Amphibolites, structures and metamorphism on Flekkerøy, south Norway

Ina Vang

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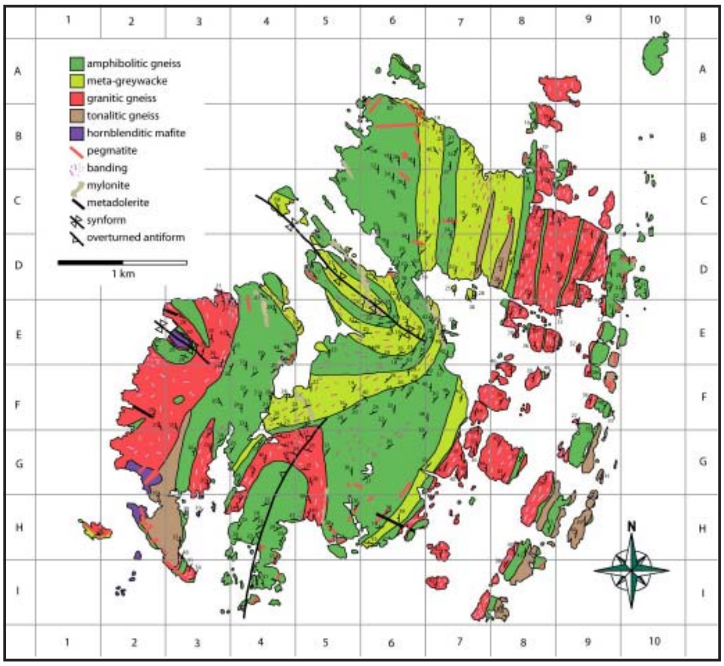

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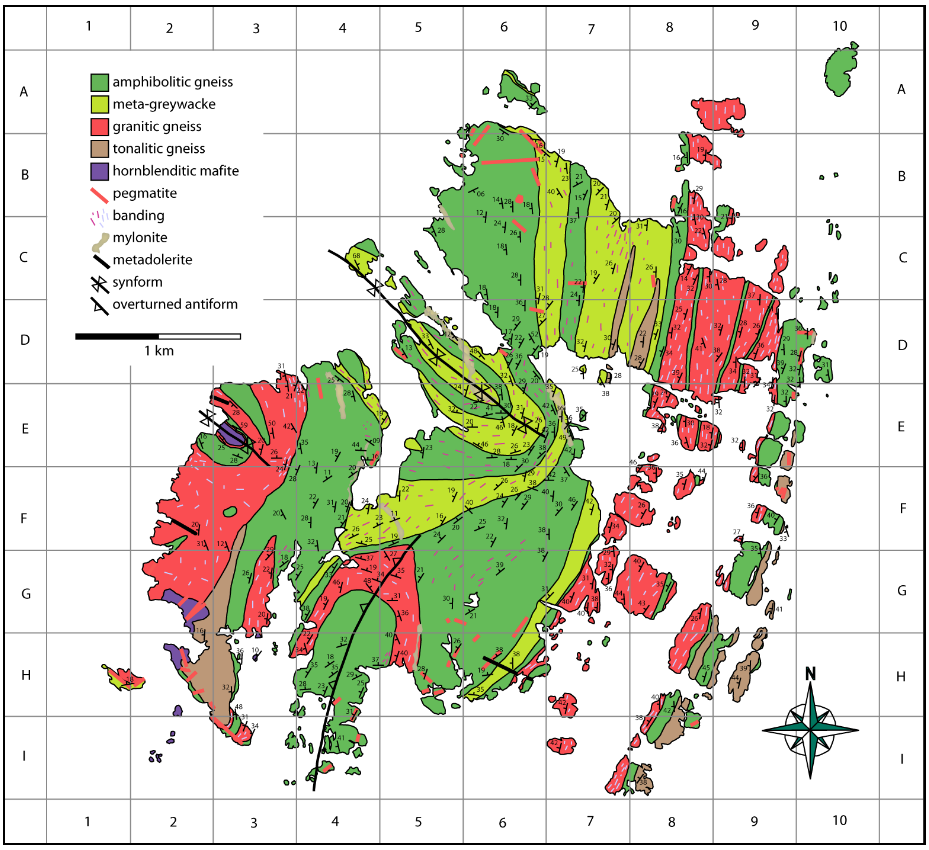

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Cover Picture: Bedrock map of Flekkerøy.

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Abstract: The island of Flekkerøy outside Kristiansand, southern Norway, consists of meta-greywacke, amphibolitic gneiss, granitic gneiss, tonalitic gneiss, hornblenditic mafite, pegmatite and metadolerite. The oldest rocks were probably formed around 1.5 Ga in an arc environment. During the Sveconorwegian orogeny, 1.14-0.90 Ga, the rocks were folded, recrystallized and metasomatosed. The rocks are therefore highly deformed and banded. The large scale structures are dominated by two synforms with fold axes running northwest and one inclined antiform with a fold axis approximately perpendicular to the two former. Lineations run northwest in general, but with a spread describing a great-circle in an equal area diagram. The structures indicate at least two stress directions. Metadolerites show alteration but are not foliated and have probably intruded after the deformation of the Sveconorwegian orogeny but before the end of the metamorphism. The different amphibolitic gneisses show variations in appearance and chemistry and most likely have different origins, either as basalt, dolerites, gabbro or calcareous clay. The trace element distribution is not similar to basites but rather to bulk continental crust. This indicates contamination of the magmas or metasomatism during the metamorphic event. The absence of good equilibrium textures makes PT-estimates uncertain. Approximate results are within the amphibolite facies.

Supervisors: **Anders Lindh** (LU), Ole Fridtjof Frigstad (Agder naturmuseum, Norge)

Keywords: amphibolite, structures, metamorphism, bedrock, Flekkerøy, southern Norway, Kristiansand.

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Amfiboliter, strukturer och metamorfos på Flekkerøy, södra Norge

INA VANG

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Sammanfattning: Flekkerøy i Kristiansand, södra Norge, består av amfibolitisk gnejs, granitisk gnejs, meta-gråvacka, tonalitisk gnejs och hornbländitisk mafit. Dessa har därefter genombrutits av flera generationer pegmatit och åtminstone en generation diabas. De äldsta bergartarna har troligen bildats utanför Baltica i en öbåge-miljö. Under den Sveconorwegiska fjällkedjebildningen blev bergarterna metamorfoserade och deformerade. Storskaliga strukturer på ön utgörs av tre veck, två synklinaler med en veckaxel som går i nordväst och en överstjälpt antiklinal med veckaxelriktning nordost. Lineationerna går generellt i nordväst men har en stor spridning. Stora delar av ön har karterats som amfibolitisk gnejs, som kan uppträda på olika sätt, till exempel i några meter tjocka band med starkt deformerade kontakter. Detta är särskilt fallet på östra sidan av ön. Några ställen har tunna, kompetenta amfiboliter brutits sönder medan berget omkring har deformerats duktilt. På andra ställen uppträder amfibolit i större kroppar. Amfibolitiska linser i amfibolitisk gnejs förekommer också. Geokemi på amfiboliterna har undersökts för fem olika prov. Generellt har amfiboliterna en spårelementfördelning som liknar granodiorit och inte basit. De medelkorniga amfiboliterna har troligen ett intrusivt ursprung, tillsammans med tonaliterna. De finkorniga amfiboliterna som innehåller låga halter hornblände, och annars innehåller kalifältspat och biotit, kan vara sedimentära tillsammans med gråvackan. Amfiboliterna som är finkorniga och huvudsakigen innehåller hornblände, plagioklas och titanit kan möjligtvis, tillsammans med amfiboliterna på ön Kinn, ursprungligen vara basalt. De tunna amfiboliterna på östra delen av ön som verkar förekomma som långsträckta intrusioner, och med starkt deformerade kontakter till den granitiska gnejsen, kan ha varit diabaser som intruderade före den senaste deformationen. Sedan korngränsorna är omvandlade och inte uppvisar equilibrium är tryck- och temperatur-estimaten osäkra, men har uppskattats till amfibolit-facies.

Handledare: **Anders Lindh** (LU), Ole Fridtjof Frigstad (Agder naturmuseum, Norge)

Nyckelord: amfibolit, strukturer, metamorfos, berggrund, Flekkerøy, Kristiansand, södra Norge.

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1 Introduction

The island of Flekkerøy is situated approximately six km south of Kristiansand on the southern coast of Norway. Results from geological mapping of Flekkerøy are published as two different map sheets (Falkum, 1982; Padget & Brekke, 1996), where the geological formations disagree. The rocks are strongly deformed and metamorphosed and may vary significantly over a distance of a few metres. Consequently, categorizing the various rocks into different types is a question of interpretation. *Banded gneiss* is a descriptive but not very informative term. This term has been avoided, and the intention has instead been to identify and characterize the major components of the unit previously mapped as "banded gneiss". However, banding of the different lithologis occurs frequently in most of the rock types on the island and is common in the whole Kristiansand area.

The aim of the study is to

- describe the different rocks found on the island and;
- characterize the field relations and structures.

1.1 Regional Geology

Southern Norway forms part of the Sveconorwegian province, which belongs to the Fennoscandian shield (Baltica). The Protogine Zone marks an approximate boundary towards the Transscandinavian Igneous Belt, TIB, in the east, mainly made up of granitoids and felsic volcanics. North of the Sveconorwegian province, younger rocks affected by the Caledonian orogeny occur (cf. Fig. 1). Bingen et al. (2005; 2006) separate the Sveconorwegian province into five terranes; the Eastern Segment and the Idefjord, Kongsberg, Bamble and Telemarkia terranes. These terranes were largely formed from 1.73-1.48 Ga old rocks. It is not known whether the margin of Baltica grew successively towards west due to arc formations (Lindh, 1987; Gorbatschev & Bogdanova, 1993; Andersen et al., 2004a; Pedersen et al., 2009) or if one or more of the terranes were exotic microcontinents accreted to Baltica (Corfu & Laajoki, 2008). However, igneous activity along active continental margins formed the terranes making up the Sveconorwegian province (Bogdanova et al. 2008).

The Eastern Segment is made up of granitoids from late magmatic stages in the TIB, 1.80-1.64 Ga

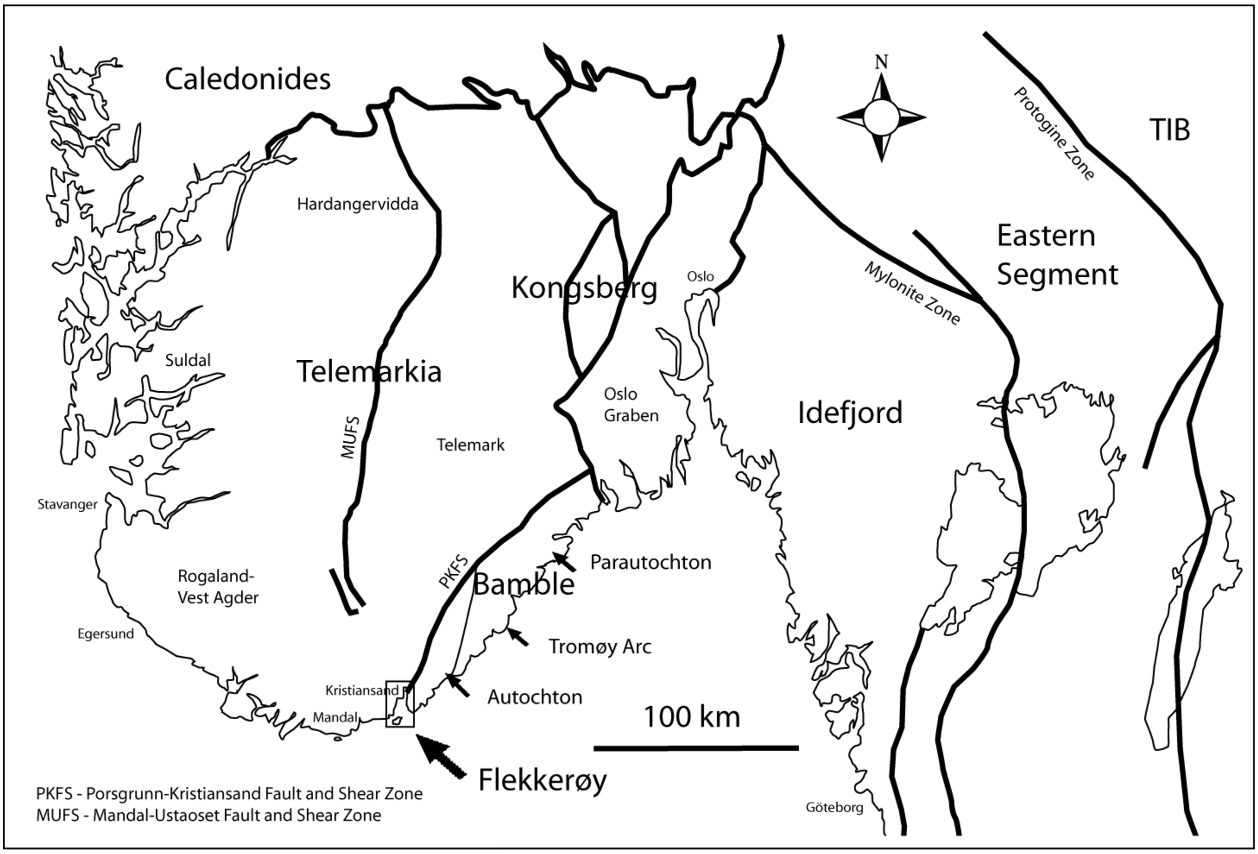


Fig. 1. Telemarkia, Kongsberg, Bamble, Idefjord and Eastern Segment are the five terranes in the Sveconorwegian province. Telemarkia is separated into the Suldal, Hardangervidda, Rogaland-Vest Agder and Telemark sectors. The Porsgrunn-Kristiansand fault and shear zone separates Kristiansand in the Telemarkia terrane from Flekkerøy in the Bamble terrane. Modified after Bingen et al. (2005).

(Bingen et al., 2006) and is the part of TIB that was affected during the Sveconorwegian orogeny. The metamorphism locally reached eclogite facies (Möller, 1998; Johansson et al., 2001). The Mylonite Zone separates the Eastern Segment from the Idefjord terrane.

The Idefjord, Kongsberg and Bamble terranes were probably formed in arc environments, where supracrustals, mainly meta-greywacke, were intruded by tholeiitic to calc-alkaline plutonic rocks (Åhäll et al., 1998; Andersen et al., 2004; Bingen et al., 2005; 2006; Bogdanova et al., 2008). Between 1.64-1.52 Ga, these terranes were accreted to Baltica during the Gothian orogeny. Bamble can be separated into two parts (cf. Fig. 1): The parautochton - the eastern part - is the oldest and show evidence of Gothian reworking, whereas the autochton - the western part - resembles the rocks in the Telemarkia terrane (Starmer, 1991). On top of the arc rocks, sedimentary sequences were deposited.

All the sectors in Telemarkia were probably formed in a continental arc setting and they display voluminous magmatism dated to 1.52-1.48 Ga. The geochemistry of this event has mainly been studied in the 1.51-1.50 Ga Rjukan volcanics, occurring in the northern part of the Telemark sector, where Brewer et al., (1998) found a continental-rift chemical signature. On top of the magmatic rocks, quartzites and other clastic sediments derived from Archean and Paleoproterozoic sources were deposited, indicating the proximity to an evolved continent (Andersen & Laajoki, 2003; Bingen et al., 2003; 2008; Pedersen et al., 2009).

The Sveconorwegian orogen was formed when Baltica collided with an unknown continent and was incorporated into Rodinia (Andersen & Laajoki, 2003; Bingen et al., 2006; Bogdanova et al., 2008). The continent might have been Amazonia and the collision led to the main deformation in the province (Alirezaei & Cameron, 2002). Before the major collisional stage, a back-arc basin was formed in the Telemark sector (Brewer et al., 2004) and continental magmatism occurred in Telemark and Bamble. From 1.22 to 1.14 Ga granites intruded and between 1.17 and 1.14 Ga, bimodal volcanics extruded and were interlayered with sediments. At 1.16, a coarse-grained or porphyritic granite intruded in the Kristiansand area, which later was transformed into augen gneiss (Fig. 2; Bingen & van Breemen, 1998) and at 1.13 Ga alkaline plutonic rocks intruded (Heaman & Smalley, 1994; Bingen et al., 2003).

The metamorphism and deformation during the Sveconorwegian orogeny lasted from 1.14 to 0.90 Ga (Bingen & van Breemen, 1998). This period is divided into four stages; the 1.14-1.08 Ga Arendal phase, the 1.05-0.98 Ga Agder phase, the 0.98-0.96 Ga Falkenberg phase and the 0.96-0.90 Ga Dalane phase.

During the Arendal phase from 1.14-1.08 Ga, an island arc was accreted to Bamble; these rocks can be seen in Tromøy, in the middle of the Bamble terrane along the coast (Fig. 1; Andersen et al., 2004). This phase represents the minimum age for docking of Telemarkia to Baltica (Bogdanova et al., 2008). The early stage of the collision led to amphibolite and granulite facies metamorphism in Bamble and Kongsberg and to NW-directed shortening and thrusting of Bamble on to Telemarkia (Kullerud & Dahlgren, 1993; Bingen et al., 1998; Henderson & Ihlen, 2004). In the Bamble terrane, gabbroid stocks differentiated from troctolite to gabbro or norite, commonly with several fractions within a single body (Starmer, 1991).

From 1.05 to 0.98 Ga the Agder phase represents the major collisional stage. Crustal thickening and metamorphism progressed to include the Telemarkia and Idefjord terranes. Idefjord was exposed to high -pressure amphibolite-facies metamorphism. The supracrustals in the central Telemark sector experienced greenschist facies, and in the southwestern part of Rogaland-Vest Agder there were granulite facies metamorphism. However, mid-amphibolite facies prevailed regionally. Granites were foliated and gabbros were altered to amphibolites. Unaltered cores in the hyperites can be found in the parautochton of Bamble but are very rare in the autochton (Starmer, 1991). The southern part of the Mandal-Ustaoset zone separates the Rogaland-Vest Agder sector from Telemark by a banded gneiss unit which was sheared around 1.05 Ga (Bingen et al., 1998). At 0.98 Ga the Holum granite intruded just north of Mandal (Fig. 1; Bolle et al., 2003).

The Dalane phase lasted from 0.96 to 0.90 Ga when extension led to the collapse of the orogeny. The Porsgrunn-Kristiansand fault and shear zone was formed, causing the juxtaposition of the autochton and parautochton of the Bamble terrane (Starmer, 1991). Large anorthosite, charnocite and granite bodies intruded (Bingen et al., 1998; Auwera et al., 2008), for example the Herefoss and Grimstad granites which are located between Kristiansand and Tromøy (Fig. 1; Starmer, 1991). In the Rogaland-Vest Agder sector a shallow gneiss dome was formed and the uplift led to exhumation and fast cooling (Bingen et al., 2006).

1.2 Local Geology

The Porsgrunn-Kristiansand fault and shear zone follows the river Topdalselva, which enters the sea in the fjord Topdalsfjorden and then probably runs between Flekkerøy and Vågsbygd, through Vestergabet (Fig. 2). This means that Kristiansand belongs to the Telemarkia terrane and Flekkerøy belongs to the Bamble terrane. However, it is not certain that the rocks on the different sides of the zone differ that much in this area since the autochton probably was a part of Telemarkia before the Porsgrunn-Kristiansand fault and shear zone was activated (Starmer, 1991). The map of NGU (Padget & Brekke, 1996) shows that the Tveit antiform continues east of the fault (Fig. 2).

The southern part of the Telemark sector has experienced amphibolite-facies metamorphism, while Bamble is considered to have a higher grade of meta-

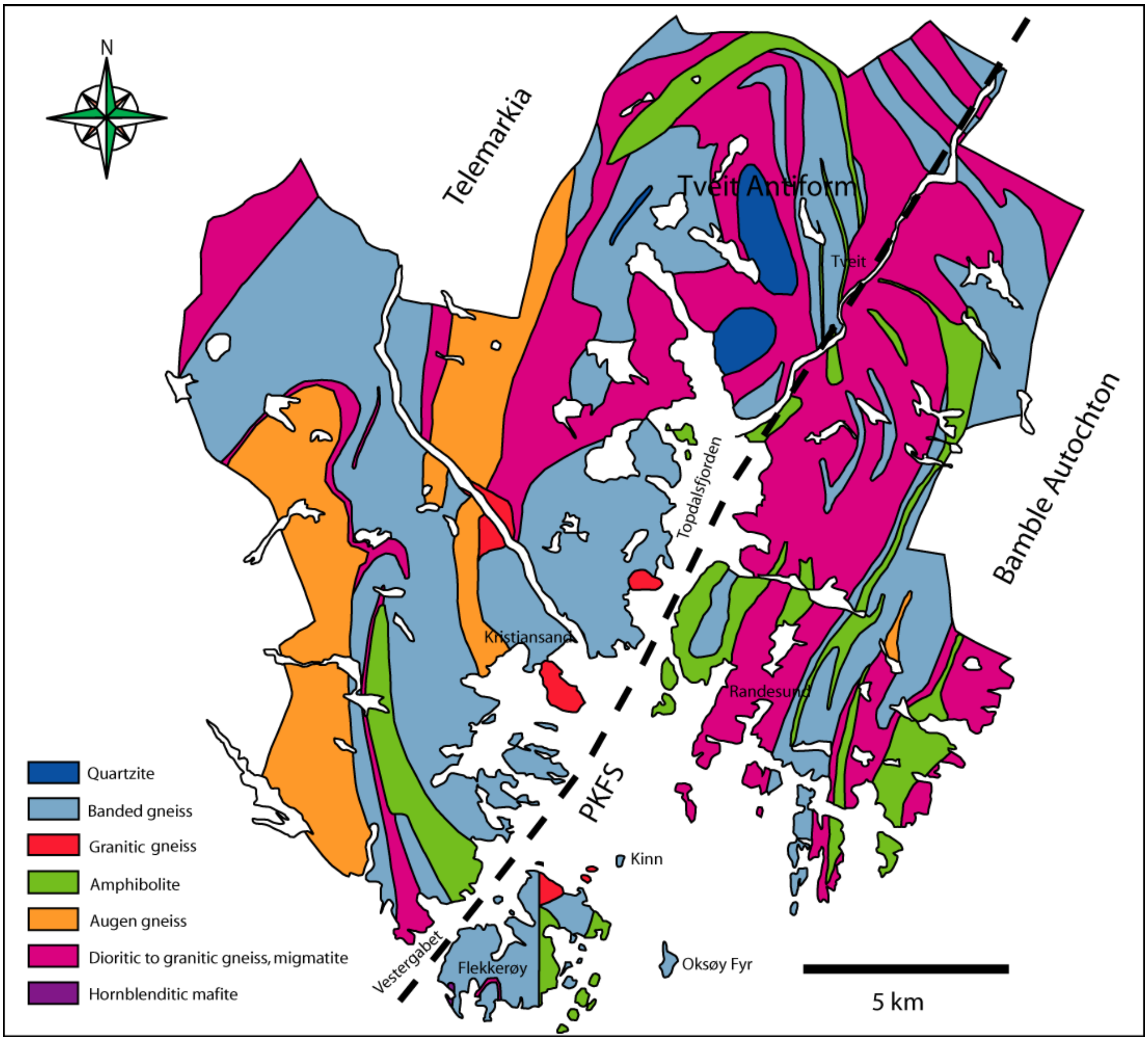


Fig. 2. Geological map of the Kristiansand area modified after Falkum (1982), Frigstad (1996) and Padget & Brekke (1996). The river which empties in Topdalsfjorden is called Topdalselva.

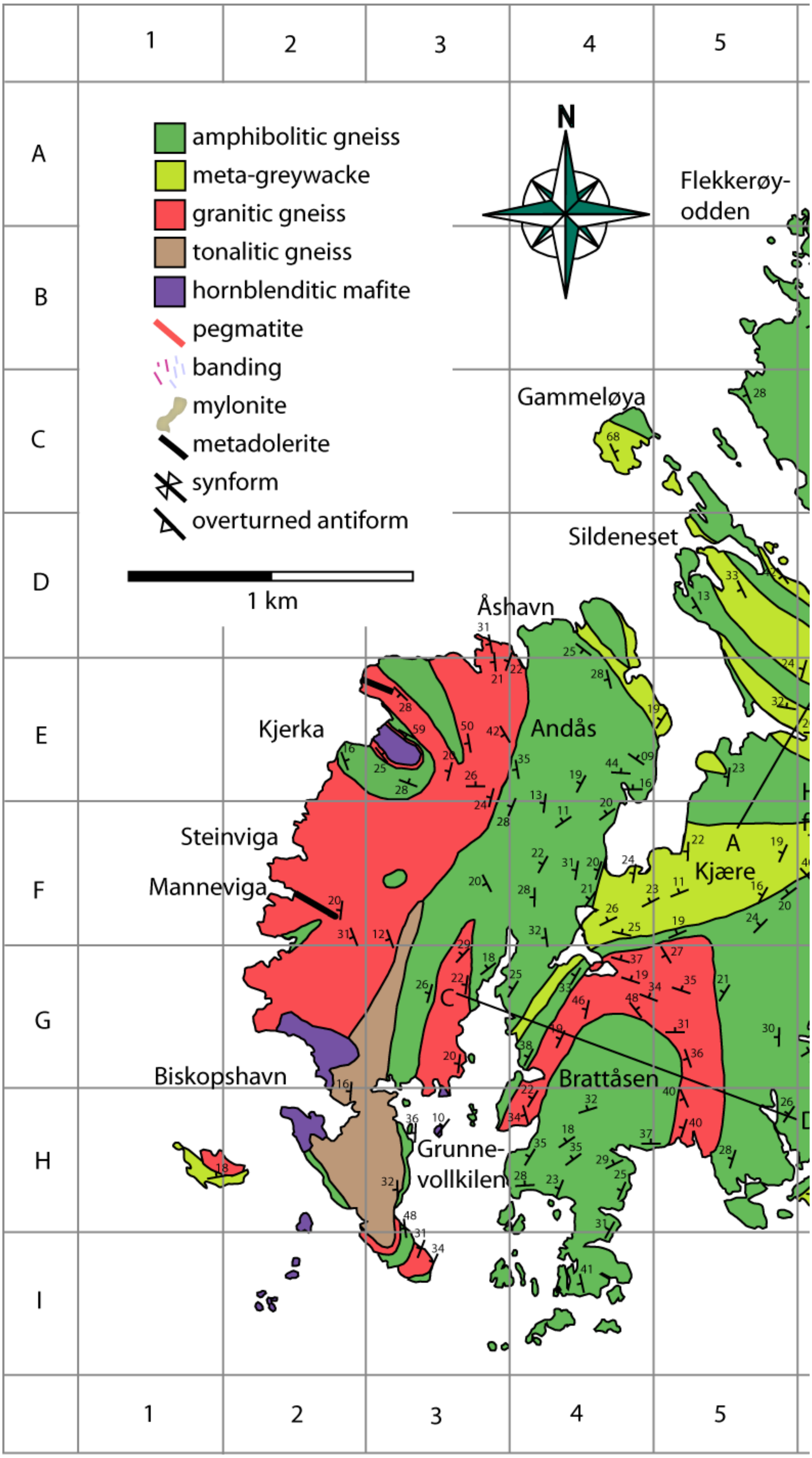
morphism, which is increasing towards the southeast. The southeastern-most area has undergone granulite-facies metamorphism and the northwestern-most area, adjacent to the Porsgrunn-Kristiansand fault and shear zone has experienced amphibolite-facies metamorphism. The Kristiansand area is therefore within the amphibolite-facies metamorphism (Alirezaei & Cameron, 2002).

The rocks in the Kristiansand area consist of metasediments, metavolcanics and plutonic rocks (Falkum, 1966, 1969, 1985). According to Starmer (1991) the granites found in the autochton of Bamble are mainly from 1.06 to 1.05 Ga, and the gabbros intruded mainly between 1.2 and 1.1 Ga.

Falkum (1969) investigated the island Kinn, which is located northeast of Flekkerøy and north to northwest of Oksøy Fyr (Fig. 2) and is made up of amphibolitic gneiss and pegmatite. He discovered angular enclaves of amphibolitic gneiss in amphibolitic gneiss and suggested that this could be surviving primary structures in what originally had been an agglomerate. He also found thin layers of more acidic composition, which he interpreted as sedimentary or tuffaceos layers. This might indicate that some of the amphibolites on Flekkerøy have a volcanic origin. At Tveit (Fig. 2), Falkum (1966) found both amphibolite that probably has a sedimentary origin and amphibolite that has an igneous origin. The antiform, seen in the area of Tveit (Fig. 2) was folded and later refolded during the Sveconorwegian orogeny. The last folding created open, upright, northwest-southeast folds with plunges controlled by earlier structures (Falkum, 1966; Starmer, 1991).

2 Methods

Lithological field mapping was carried out during the summer of 2009. Foliations and, to some extent, lineations were measured and plotted in STEREO. 26 rock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2
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A
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amphibolitic gneiss
meta-greywacke
granitic gneiss
tonalitic gneiss
hornblenditic mafite
pegmatite
banding
mylonite
metadolerite
synform
overturned antiform
1 km
N
Flekkerøy-
odden
Gammeløya
Sildeneset
Åshavn
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Andås
Steinviga
Manneviga
Kjære
Biskopshavn
Brattåsen
Grunne-
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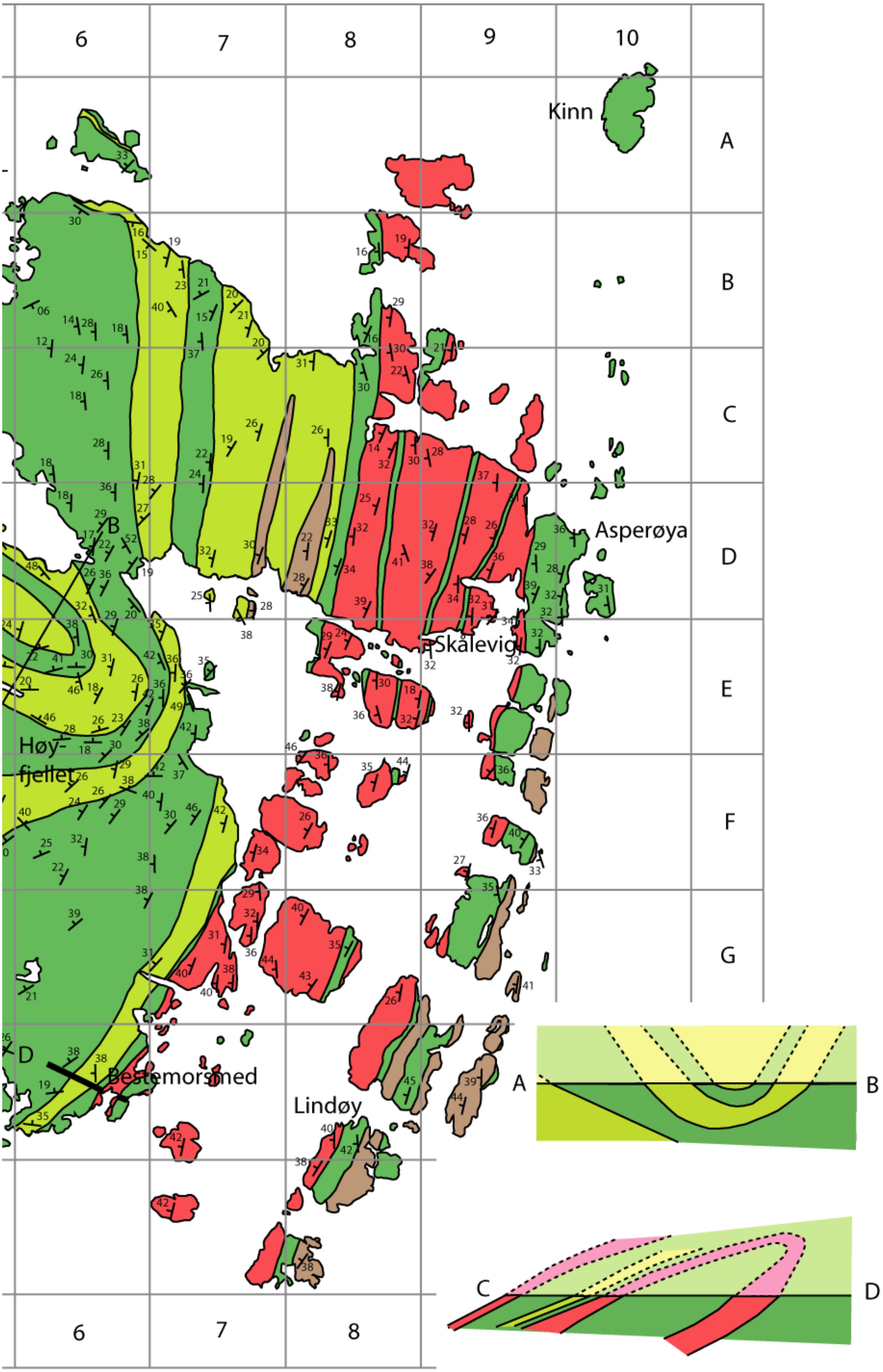
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Kinn
Asperøya
Skålevig
Høy-
fjellet
Bestemorsmed
Lindøy
A
B
C
D

Fig. 3, previous page. Bedrock map over Flekkerøy. The cross-sections in the right lower corner of the figure illustrates approximate shapes of the folds at Sildeneset (A-B) and Brattåsen (C-D).

samples were investigated using polarizing microscopy and a scanning electron microscope (Hitachi S3400N fitted with an EDS analytical device (Link INCA)). The acceleration voltage used was 15 kV. The samples were polished and coated with carbon.

Five samples were analysed chemically, both with ICP-MS and with XRF. The ICP-MS analyses were performed by Acme Labs in Vancouver, Canada. Mo, Cu, Pb, Zn, Ni, As, Cd, Sb, Bi, Ag, Au, Hg, Tl and Se were analysed in the ICP-MS using Aqua Regia Digestion. The rest of the elements were analysed in the ICP-MS using a Lithium metaborate/ tetraborate fusion and nitric acid digestion. The XRF analyses were performed at the Geological Department of Hamburg University. The results were plotted using the software GCDkit.

3 Results

3.1 Petrographic description

3.1.1 Meta-greywacke

The rock interpreted as meta-greywacke is common on Flekkerøy. It is fine-grained and most often dark grey in colour on fresh surfaces although light grey and bluish grey also occur. Due to its fine-grained nature, it is difficult to determine the relative amounts of feldspar and quartz in the field. Weathered surfaces give an indication of a changing quartz content, the colour varies between almost white, which can be seen in Fig. 4, to grey and yellow. The amount of mafic minerals varies from almost leucocratic to something that looks like an amphibolite with too much quartz. Garnet is common and the mica and hornblende contents sometimes vary strongly over only a few metres. At some places K-feldspar or plagioclase augens occur. Layers with varying composition, millimetres to centimetres thick, are common (cf. Fig 5). The foliation is sometimes strongly developed and sometimes only visible on weathered surfaces. Normally the contact between the meta-greywacke and the amphibolitic gneiss cannot be properly localized, due to a gradual change towards higher contents of mafic minerals.

Only one thin-section has been studied from meta-greywacke and consequently the description is incomplete. The sample was taken at Sildeneset (Fig. 3, E:6). The thin-section is rich in quartz and plagioclase with little or no twinning. K-feldspar is also common. Strongly pleocroitic biotite makes up approximately 20 % of the rock. Hydroxyl apatite makes up 1 % of the sample, some grains of garnet with apatite inclusions are also found. The opaque phases consist of ilmenite and pyrite.

Fig. 4. Homogenous meta-greywacke, dark grey on fresh surface but the weathered surface give indication of a high plagioclase content, photo taken at E:8 (Fig. 3).

Fig. 5. Layered meta-greywacke, photo taken at E:6 (Fig. 3).

3.1.2 Amphibolitic gneiss

What has, in this paper, been classified as amphibolitic gneiss covers large areas of the island. Normally it is

Fig. 6. Folded amphibolitic gneiss with leucosomes and epidote rich areas, photo taken at I:4 (Fig. 3).

Fig. 7. Amphibolitic gneiss with leucosomes, photo taken at B:5 (Fig. 3).

deformed and migmatitic. Leucosome occurs as bands and as lens-shaped volumes of some centimetres to decimetres in diameter (cf. Figs. 6 and 7). The amphibolitic gneiss has weathering surfaces from yellow to grey. The amount of mafic minerals varies and microscope studies show that the hornblende content may be as low as approximately 20 %. It is therefore possible that the field classification of the rocks is not entirely correct and that some of the rocks classified as amphibolitic gneiss might be a member of the metagreywacke sequence. It seems that there are at least four types of amphibolite: The first is a fine-grained type with 60-70 % hornblende and plagioclase and titanite (Fig. 8a). The second type contains the same minerals in approximately the same amounts but is medium-grained and less foliated (Fig. 8b). The third type also contains mainly hornblende, plagioclase,

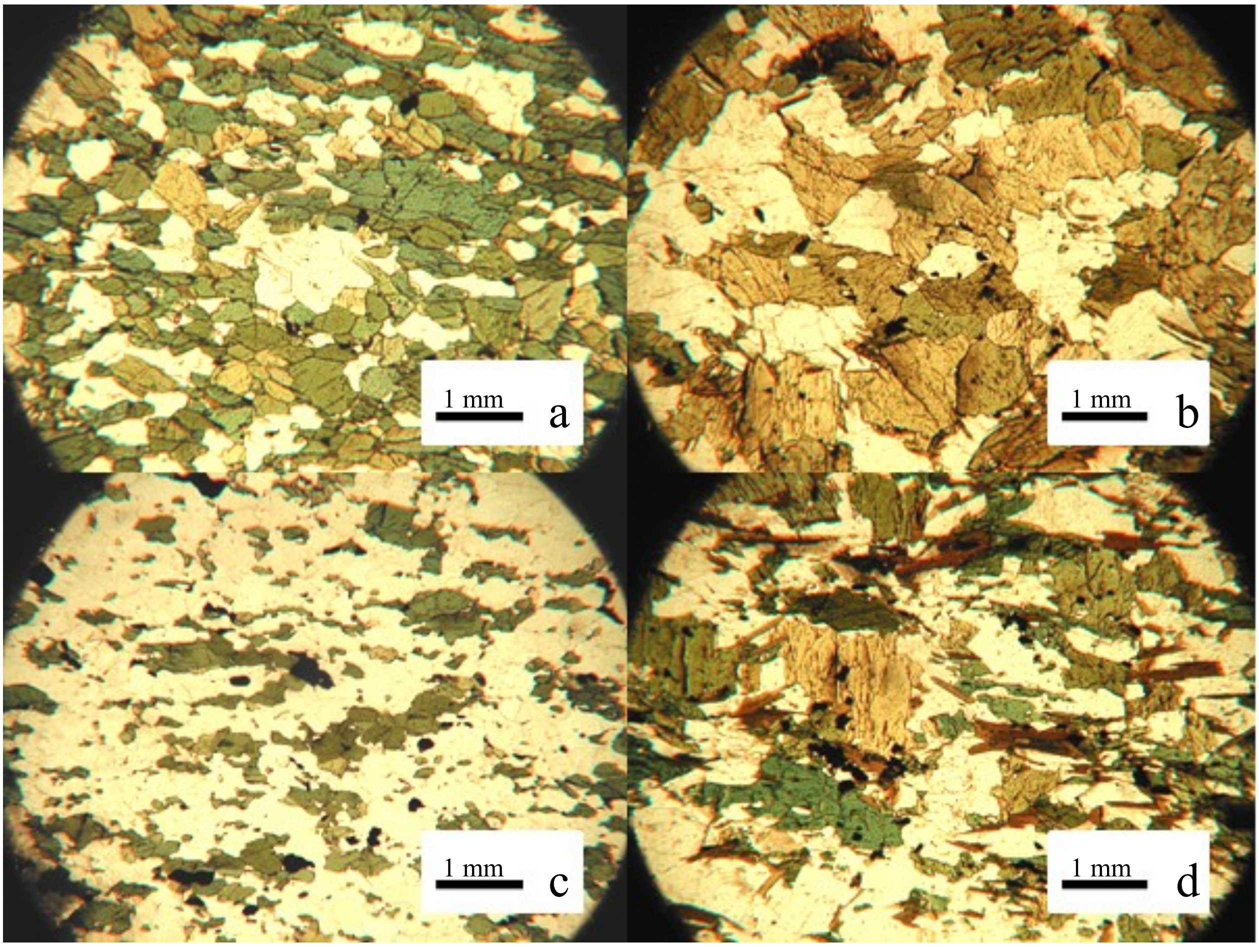

Fig. 8. Microscope photo, plane polarized light, of four different amphibolitic gneisses. a) Sa-450 (Fig. 3, E:8) contains 60 % hornblende, plagioclase and some quartz and biotite. The opaques (small, black grains) make up approximately 5 %, chiefly ilmenite. Chlorite and zircon is also present. b) Sa-179 (Fig. 3, F:4) is medium-grained and contains ~60 % altered hornblende. Plagioclase might show zoning. The small brown grains in the lower part is biotite. Accessory minerals are epidote, apatite, ilmenite, pyrite. c) Sa-437 (Fig. 3, I:4) was collected south of Brattåsen and contains ~20 % hornblende. It is rich in quartz and plagioclase. Apatite and ilmenite are accessories. d) Sa-447 (Fig. 3, G:4) is fine– to medium-grained with 40 % hornblende. Other minerals are quartz, plagioclase, biotite, K-feldspar, apatite, magnetite and ilmenite.

titanite and opaques but with a hornblende content of 20-30 %. This type is fine-grained (Fig. 8c). The fourth type is fine– to medium-grained and contains hornblende, plagioclase, quartz and biotite, sometimes also garnet (Fig. 8d). Most often the amphibolitic gneiss is fine-grained and light grey, indicating that the third type is the most common on Flekkerøy.

The easternmost point of the main island (Fig. 3, D:10) consists of a small peninsula with deformed amphibolitic gneiss, rich in feldspar and with 20-30 % hornblende. At the waterline on the northern side of the peninsula, two lenses of amphibolitic gneiss are found in the main amphibolite. They have hornblende contents of 60-70 %. The lenses follow the foliation, their maximum thickness is a few metres but after some five to ten metres they taper. This type of amphibolite is also found on Kinn, A:10, and as a roughly 50 metres thick band separating meta-greywacke and granitic gneiss in area E:7 (Fig. 3). Accessory minerals in this type of rock are hydroxyl apatite, epidote, chlorite, pyrite, ilmenite, zircon and biotite. Calcite occur as thin fracture fillings.

The main amphibolite in which the amphibolite lenses were found, is the type with 20-30 % hornblende. Plagioclase is the main mineral. Other minerals are quartz, titanite, hydroxyl apatite, epidote, magnetite, ilmenite and zircon. This type weathers to a light grey colour and can also be found at Brattåsen (Fig. 3, H-I:4-5) and on the northern part of the island (Fig. 3, A-C:6).

Microscopic studies of the third type of amphibolite (Fig. 8c) often reveal that it is strongly altered. It contains plagioclase, quartz, hornblende, biotite, titanite ±garnet, epidote, apatite, K-feldspar, magnetite, ilmenite, pyrite, calcite and zircon. It is common all over the island, especially in what has been categorized as the larger amphibolite bodies (Fig. 3, E-G:3-4, B-D:6 and F-G:5-7). The three types of amphibolite is fairly easy to distinguish under the microscope but in field they show successive transitions.

At Brattåsen (Fig. 3, G-H:4), on the southern side of the island, amphibolitic gneiss makes up the inner part of an antiform. Plagioclase veins, some centimetres thick, are folded on a decimetre scale with fold axes that seem to follow the main fold at Brattåsen. Decimetre-large areas rich in epidote are especially common on the skerries south of Brattåsen (Fig. 3, I:4 and Fig. 6). Amphibolitic gneiss also occurs as thin lenses and continuous bands from centimetre thickness up to some metres in granitic gneiss, meta-greywacke and possibly also the tonalitic gneiss. This can most easily be seen in the granitic gneiss on the eastern part of the island and the skerries to the south (Fig. 9; Fig. 3, C-I:7-9). The contacts are deformed and folded. Biotite schist, centimetres to several tens of metres in thickness, occurs as layers following the foliation in the amphibolitic gneiss. Biotite gneiss is sometimes also found in the contact between amphibolitic gneiss and pegmatite. Quartz and feldspar are found as millimetre thick layers in the biotite gneiss, garnet may also occur.

Fig. 9. One of the thin amphibolites in the granitic gneiss on the eastern side of the island, photo taken at E:8 (Fig. 3).

3.1.3 Granitic gneiss

The granitic gneiss at Flekkerøy is fine-grained, most often pink in colour and weathers yellow to orange. The content of mafic minerals varies and can be less than 1 %. Accessory minerals are garnet, muscovite, epidote, chlorite, rutile, calcite, ilmenite and magnetite. The granitic gneiss is strongly foliated and often migmatitic.

3.1.4 Tonalitic gneiss

Tonalitic gneiss consisting of plagioclase, quartz, biotite and small amounts of K-feldspar, is found in several areas on Flekkerøy. The grain size and the grade of deformation vary and make it sometimes difficult to identify the rock. On the northeastern part of the island, along the road to Skålevig (Fig. 3, D:7-8), the tonalite is medium-grained and not very deformed. The feldspar and quartz show myrmekitic intergrowths. No hornblende was found, accessory minerals are mainly muscovite, apatite, epidote, zircon and ilmenite. The occurrences are probably tectonic lenses that lie in the meta-greywacke. Another possibility is that it is two fold limbs with a hinge fold either to the south, hidden by the sea, or to the north, covered by vegetation. The meta-greywacke found between the two medium-grained areas is fine-grained but seems to have a similar composition. Along the small islands to the east (Fig. 3, E-I:8-9), another zone with tonalitic gneiss is found. The zone also looks like at least two lenses. This occurrence of tonalitic gneiss is fine- to medium-grained and more strongly deformed than the bodies along the road to Skålevig (Fig. 3, D:7-8). The third tonalitic gneiss body is located at Biskopshavn (Fig. 3, G-H:2-3). It contains less quartz than the ones previously mentioned. It is found south and east of the hornblenditic mafite, it occurs structurally below the hornblenditic mafite. Millimetre– to centimetre thick banding is common, both with quartz and plagioclase and with bands richer in mafic minerals (Fig. 10). A

Fig. 10. Tonalitic gneiss which is more heterogenous than normal, photo taken at H:2 (Fig. 3).

small body of medium-grained, unfoliated tonalite was also found at Bestemorsmed (Fig. 3, H:6). It contains quartz, plagioclase, 30 % biotite, 5 % hornblende and small amounts of K-feldspar. Accessory minerals are titanite, zircon, ilmenite and hydroxyl apatite. The opaque minerals are clustered and consequently it is difficult to estimate their approximate amounts. One sample of tonalitic geniss was taken on the island east of Lindøy (Fig. 3, G:9). Here, the tonalite contains ca 5 % biotite and some amounts of epidote. The plagioclase is altered. Since K-feldspar is present in small amounts, it is possible that the rock should be classified as granodiorite instead. Hornblende, titanite, epidote and apatite occur in minor amounts.

3.1.5 Hornblenditic mafite

Hornblenditic mafite occur on the western side of Flekkerøy as two separate bodies, approximately one kilometre from each other. The largest body is at Biskopshavn (Fig. 3, G-H:2) on the southwestern tip of the island; two small outcrops can also be found 100 metres to the east of the main body, at Grunnevoldkilen (Fig. 3, H:3). South-southwest of Biskopshavn there are several skerries made up of hornblenditic mafite. The dominating mineral is hornblende, which causes the black colour. A thin-section study reveals 20 % strongly altered plagioclase, 5 % opaques, mainly ilmenite, and small amounts of biotite. It is for the most part coarse-grained, but with decimetre- to metre-large areas of medium- or fine-grained rock where plagioclase also is present in visible amounts. There are pegmatite dykes, up to three metres thick, cutting the body. They have a well developed central quartz core, in which small scale mining has taken place (cf. Fig. 11).

Fig. 11. Hornblenditic mafite (Fig. 3, G:2) cut by pegmatite with well developed central quartz.

The hornblenditic mafite on the northwestern side of the island, at Kjerka (Fig. 3, E:3), is more fine-grained and green in colour. It contains more feldspar than at Biskopshavn and also chlorite, especially in the peripheral parts of the body. In the inner parts, clinopyroxene is preserved. However, hornblende is probably the dominating mineral in the rock, possibly together with plagioclase. The surrounding rock curves around the hornblenditic mafite, suggesting that the mafite make up the central part of a synform.

3.1.6 Pegmatite

Pegmatite occurs frequently as dykes in all the different rock types, sometimes cutting and sometimes parallel to the foliation. There are at least two generations of pegmatite; The younger generation looks more or

Fig. 12. Deformed pinch-and-swell pegmatite in amphibolitic gneiss with variable composition. Photo taken south of Brattåsen, at I:4 (Fig. 3).

less undeformed and cuts the foliation. The older generation is strongly deformed (Fig. 12), follows the foliation and sometimes occurs as boudins. Quartz, K-feldspar and muscovite are the dominating minerals; garnet is also common. Some of the pegmatites have two types of pinkish feldspar, one dark pink and one beige/light pink. In the northern part of the island, around Flekkerøyodden (Fig. 3, B:6), pegmatite is especially dominant. Pegmatite occurring in the hornblenditic mafite and the amphibolitic gneiss has often developed a central quartz core. A central quartz core may also be found in the granitic gneiss and in younger pegmatite cutting older pegmatite dykes. The dykes that are marked on the map (Fig. 3) make up only a small selection of the pegmatite dykes occurring on the island. There are also some thin fracture-filling layers consisting mainly of feldspar, which are 0.5 to 5 cm thick and cut the foliation. These are often ptygmaticly folded. Garnet-rich layers following the foliation plane are frequent; the crystals are often up to one centimetre in diameter. Altered garnet is common.

3.1.7 Metadolerite

Metadolerite is found at four different localities on Flekkerøy with a thickness of between one and two metres. One sample, collected at F:2 (Fig. 3) was studied under the polarizing microscope and scanning electron microscope. It contains 60-70 % plagioclase needles, strongly pleocroitic hornblende, 5 % subhedral titanite, 1 % opaque minerals and some biotite and apatite. The sample is unfoliated. At Bestemorsmed (Fig. 3, H:6) another outcrop of dolerite occurs. These dykes have the same strike. It cannot be proven by field observations whether the two outcrops belong to the same dyke, since there is a topographic depression without outcrops between them. Dolerite is also found south of Brattåsen (Fig. 3, I:4) as two dykes separated by a distance of 0.5-1 metres. They seem to have the same direction as the two former dolerite dykes. A thin dolerite is cutting the hornblenditic mafite in Biskopshavn (Fig. 3, G:2) and is cut by pegmatite.

3.1.8 Contacts

Most of the contacts on the map are highly banded and the banding might occupy large zones. Sometimes the banding decreases towards the centre of the rock body and sometimes the banding occurs throughout the area. I have tried to display the major rock types on the map (Fig. 3) instead of categorizing everything as banded gneiss.

3.2 Structures

The foliations on Flekkerøy most often strike southwest and dip between 20º and 40º towards northwest. A southeastern strike is also common (Fig. 13). The

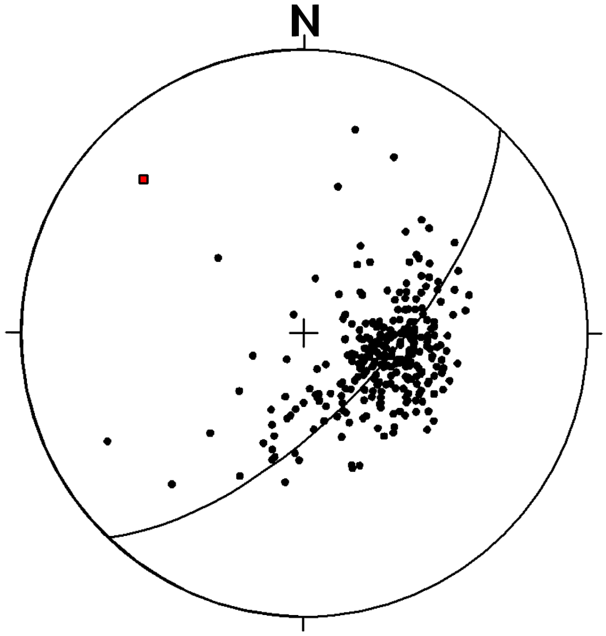

Fig. 13. The poles to the foliation surfaces with the best fitted great circle, which strikes 044 with a dip of 57º. The red square is the pole to the best-fitted great circle (Equal area net).

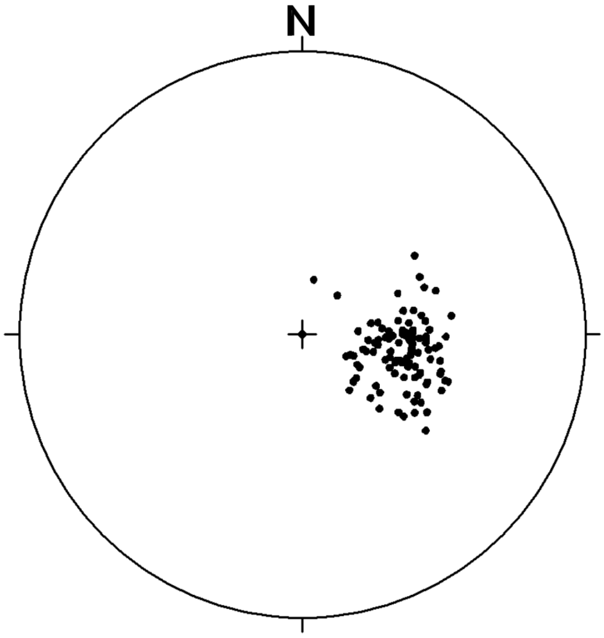

Fig. 14. Stereoplot of the foliation measurements from eastern part of Østerøya and the islands in the SE part (Equal area net), showing an approximately uniform foliation.

eastern part of the island has a rather constant strike with a low-angle dip (Fig. 14), resembling the structure pattern on the mainland in the east, the Randesund area (cf. Fig. 2). The western part of the island shows more variation with several map-scale fold structures.

In the area between Biskopshavn and Kjerka (cf. Fig. 3, E-G:2), the dip is gentle and the foliation undulates with a wavelength of some 10 to 50 meters. Small-scale folds are not very common here. The hornblenditic mafite at Biskopshavn (Fig. 3, G-H:2) lies tektonostratigraphically above the tonalite in the south and under the granitic gneiss in the north.

The peninsula south of the hornblenditic mafite in Biskopshavn might be a fold hinge (Fig. 3, H-I:2-3). The rocks are intensely folded in centimetre to metre scale and it is difficult to get an overview of the area although most of the bedrock is exposed. Inwards from the shoreline (Fig. 3, G:3) it is unknown whether the structures are similar to those in the granitic gneiss between Biskopshavn and Kjerka or if they also are characterized by small-scale folding. At some outcrops in this area an undulating foliation is seen on dm scale.

The other hornblenditic mafite, Kjerka (Fig. 3, E:3), forms the uppermost layer in a slightly inclined synform where the northern fold limb dips steeper than the southern one. On the southern fold limb granitic gneiss is in contact with the hornblenditic mafite, while on the northern side amphibolitic gneiss make up the bordering rock. This is, however not certain because there are some meters that are covered by loose material. An approximate fold axial trace has been drawn on the map (Fig. 3).

The amphibolitic gneiss at Brattåsen (cf. Fig. 3, G-H:4-5) is the inner part of an overturned antiform, with the axial plane dipping westwards. Figure 15 shows the typical appearance of this amphibolite where mm-thin fine-grained layer-parallel leucosome and thicker medium-grained - pegmatitic leucosome and leucocratic veins are folded on a decimetre to metre scale.

Fig. 15. The amphibolititc gneiss at Brattåsen is migmatitic and folded on decimeter to metre scale with a fold axis following the main fold axis direction.

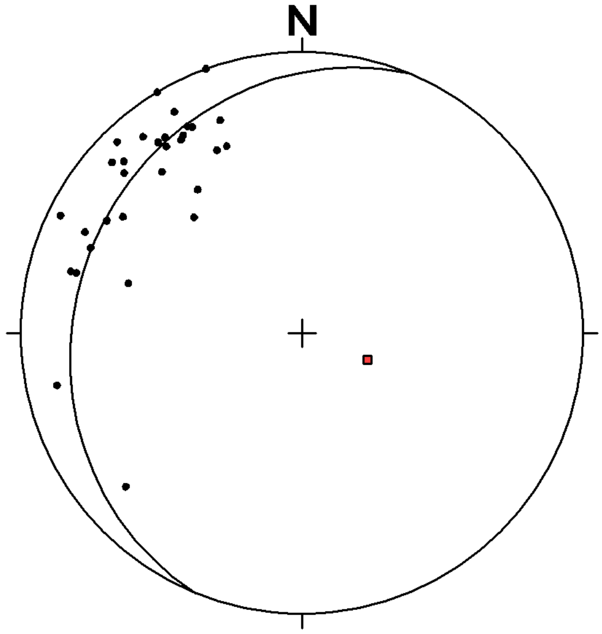

Fig. 16. The lineation measurements have a large spread and approximately follow a great circle striking 204, 22. The pole to the best-fitted great-circle (red square) is at 112.69.

The measured lineations are defined by oriented minerals, mainly hornblende crystals. They trend northwest in general, but show a large spread (cf. Fig. 16). The plunge of the lineations are gentle, around 20º.

The fold in the middle of the island, at Sildeneset (Fig. 3, C-E:4-6) is a synform, which seems to be asymmetric with a slightly curved axial surface. In the innermost layer of the synform, the rock is isoclinally folded (cf. Fig. 17).

The eastern part of the island forms part of a largescale fold, hidden by the sea. At some places in the granitic gneiss, thin mafic layers form boudins where the layers have broken off and also been dextrally sheared (cf. Fig 18).

Protomylonite and mylonite occur frequently on the island and most often trend north or north-northwest, almost coinciding with the fold axes of the fold at Sildeneset (Fig. 3, C-E:5-6) and the fold at Kjerka (Fig. 3, E:2-3). Eight mylonitic zones have been mapped. In Mebø (Fig. 3, E:7) a zone of mylonite cut the foliation at a low angle and includes both amphibolitic gneiss and meta-greywacke. It is separated into bands dominated by dark and light minerals, respectively. Biotite dominates and is assembled in layers of 5-10 centimetres width, and areas or layers of quartz and feldspar are found in between. The zone is rusty. In the northern part of the zone, garnet of 1-2 centimetres in diameter is common. Strongly deformed pegmatite is often found in the mylonite.

At Sildeneset (Fig. 3, D:5-6), a mylonitic zone runs in a NNW direction out towards the sea. It is rich in quartz and muscovite, and has 1-3 centimeters large plagioclase and K-feldspar augens. It is rusty and often


Fig. 17. Photos taken on the western side of Gammeløya (Fig. 3, C:4), up in the photos is north, the right photo is taken just north of the left photo. In the left photo there are some decimetre thick amphibolitic layers with a steep dip, in the right photo there is ptygmatic folding of an amphibolitic layer. This indicates that the amphibolitic layers in the left photo is in fact one continuous, folded layer. This is possibly the innermost layer in the large fold at Sildeneset (Fig. 3, C-E:5-6).

has a yellow-green colour. Mylonite with yellow-green colour can also be seen east of Åshavn (Fig. 3, D-E:4) and at Kjære (Fig. 3, F:5). The mylonite at Kjære has 1 -3 centimeters large K-feldspar augens. The small mylonite east of Skålevig (Fig. 3, D:10) is more homogenous: It is fine grained; no megacrysts are observed. At Andås (Fig. 3, E-F:4), the mylonite follows the shore line. It is rusty and appears to consist mainly of quartz. East of Brattåsen (Fig. 3, H:5) a mylonite is well exposed along the shore (Fig. 19). It runs north-south, following the contact between amphibolitic gneiss and granitic gneiss. Garnet-rich zones are very common. In the contact between granitic gneiss and amphibolitic gneiss at Bestemorsmed (Fig. 3, H:6), a protomylonite is found which runs northeast-southwest.

3.3 Geothermobarometry

Three samples were used for the pressure-temperature estimations, their locations can be seen in the right corner of Fig. 20. The minerals used follow the foliation with the exception of garnet which is rounded. Grain boundaries are normally not straight but curved; amphibole and biotite are often slightly chloritized. Both these observations suggest that the equilibrium has been disturbed. On the other hand the analysed crystals are not zoned but seem to be chemically ho-

Fig. 18. Photo taken on Lindøy (Fig. 3, I:8). Competent amphibolitic layer has been boudinaged and dextrally sheared while the granitic gneiss is deformed ductilely.

Fig. 19. Photos taken at Brattåsen, H:5 (Fig. 3) where a mylonite zone runs north-south approximately following the granitic - amphibolitic gneiss contact.

mogeneous. The indications of a disturbed equilibrium make the results uncertain; the errors are larger than those caused by analytical errors and shortcomings in the thermo-barometer calibrations.

The geothermometer of Holdaway (2000) for the garnet - biotite system was calculated using Excel. Since the pressure has little influence on the composition, the estimated results are almost completely horizontal. From 0.3 to 1.5 GPa, the temperature decrease within the range of 0.001°. Obtained temperatures vary much among the samples, indicating that at least one of the minerals have been opened after the metamorphose. Especially the samples showing 839°C and 739°C are regarded too high. Both these results are from Sa-41. The other results range between 539°C and 667°C and are from Sa-430 and Sa-453 (Fig. 20). The obtained temperatures from Sa-430 are 571, 539 and 618°C and the temperatures from Sa-453 are 586, 609, 641, 665 and 667°C. The errors in the formula regarding the constants will give a uncertainty of ±25° C.

The hornblende-garnet-plagioclase (Dale et al., 2000) temperatures were calculated in a computer program offered by Tim Holland. All the temperatures are measured from Sa-453 (Fig. 20). The garnet-hornblende temperatures have a spread of approximately 100°C, and vary at from 450 to 548°C at 0 GPa, from 499 to 605°C at 1 Gpa and from 548 to 662°C at 2 GPa. The standard deviation is varying between ±26 and 32°C. The hornblende barometer (Dale et al., 2000) is an average value from the tremo-

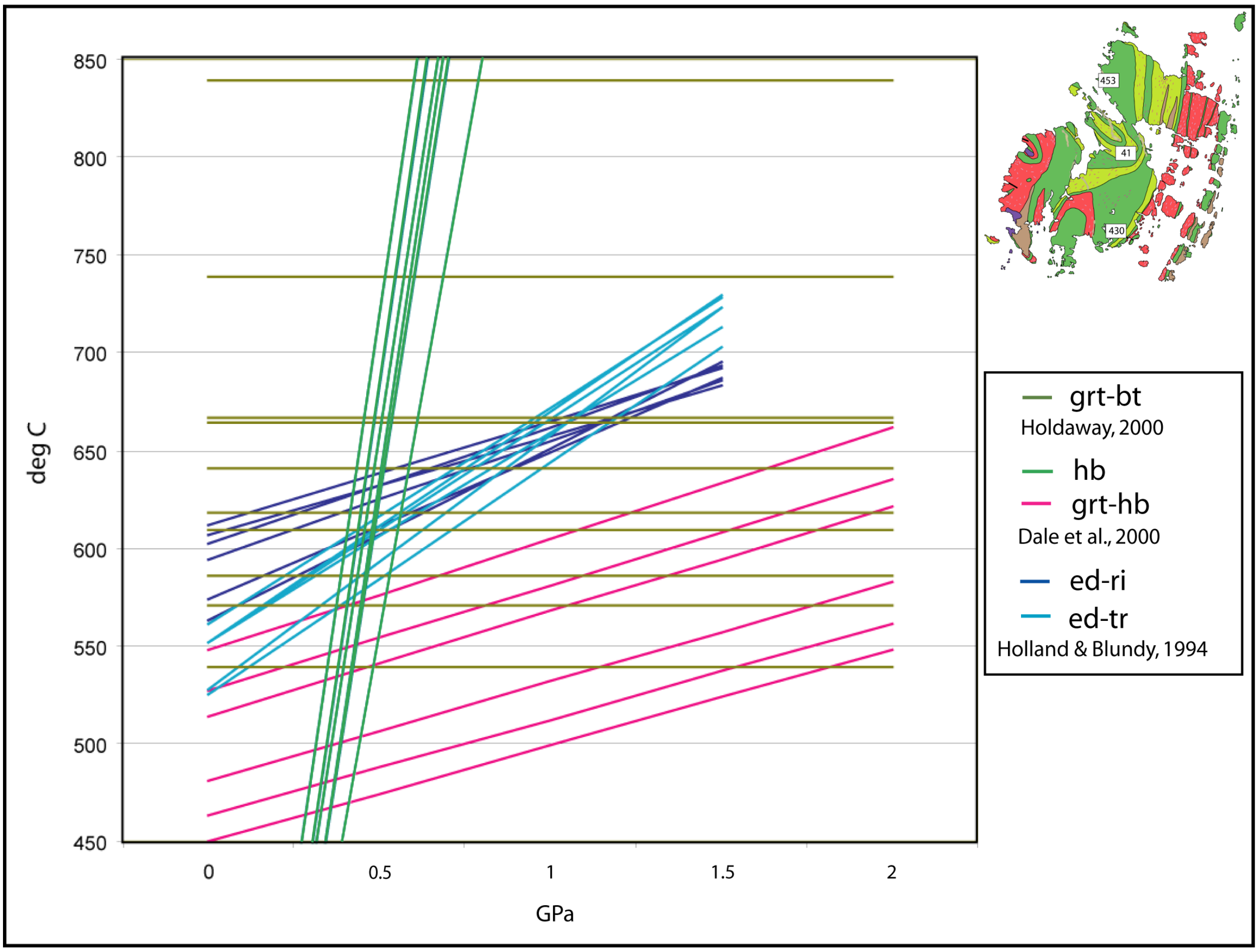

Fig. 20. Pressure and temperature estimations for the garnet-biotite thermometer of Holdaway (2000), the hornblende-garnet-plagioclase thermobarometer by Dale et al. (2000) and the amphibole-plagioclase thermobarometer by Holland and Blundy (1994).

lite – tschermakite, tremolite - K-pargasite and tremolite – glaucophane end member equilibrium. The temperature increases drastically with increasing pressure from 50-127°C at 0 GPa to 1047-1310°C at 1 GPa.

The thermometer from Holland and Blundy (1994) was also calculated in a computer program offered by Tim Holland. Sample 453 were used. The edenite - tremolite thermometer varies from 563-612° C at 0 kbar and from 683-695°C at 1.5 GPa. The edenite - richterite thermometer varies from 525-561° C at 0 Gpa and 703-729°C at 1.5 GPa. The errors are ±40°C.

In general, the hornblende crystals were chloritizated and anhedral to subhedral. The plagioclase were also slightly altered and anhedral. The garnet crystals were subhedral. Zoning was not detected in the used crystals.

The system has not remained closed. The results suggest that biotite is the mineral that has been mostly affected, however, probably all minerals are affected but to a lesser degree. Due to the uncertainties, these tentative results are regarded as approximate and are not claimed to represent the peak temperature and/or pressure.

3.4 Geochemistry

Five samples have been analyzed chemically. They represent five macroscopically different rocks. The localities for sampling are displayed in Fig. 21 and the results can be seen in Tables 1, 2 and 3. Sa-133 from Manneviga is made up of dolerite. Sa-444 was taken east of Kjerka and is a medium-grained amphibolitic rock. Sa-418 was taken at Høyfjellet and is fine-grained and rich in quartz. Sa-445 was taken in Steinviga and, although foliated, it looks more massive than the other amphibolites on the island. On Asperøya, interbedded in the main amphibolite, two amphibolitic lenses separated by approximately ten metres were found. The lenses follow the foliation and taper after some ten metres. Sa-434 was collected from the largest of these lenses. The main amphibolite is slightly lighter in colour than the lenses.

The samples were milled in a swing disc mill made from an alloy of Co and W. Due to the risk of contamination these elements were removed from the results. The elements that were analyzed with both XRF and ICP-MS show good agreement, indicating trustworthy measurements.

In the Kristiansand area, the bedrock consists of metasediments (eg marble and quartzite; Falkum, 1966), metavolcanic rocks (e.g. the amphibolite at Kinn, cf Fig. 3, A:10) and intrusive rocks (granite, dolerite and pegmatite). The metabasites at Flekkerøy might originate from either basalt, dolerite, gabbro or carbonate-rich clay. It is also possible that several of the mentioned types occur. An attempt to find possible origins was done by examining the relations among major and trace elements.

The normative calculations (Table 3) were done by assuming that 10 % of the iron is ferric. All the basites, except Sa-445, have normative quartz and are thus oversaturated. They are quartz-hypersthene normative rocks, whereas Sa-445 is olivine and hypersthene normative. Sa-418 and Sa-444 have normative corundum. Sa-133, Sa-434 and Sa-445 have normative minerals resembling basalt. Sa-418 has a normative mineralogy corresponding to granodiorite but with an extremely high anorthite content in its plagioclase. Sa-444 has, except it being corundum normative, a normative composition within the range of diorite (Le Maitre, 1976).

The primitive-mantle normalized spider diagram by Sun & McDonough (1989) (Fig. 22) has ele-

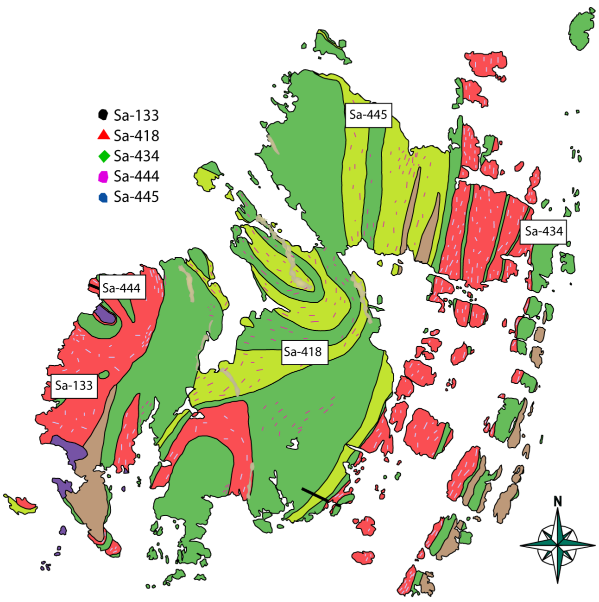

Fig. 21. Locations where the chemically analysed samples were collected.

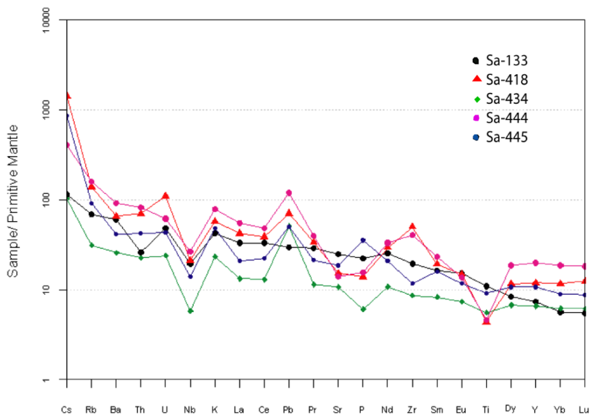

Fig. 22. The primitive-mantle normalized spider diagram by Sun & McDonough (1989).

Sample		Sa-133	Sa-418	Sa-434	Sa-444	Sa-445
SiO_2	%	51.19	66.63	51.51	58.18	49.18
Al_2O_3	%	16.20	13.60	13.88	16.45	17.72
Fe_2O_3	%	11.25	7.70	13.28	8.84	11.57
MnO	%	0.13	0.11	0.20	0.15	0.17
MgO	%	4.14	1.65	6.04	1.94	3.95
CaO	%	6.80	5.39	9.23	4.75	8.68
Na_2O	%	3.47	1.25	2.42	3.66	2.91
K_2O	%	1.26	1.71	0.70	2.34	1.45
TiO_2	%	2.38	0.94	1.19	1.00	1.98
P_2O_5	%	0.48	0.30	0.13	0.34	0.77
SO_3	%	0.18	b.d.	0.02	0.03	b.d.
H_2O^+	%	2.26	0.60	0.83	1.24	0.99
H_2O^-	%	0.14	0.15	0.20	0.22	0.20
SUM	%	99.88	100.04	99.64	99.15	99.57
Ba	ppm	420	448	174	645	296
Ce	ppm	46	51	25	73	40
Cr	ppm	16	b.d.	42	b.d.	b.d.
Cu	ppm	38	7	50	15	28
Ga	ppm	22	12	14	20	13
La	ppm	26	21	11	33	18
Nb	ppm	15	20	6	25	12
Nd	ppm	27	24	14	36	24
Ni	ppm	37	23	39	24	14
Pb	ppm	10	10	9	13	7
Rb	ppm	44	88	21	102	58
Sc	ppm	12	25	41	12	27
Sr	ppm	509	302	213	285	376
Th	ppm	5	7	b.d.	10	5
U	ppm	b.d.	3	b.d.	5	b.d.
V	ppm	165	26	277	66	121
Y	ppm	31	52	27	91	45
Zn	ppm	120	63	103	129	107
Zr	ppm	229	556	111	481	138

Table 1. XRF analysis, major element oxides in weight percent and trace elements in ppm. Total iron is reported as Fe_2O_3.

Sample		Sa-133	Sa-418	Sa-434	Sa-444	Sa-445
Ba	ppm	422.0	456.0	179.0	644.0	288.0
Be	ppm	1.0	2.0	<1.0	2.0	2.0
Cs	ppm	0.9	11.3	0.8	3.2	6.8
Ga	ppm	21.4	17.9	18.2	23.6	20.2
Hf	ppm	6.3	13.3	3.2	11.8	4.6
Nb	ppm	13.8	15.0	4.1	18.6	9.8
Rb	ppm	43.7	88.3	19.7	101.1	58.6
Sn	ppm	2.0	2.0	1.0	1.0	2.0
Sr	ppm	524.6	317.4	224.1	290.1	391.5
Ta	ppm	0.7	1.1	0.3	1.1	0.5
Th	ppm	2.2	5.9	1.9	7.0	3.6
U	ppm	1.0	2.3	0.5	1.3	0.9
V	ppm	171.0	30.0	287.0	67.0	126.0
Zr	ppm	216.2	555.5	96.0	452.8	130.3
Y	ppm	32.8	53.7	29.7	90.4	48.1
La	ppm	22.7	29.0	9.1	37.3	14.1
Ce	ppm	57.8	68.3	22.8	84.6	39.4
Nd	ppm	34.0	39.3	14.5	44.3	28.0
Eu	ppm	2.5	2.5	1.2	2.3	2.0
Gd	ppm	6.6	8.6	4.1	11.8	7.9
Tb	ppm	1.1	1.5	0.8	2.4	1.4
Dy	ppm	6.1	8.4	4.9	13.7	7.9
Ho	ppm	1.2	1.9	1.1	3.3	1.7
Er	ppm	3.1	5.6	3.0	9.7	4.8
Tm	ppm	0.5	0.9	0.5	1.4	0.7
Yb	ppm	2.8	5.7	3.0	9.1	4.4
Lu	ppm	0.4	0.9	0.5	1.4	0.6
Mo	ppm	0.2	0.7	0.1	1.0	0.3
Cu	ppm	44.7	5.8	87.5	12.3	10.5
Pb	ppm	2.1	5.0	3.6	8.4	3.6
Zn	ppm	98.0	72.0	28.0	118.0	50.0
Ni	ppm	34.4	13.5	22.1	10.3	0.9
As	ppm	0.6	<0.5	<0.5	<0.5	1.0
Cd	ppm	<0.1	<0.1	<0.1	0.1	<0.1
Sb	ppm	<0.1	<0.1	<0.1	<0.1	<0.1
Bi	ppm	0.1	0.1	<0.1	<0.1	0.2
Ag	ppm	<0.1	<0.1	<0.1	<0.1	<0.1
Au	ppb	1.1	18.4	1.8	<0.5	2.5
Hg	ppm	<0.1	<0.1	<0.1	<0.1	<0.1
Tl	ppm	<0.1	0.5	<0.1	0.3	0.2
Se	ppm	<0.5	0.6	0.7	<0.5	<0.5

Table 2. Trace elements in ppm analyzed with ICP-MS (Au in ppb).

	Sa-133	Sa-418	Sa-434	Sa-444	Sa-445
Q	2.5	35.3	2.9	10.8	0
C	0	0.6	0	0.1	0
Or	7.5	10.1	4.1	13.8	8.6
Ab	29.4	10.6	20.5	31	24.6
An	24.9	24.8	24.9	21.3	31
Di	4.7	0	16.6	0	5.9
Hy	20.1	13.6	23.9	15.9	19.6
Ol	0	0	0	0	0.5
Mt	1.6	1.1	1.9	1.3	1.7
Il	4.5	1.8	2.3	1.9	3.8
Ap	1.1	0.7	0.3	0.8	1.8
sum	96.3	98.6	97.4	96.9	97.4

Table 3. The results of CIPW norm calculations.

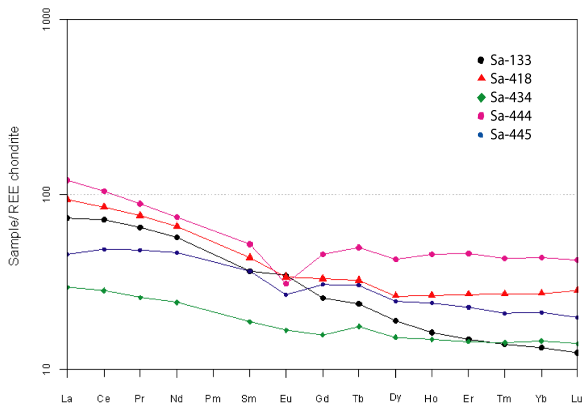

Fig. 23. Chondrite normalized REE diagram by Boynton (1984).

	La_N/Lu_N	La_N/Sm_N	Gd_N/Lu_N	Eu_N/Eu^*
Sa-133	5.90	2.00	1.90	1.13
Sa-418	3.31	2.15	1.14	0.89
Sa-434	2.10	1.57	1.25	0.98
Sa-444	2.87	2.31	1.18	0.63
Sa-445	2.29	1.25	1.52	0.80

Table 4. The differentiation of the REE elements in the REE diagram by Boynton (1984). Eu* is $(Sm_N+Gd_N)/2$.

ments with increasing compatibility towards the right. To the left, mobile elements are plotted. The mobile LIL elements (Cs, Rb and Ba) are strongly enriched in the samples, especially Cs in Sa-418, Sa-444 and Sa-445. Sr and Eu, however, are less enriched. All the samples have a clear negative Nb anomaly, which is characteristic for continental crust or involvement of a crustal component in the magmatic process. Sa-418 and Sa-444 have positive Zr anomalies. There is a positive Pb anomaly for all the samples except the dolerite. In this type of diagrams, MORB plots as a smooth curve, depleted in incompatible elements and enriched in compatibles. This is opposite to the obtained patterns.

The chondrite-normalized REE diagram (Fig. 23; Boynton, 1984) shows a small differentiation between the light and the heavy REEs (Table 4). Sa-133 is the most differentiated sample. The LREEs are more differentiated than the HREEs, for all samples except Sa-445. The samples Sa-418, Sa-434 and Sa-444 show barely any differentiation in the HREE at all. All the curves are smooth. Sa-444 and Sa-445 have a small negative Eu-anomaly and Sa-133 has a small positive Eu-anomaly (Fig. 23).

The trace elements were compared to upper continental crust (Taylor & McLennan, 1981), average continental crust and lower continental crust (Weaver & Tarney, 1984), ocean island basalts (OIB; Sun, 1980), North American shale composite (NASC; Gromet et al., 1984) and mid-ocean ridge basalt (MORB; Sauders & Tarney, 1984; Sun, 1980). Sa-418 and Sa-444 most often resemble upper continental crust, Sa-133 and Sa-445 resembles average continental crust and Sa-434 most often resembles lower continental crust.

4 Discussion

The different metabasites show large variations in the field. However, the chemical compositions were not expected to vary to such an extent as seen in the results (Table 1, 2 and 3). What is more surprising is that the major elements for Sa-418 and Sa-444 and the trace elements for all the samples show similarities with the continental crust, which has a granodioritic composition rather than a basaltic. The possible origins are as mentioned, crustal contaminated basalt, dolerite or gabbro, or calcareous clay. After formation, the rocks have recrystallized and been folded during several deformational stages. Metasomatose has, to an unknown extent, changed the chemistry.

4.1 Structures

The foliations show three large-scale folds. The fold at Sildeneset and the fold at Kjerka (Fig. 3, D,E:5,6 and E:3) have approximately parallel axial traces. The fold at Brattåsen (Fig. 3, G,H:4,5), which can also be seen in the map of the Norwegian Geological Survey, NGU (Falkum, 1982), has a fold axis which is almost perpendicular to the two former ones. When two compressive stress orientations act perpendicular to each other, dome and basin structures are formed. It is possible that Brattåsen is a dome structure and Kjerka and Sildeneset are basin structures. Since the stress angles are not completely perpendicular, the structures that could be expected are between dome and basin and mushroom structures. The eastern part of the island shows an almost homogenous foliation, striking south-southwest and the form suggest it to be a fold limb on a large scale fold hidden by the sea. Another possibility is that the eastern part of the island is isoclinally folded, even though none of the fold hinges have been found.

The lineations on Flekkerøy are similar to those on Kinn (Falkum, 1969) with a general trend towards northwest but with a large spread approximately following a great circle. Falkum interpreted this pattern to prove that the lineation formed first and then followed by cylindrical folding. The lineations on Flekkerøy support this theory.

Starmer (1991) has found evidence for seven different deformational episodes in the Bamble terrane together with six episodes of mylonitisation; the last deformation and folding occurred between 1 and 0.95 Ga. This folding episode led to northwest-southeast trending folds. The fold at Kjerka and Sildeneset may originate from this episode. Parasitic folds which can be found over most parts of the island also show this direction of the fold axes. The antiform at Brattåsen has approximately the same fold axis as the Tveit antiform (Fig. 2) and both plunges towards north-northeast. According to Starmer (1991) the folding of the Tveit antiform occurred slightly before the last deformational phase; both of them belong to the main collisional stage of the Sveconorwegain orogeny. When Bamble was thrusted onto Telemarkia, during the Arendal phase, 1.14-1.08 Ga, a NW-directed shortening took place (Kullerud & Dahlgren, 1993; Bingen et al., 1998; Henderson & Ihlen, 2004). The fold at Brattåsen might originate from this episode. The Agder phase, from 1.05 to 0.98 Ga, was when the main collision took place. Baltica collided with an unknown continent coming from southwest, leading to a northeast-directed shortening (Bingen et al., 2006). This episode might be responsible for the synforms at Kjerka and Sildeneset.

Minerals	Closure
Grossular	980°C
Almandine	890°C
Pyrope	730°C
Biotite	520°C
Hornblende	400°C

Table 5. Approximate closure temperatures for some of the used minerals (Best, 2003).

4.2 Thermobarometry

In general, the Telemark sector has undergone amphibolite facies metamorphism whereas the Bamble terrane shows higher grades of metamorphism, from upper amphibolite facies along the Porsgrunn-Kristiansand Fault and Shear Zone, to granulite facies in the southeastern part. Several termobarometer studies have been made on the high grade areas of Bamble. Knudsen (1996) calculated the main metamorphism to be 0.59-0.91 GPa and 790-884˚C. Harlov (2000a; 2000b) estimated the temperature to be 793 ±58°C and 791°C and the pressure to 0.71±0.09 GPa and 0.7±0.11 GPa.

A source of error for thermobarometry is that minerals have different closure temperatures for element diffusion (Table 5). In the garnet-biotite termobarometer, the grains used were in contact with each other. However, in the hornblende-garnet-plagioclase thermobarometer it was difficult to find triple-point grains. Therefore the grains that were used were often only in contact with one of the other minerals and might not have been in equilibrium. This might have led to larger spread in the results. The garnet-biotite geothermometer is considered to have the largest errors due to chloritization of the biotite. The results vary with 300°C. Some hornblende grains are also altered to chlorite. The garnet-hornblende thermobarometer varies with 100°C between the different samples, which might be due to chloritization of hornblende. Since both the thermobarometers using garnet have a large spread, it is likely that the garnet has opened after the metamorphism. The chloritization of the biotite can be seen as thin lamellae. Both the biotite and the garnet crystals are subhedral.

When trusting the hornblende curves from Dale et al. (2000) and the hornblende-plagioclase curves from Holland and Blundy (1994), a temperature interval of 620 ± 40°C and a pressure interval of 0.6 ± 0.2 GPa is obtained. These curves have the smallest spread of the obtained results. This probably reflect the retrograde metamorphism and not the peak. The estimated pressure and temperature does not have to represent the exact same age. The conclusion that can be drawn is that the rocks on Flekkerøy have experienced amphibolite facies metamorphism.

4.3 Geochemistry

The charge/radius ratio and the ionic potential decide the behavior of an element during a metamorphic or metasomatic event. Elements that form ions with a low ionic potential might be removed in solution, elements that form ions with a high ionic potential might be removed as hydrated oxy-ion complexes. Ions with an intermediate ionic potential remain in the solid product and are therefore rather immobile elements. This means that the HFS elements like Zr, Hf, Nb, Ta, Y, Ti, Cr, the REEs apart from Eu and possibly La, Th, Ga and Sc are the most immobile and maintain the same ratios as that of the source. But if the hydrothermal fluid is rich in CO_2 or SiO_2, these elements might also be mobilized (Hastie et al., 2007). Sr, K, Rb, Ba and to a less extent Cs and Eu are the most mobile elements and will in metasomatic rocks show how the fluid has interacted with the rock.

The numerous pegmatite dykes and the contacts between different rock types might have acted as pathways for volatiles. Since there are not many homogenous, large rock bodies present, one must expect that metasomatism can have changed the composition of most of the rocks on the island.

A plot of the concentration of Rb against K reveals a strong linear correlation with a ‘goodness of fit’ value of 0.93; even the dolerite reinforces this trend (Fig. 24). This is surprising since the chemical composition vary much among the samples. The correlation is either merely reflecting an original correlation or the correlation was strengthened during metasomatism. According to Alirezaei & Cameron (2002) the transition of gabbros into amphibolites in the Bamble terrane led to enrichment in LILE, especially K, Rb and Ba, whereas the transition metals, REE and HFSE

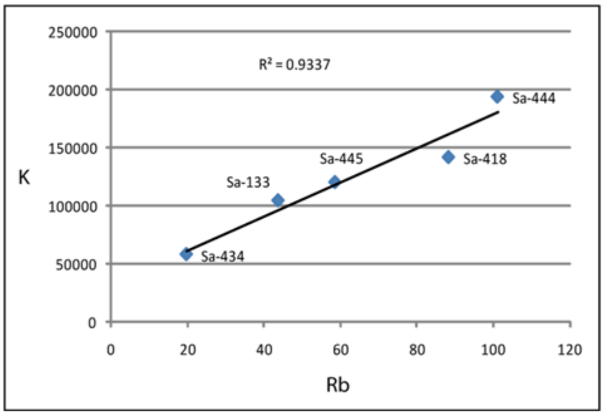

Fig. 24. Rb and K concentrations in ppm are plotted, showing a strong correlation.

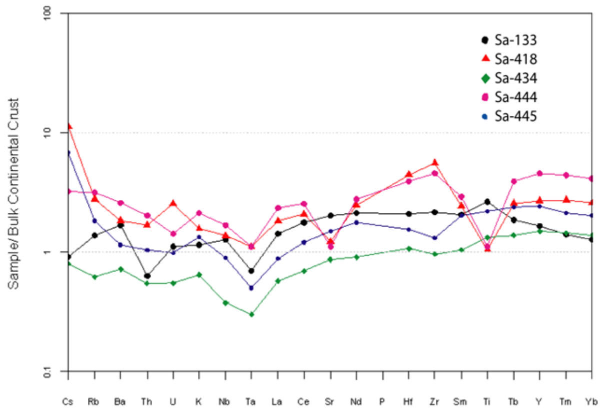

Fig. 25. The bulk continental crust normalized diagram of Taylor & McLennan (1995).

remained constant. K and Rb have therefore probably been mobilized during metasomatism, and enrichments or depletion in these elements in the different amphibolites are now reduced and evened out.

The samples remain within one magnitude from the composition of bulk continental crust (Fig. 25; Taylor & McLennan, 1995). Basites have lower amounts of the incompatible elements to the left in the diagram and are enriched compared to bulk continental crust in the compatibles to the right. What has in this paper been classified as metabasites on Flekkerøy does not have a trace element distribution similar to basites.

Field relations and microscope studies prove that Sa-133 is without doubt a metadolerite. The mineral composition with mainly plagioclase and hornblende and some titanite, biotite and K-feldspar gives proof of hydration and amphibolite facies metamorphism. The dolerite is, however, not foliated (cf Fig. 26). According to Starmer (1991) the last deformation

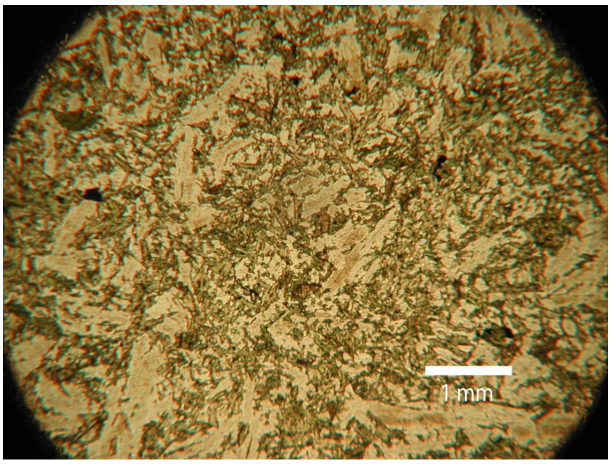

Fig. 26. Plane polarized microscope photo of the dolerite showing ophitic texture. Green grains are hornblende, colourless grains are feldspars and brown, small grains are titanite. The mineral assemblage indicates recrystallization but no foliation has been formed.

and folding in Bamble occurred between 1 and 0.95 Ga. The dolerite has most likely intruded after the last deformational episode and before the retrograde metamorphism was finished. Perhaps the stress release in the relaxation phase led to fractures where dolerites could intrude. Falkum & Petersen (1980) report dolerite dikes running west-northwest in southern Norway which intruded around 0.8 Ga, but this is probably too late for amphibolite facies metamorphism. The trace element distribution and the Mg/Fe ratio indicates that fractionation, crustal contamination and/or metasomatose has changed the composition of the dolerite. The thin amphibolites found in the granitic gneiss in the eastern part of the island is probably also dolerites, but since they are folded and have strongly deformed contacts to the host rock (Fig. 9), they have probably intruded before or during early stages of the Sveconorwegian orogeny.

Sa-434 and Sa-445 follow each other quite well in the trace element diagrams but the normative minerals differ. Sa-434 has normative quartz and Sa-445 has normative diopside and olivine. Sa-445 is the only sample with a basic composition according to Peccerillo and Taylor (1976); Sa-434 has an intermediate composition. When comparing trace elements to upper, lower and average continental crust and NASC, MORB and OIB, Sa-434 most often show similarities to lower continental crust whereas Sa-445 more often resembles average continental crust. Sa-445 is medium -grained and has a massive appearance; therefore an intrusive origin as a small gabbro stock with some crustal contamination seems likely. It is unknown whether this amphibolite is a rounded body or if it is part of an elongated, larger amphibolite body, as is shown on the bedrock map (Fig. 3). Sa-434 is an amphibolitic lens in amphibolitic gneiss. A chemical analysis of the host amphibolite was not conducted, but using the microscope the amphibole content in the amphibolitic lens was estimated to 60 % and in the host amphibolite to only approximately 25 %. Under the polarizing microscope, Sa-434 closely resembles Sa-431 taken at Kinn (Fig. 9 and 10) although the grain size in Sa-434 is slightly finer. Falkum (1969) analyzed the amphibolites at Kinn, and when comparing his results with Sa-434, they are found to be similar. The similarities and the short distance between them might indicate that they have the same volcanic origin.

Sa-418 and Sa-444 have similar patterns in the spider diagrams and REE diagram but Sa-418 has a much higher amount of normative quartz; 35.3 % whereas Sa-444 has 10.8 %. They both have normative corundum, which should not be found in unaltered basite, Sa-418 has 0.6 % and Sa-444 has 0.1 %. If high amounts of alkalis were removed during metasomatism, the amount of normative orthoclase and albite would be smaller. This would give rise to excess Al and normative corundum. The amount of Na and K is, however, high when compared to average basalt. This explanation for the normative corundum would indicate an even higher original content of alkalis. Another possibility is that there has been crustal contamination of the magma. A hypothesis for the formation of norite is that olivine gabbro gets contaminated with continental crust and instead of normative clinopyroxene and wollastonite, norite has normative orthopyroxene and in some cases corundum (Chai & Eckstrand, 1994). This hypothesis can be supported by the immobile trace elements which when comparing with upper and lower continental crust, most often resemble upper continental crust. Starmer (1991) reports numerous suites of leucogabbro, olivine gabbro, gabbro, norite, diorite, syenodiorite, mangerite, granodiorite and monzogranite that intruded in the Bamble terrane before the Sveconorwegian orogeny. He also reports gabbro and norite intruding during the early collisional stage of the Sveconorwegian orogeny where there are several fractions within a single suite. A crustal contamination of a basic magma seems most likely for Sa-444, which also is medium-grained.

Amphibolite can originate from dolomitic or calcareous clay. Thin marble horizons can be found on the mainland, suggesting this to be a viable possibility. The REE patterns in amphibolites with a sedimentary origin will reflect the provenance of the clay and be diluted by the carbonate. A sedimentary origin would explain the banding and the transitional zones that are often found where one rock type gradually changes into another. When using NASC as an example of the clay composition, the amount of carbonate would have to be very small to fit the samples from Flekkerøy, unless later metasomatism has exhausted the rocks in immobile Mg and less immobile Ca. Sa-418 is however not so rich in hornblende and would not require a high percentage of carbonate to form the hornblende present. It is fine-grained and varies strongly over some metres distance. The sample did not contain any garnet but garnet was abundant in the other amphibolites found at the location. It is likely that it would be better to map this as meta-greywacke, containing hornblende. A sedimentary origin seems most likely for Sa-418.

The banding is not a proof of sedimentary origin, because it can have been formed or has at least been accentuated by tectonic activity like shearing, thinning and isoclinal folding (Leake, 1964). Parallel dykes intruded in the host rock will also give banding and the same goes for volcanic eruptions with varying compositions. Though discordant contacts have not been detected, they might well exist or have existed before transposing.

Further work to determine the origin of the amphibolites should include isotope studies of, for example, O, Sr and Nd which show different evolution in the crust compared to the mantle. More detailed studies of the structures and field relations could possibly indicate origins; for example agglomerates, discordant contacts, etc.

5 Conclusions

- Flekkerøy consists to a large extent of dark gneisses with varying composition, consisting mainly of plagioclase, hornblende, titanite ± quartz, biotite, K-feldspar and garnet.
- There are at least three map-scale folds and two axial plane directions (NW and NNE) on Flekkerøy.
- The lineations display a spread that roughly follows a great circle, indicating at least one episode of deformation after their formation.
- The mylonitic zones generally trend NNW, cutting the direction of the foliation. Therefore the mylonites have been formed after the NW-trending folds.
- The pressure-temperature estimations agree with former studies saying that the area has experienced amphibolite facies metamorphism.
- The metasomatose has changed the chemical composition of mobile elements and presumably also other elements (exemplified with Rb and K).

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