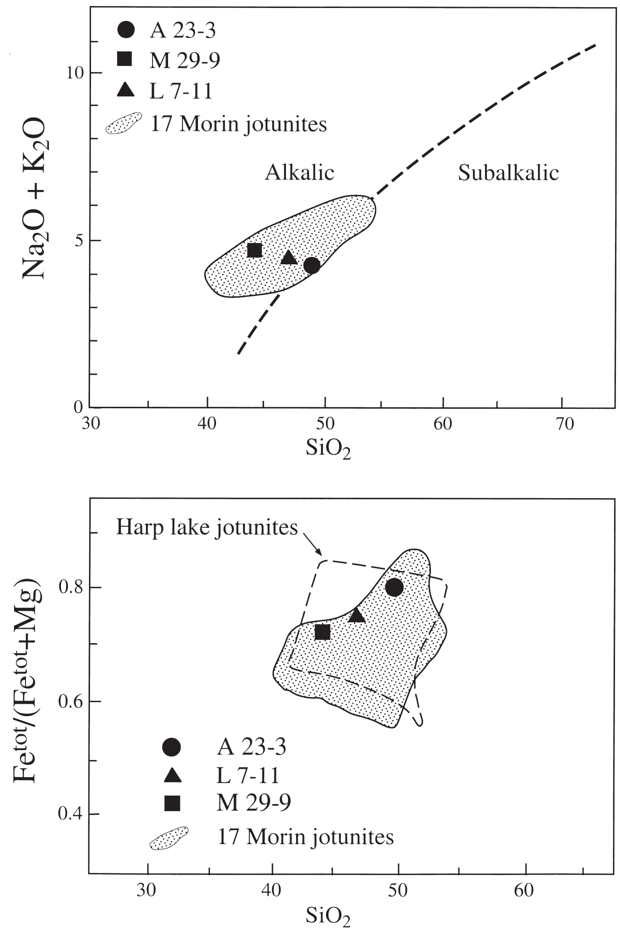

Fig. 7. Alkali-silica and ferromagnesia-silica diagrams. The solid line encloses 17 jotunites from Morin (Emslie 1975) and the stippled line encloses 17 samples of ferrodiorites from Harp Lake (Emslie 1980). All 7 samples from the matrix of the Flekkefjord big-feldspar amphibolite plot within these areas.

samples (M29-1, 2, 3 and 9) have slightly higher MgO and lower Na_2O than all the jotunitic rocks (Tables 3 & 4).

The FeO^{tot}/MgO ratio for the jotunites from the northern part of the Bjerkreim-Sokndal layered intrusion is between 2.4 and 2.8 (Wilson et al. 1996), and for the Hidra massif and the Eia-Rekefjord intrusion it is between 2.8 and 3.9 (Duchesne et al. 1974, Duchesne 1999) compared with 3.3 to 3.4 for the hypersthene amphibolite A23-1 & 3 (Table 3) and 1.7 to 1.8 for the biotite amphibolite (M29-1, 2, 3, 9). The lower ratio in the latter samples is caused by the relatively high MgO content (around 7.7%), while the FeO^{tot} contents of 13.0 - 13.4% are close to the lowest value in the Hidra massif but higher than the total iron in the Bjerkreim jotunite (12.1 - 12.6%, Wilson et al. 1996). Extensive anatexis occurred elsewhere in the area and it is therefore possible that these rocks have also suffered some partial loss of K and Si while Mg, in particular, has been retained. Judging from the analyses, this loss must have been subordinate.

When plotting the analyses from the samples of the matrix of the amphibolites in the AMF diagram and the triangular diagrams with ($FeO^{(tot)}$+MgO)-CaO-Na_2O and

$(FeO^{(tot)}+MgO)-Al_2O_3-CaO$, they overlap with either jotunites from Morin or ferrodiorites from Harp Lake in Canada (Fig. 6). Furthermore, they plot inside the jotunite area in the silica-alkali and silica-iron/magnesium diagrams (Fig. 7). They plot consistently near jotunites from the northern parts of the Bjerkreim-Sokndal intrusion (Wilson et al. 1996) or the monzonorites (= jotunites) or even some of the leuconorites from the Eia-Rekefjord (Duchesne et al. 1974, Duchesne 1999, Wiebe 1984).

It is therefore clear that the amphibolite matrix has a chemical composition close to the post-metamorphic jotunites (ferrodiorites, monzonorites) or some of the rocks classified as leuconorites. Even though the amphibolites intruded several hundred million years earlier, there seems to be a compositional similarity with the intrusive rocks of the Rogaland anorthosite complex to the west. This probably implies that similar magma-producing processes were in operation in the region at discrete intervals over a period of several hundred millions of years.

Discussion

Interpretation of the origin of this unusual orthopyroxene or biotite amphibolite with plagioclase megacrysts is not as straightforward as was believed when the rock was discovered. The first impression was that it was a kind of conglomerate. The field occurrences, on the other hand, with rather thin, elongated, concordant lenses confined to one particular lithostructural formation, suggest an original shape as sills or lava flows that were later deformed and disrupted in a large-scale boudinage structure. In addition, the chemical composition of the amphibolite matrix suggests a magmatic origin. Whether the plagioclase megacrysts were phenocrysts or xenocrysts remained a problem.

A supracrustal origin is not impossible, but rather unlikely as all the 'pebbles' are of pure plagioclase. Had it been a local occurrence, this might have been feasible, but since the rock type occurs over an area of several hundred km^2, this mode of origin seems unlikely, particularly as there is no indication of anorthosite-kindred rocks within the older part of the preserved rock sequence. Furthermore, in this area almost all recorded amphibolites are of intrusive origin (Falkum 1998).

Assuming an intrusive magmatic origin, it is tempting to compare this rock with other, similar but less deformed and metamorphosed occurrences. One such occurrence is that of the unmetamorphosed Gardar dykes in southwest Greenland called the 'big feldspar dykes' (Bridgwater 1967). Inspection of these dykes in the field convinced the first author that similar, intrusive, mega-plagioclase dykes would, after deformation and metamorphism, result in a rock like the big-feldspar amphibolites in the Flekkefjord area. Bridgwater & Harry (1968) concluded that the mega-plagioclases in the Gardar dykes had grown in the rock in which they are situated, claiming the existence of "a cognate rather than an accidental relationship between inclusions and the magmas in which they became incorporated." It is tempting to extrapolate this conclusion to the present rocks, i.e., the plagioclases represent phenocrysts and not xenocrysts.

There are, however, many other possible magmatic scenarios. If a basic magma intruded into a consolidated anorthosite massif it could dislodge anorthosite fragments and transport them upwards as xenoliths. The many single crystals in the Flekkefjord big-feldspar rock (Fig. 2) make this process seem less likely. In another scenario, plagioclase crystals may have nucleated and grown in a basic magma in a deep-seated magma chamber and later been transported upwards within a jotunitic magma which ultimately intruded into the Flekkefjord gneiss complex as sills.

Understanding the importance of magma mixing has led to successful interpretations of many composite plutons (Wiebe 1984, Wilson et al. 1996, Wiebe et al. 1997a,b). The large plagioclases are almost certainly related to the type of magma that leads to crystallization of massive anorthosites. It is therefore possible that jotunitic magma and a plagioclase-rich mush mingled at depth. Furthermore, if such a magma chamber was repeatedly replenished by jotunitic melts at the base, it would probably result in a stratified magma with buoyant plagioclase crystals in the upper regions, similar to the mechanism proposed by Wiebe (1990). Subsequent intrusions, fed by a diapiric mush of a mix of jotunitic melt from the lower regions and large crystals from the upper part, could result in a rock which, after deformation and high-grade recrystallization, was transformed into the metamorphic big-feldspar lithology.

Whatever the detailed mode of origin of these big-feldspar amphibolites, their present shapes indicate that they were emplaced as sills. If they had been emplaced as dykes discordant to the preexisting foliation and layering, extreme deformation would have been required to produce their concordant nature. They intruded earlier than, or simultaneously with voluminous basic magmas that were later metamorphosed to homogeneous orthopyroxene amphibolites which in one area cross-cut the earliest foliation in the banded gneiss (Falkum 1998). These amphibolites were emplaced exclusively in the banded gneiss suite, and probably before the granitic gneisses. The Hidderskog metacharnockite intruded both the banded and the granitic gneisses and, together with its considerably less deformed nature, implies that it was emplaced after the amphibolites. Zhou et al. (1995) dated the Hidderskog metacharnockite to 1.16 Ga. These rocks were subsequently deformed and metamorphosed during formation of the large-scale, isoclinal, recumbent folds that developed during the major F_2/F_3 phases of compressional folding. In contrast to this, intrusion of dykes and/or sills generally suggests a tensional tectonic setting. Emplacement in connection with delamination or convective thinning of the lithosphere following a period of crustal thickening formed during a gneiss-forming phase, as suggested by Corrigan & Hanmer (1997) for two distinct pulses of anorthosite emplacement in the Grenville orogen, could also apply for the Sveconorwegian orogen. They concluded that during convective thinning, magmas were emplaced in an extending crust in an overall convergent orogen. In the Flekkefjord area, crustal thickening in connection with plate collisions could have been followed by convective thinning of the lithosphere, paving the way for large-scale intrusion of magmas, now found as the big-feldspar amphibolites, homogeneous amphibolites and the voluminous granitic gneisses.

These early intrusions were later deformed and metamorphosed during continued convergent plate movements during the F_2/F_3 phases of deformation. A later pulse of magma emplacement, represented by enormous volumes of porphyritic granites, has been dated to 1.05 Ga (Bingen & van Breemen 1998). Later deformation and high-grade metamorphism resulted in a recrystallization of these granites to augen gneisses. During the subsequent 60 million years granitic magmas again intruded the increasingly more complex, folded terrane. These granitic rocks were deformed and metamorphosed in amphibolite facies during the last regional metamorphic event between 0.99 and 0.98 Ga (Falkum & Pedersen 1979). This periodicity, with five major phases of deformation and magmas intruding between the major phases of folding, is characteristic for the Flekkefjord area, but can also be found elsewhere in the Sveconorwegian province of South Norway (Falkum 1998).

In a post-metamorphic, late-orogenic period, the Rogaland anorthosite complex was emplaced at around 932 Ma (Schärer et al. 1996). Subsequently, the region to the northeast of this complex was intruded by the post-tectonic Hunnedalen dykes. They have been dated to 834 ± 9 Ma (Rb-Sr) and 835 ± 47 Ma (Sm-Nd) by Maijer & Verschure (1998) who suggested a genetic link to the Rogaland anorthosite magmatism. If correct, this implies that similar magma-producing processes have been in operation sporadically in the southwestern part of southern Norway over a period covering at least 325 million years.

Geophysical modelling based on gravity and magnetic surveys by Olesen et al. (2000) suggested that the so-called 'Skagerrak volcano', 20 km offshore to the south of the present area, is built up of a 7 km-thick complex of ultramafic/mafic intrusive rocks of Sveconorwegian age. Furthermore, they suggested that it could represent the "residue of the parental magma that produced the voluminous Rogaland anorthosites." It could also be the residual part of the magma chamber that supplied the mega-feldspar amphibolites.

Conclusions

The presence of plagioclase megacrysts in high-grade metamorphic orthopyroxene amphibolites, with an age of more than 1.16 Ga, suggests that a magma or crystal mush which could lead to the formation of massif-type anorthosites and related rock suites was present in the upper mantle or lower crust before the time-interval 1.2-1.5 Ga. This magma or mush was later emplaced as sills into the mesozonal crustal level occupied by high-grade gneisses, several hundred million years before the intrusion of the main, post-metamorphic, Rogaland anorthosite complex.

The geochemistry of the matrix of the amphibolites reveals a certain similarity with jotunitic rocks within the Rogaland anorthosite complex and Canadian jotunites (ferrodiorites), when allowing for some differences caused by alteration during the high-grade metamorphism associated with the last five phases of deep-seated deformation during the Sveconorwegian orogeny. Jotunitic dykes are considered to represent the parental magma composition of the Bjerkreim-Sokndal layered intrusion (Wilson et al. 1996). Several hundred million years earlier, a similar type of magma probably formed in a deep-seated magma chamber with large plagioclase megacrysts concentrated in the roof-zone as a flotation cumulate leading to diapirism initiated during a phase of tensional tectonics. This crystal-liquid mush was ultimately emplaced as sills. The process leading to the formation of the mush is unclear, as the mega-plagioclase crystals could alternatively have been included either by stoping of an anorthosite massif or by mingling with an anorthositic mush periodically supplied by jotunitic magma from the base of the magma chamber. The emplacement took place before intrusion of the Hidderskog meta-charnockite, dated to 1160 Ma (Zhou et al. 1995).

In more general terms, these magmas have some similarities with those formed in the earlier phases of continental break-up or in an extensional tectonic setting in an overall convergent orogen. These plagioclase-megacryst amphibolites and homogeneous amphibolites are interpreted to reflect an extending crust in an overall convergent setting, possibly in connection with delamination or convective thinning of the lithosphere, as proposed by Corrigan & Hanmer (1997) for the Grenville orogenic belt in the Canadian Shield. This event followed a period of crustal thickening before the onset of the next phase of strong compressional tectonics during the main, Sveconorwegian, deformational phases.

This special rock also suggests the presence of magmas producing jotunites and anorthosites in the lower crust or upper mantle at least 230 million years before intrusion of the large anorthosite massifs of the post-metamorphic Rogaland anorthosite complex, dated to 950-930 Ma, with most intrusions emplaced in a short time interval at around 932 Ma (Schärer et al. 1996). The monzonoritic (jotunitic) Hunnedalen dyke swarm (emplaced at 835 Ma) also shows a genetic relationship to the Rogaland anorthosite complex (Maijer & Verschure 1998). This widens the time interval for magma emplacement to more than 325 million years for the Rogaland magmatic province in southwestern Norway. The preponderance of intrusive complexes in southwestern Norway demonstrates that this crustal region was underlain by an anomalously high heat source and that this special environment probably controlled the magmatic and tectonic evolution during a period of several hundred million years.

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