Geology of the Minor Bergen Arc, West Norway

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Detailed mapping of the Minor Bergen Arc has revealed the presence of a variety of highly deformed rocks of different origin and age. Three rock units have been separated and named. The Nordåsvatn Complex comprises deformed and metamorphosed sedimentary and igneous rocks which resemble a dismembered ophiolite complex and related rocks. The Storetveit Group represents a clastic cover sequence to the ophiolitic rocks and is correlated with the Late Ordovician-Early Silurian Holdhus Group in the Major Bergen Arc. The Gamlehaugen Complex comprises slices of Precambrian gneisses and quartz-rich metasediments of unknown age, interpreted as a detached and sheared continental basement-cover couplet. Intense deformation (D2) of all rocks under metamorphic conditions close to the greenschist-amphibolite facies transition is ascribed to the Late Silurian-Early Devonian Scandian event, and mapping has shown that extensive basement-involved imbrication accompanied the deformation. Pre-Scandian deformation structures (D1) may be present and there are indications that an early, greenschist-facies metamorphic event has affected the ophiolitic rocks.

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Introduction

The Minor Bergen Arc is located in and near the city of Bergen, West Norway, in the Bergen Arc System (Kolderup & Kolderup 1940). The Bergen Arc System is composed of five arcuate tectonic units (Fig. 1) which differ in terms of tectonometamorphic development as well as in lithology. The units are termed, from west to east, the Øygarden Complex, the Minor Bergen Arc (MiBA), the Ulriken Gneiss Complex (UGC), the Anorthosite Complex and the Major Bergen Arc (MaBA).

The Øygarden Complex consists of Precambrian (Sturt et al. 1975) igneous rocks and migmatites which suffered strong, Caledonian, ductile reworking with the formation of a gneissic (blastomylonitic) L-S fabric (Bering 1984). An early Caledonian(?) tectonometamorphic episode involved non-coaxial deformation with movement towards the west (Fossen & Rykkelid 1988), prior to the main Caledonian or Scandian (Gee 1975) thrusting to the east. The Øygarden Complex has a mylonitic contact with rocks of the MiBA which again has a tectonic contact with the Precambrian UGC (Fossen 1988a). The psammitic metasediments of the possible Late Proterozoic Rundemanen Formation are preserved along three major Caledonian shear zones in the UGC. Both the metasediments and the UGC have experienced inhomogeneous Caledonian strains (Fossen 1986, Holst & Fossen 1987) under

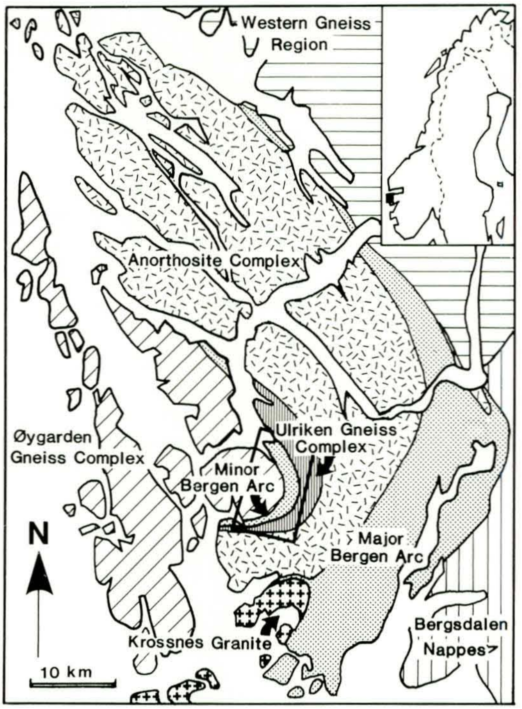

Fig. 1. Geological units in the Bergen area.

greenschist-facies metamorphic conditions. The Anorthosite Complex comprises Precambrian anorthositic, charnockitic, mangeritic, dioritic, noritic, gabbroic, ultramafic, migmatitic and minor metasedimentary rocks, most of which were metamorphosed under granulite facies in Sveconorwegian times (Austrheim 1978). The Caledonian reworking of this complex locally started with high-pressure, eclogite-facies, shear deformation and advanced to retrograde amphibolite-facies and greenschist-facies movements (Austrheim & Griffin 1985, Austrheim 1987). Both the Precambrian and the Caledonian tectonometamorphic development contrasts with the development in the UGC to the west, and the MaBA to the east.

In the Major Bergen Arc, Lower Palaeozoic rocks are imbricated and locally separated by slivers of strongly reworked Precambrian gneisses (Færseth et al. 1977). The Lower Palaeozoic rocks comprise the Gulfjellet Ophiolite Complex (Thon 1985a) and its volcano-sedimentary cap (chert-lutite, mica schists, pillow lava, etc.), its unconformably overlying sedimentary cover (the Holdhus and Ulven Groups), and the Samnanger Complex which embraces mica schists, tectonic melanges, quartzites and fragments of ophiolitic rocks separated by slivers of mylonitic gneiss. In addition, granitic intrusions occur, of which the youngest and largest, the Krossnes Granite (Fossen & Ingdahl 1987), has been Rb-Sr-dated to 430 ± 6 Ma (Fossen & Austrheim 1988). A plagiogranite differentiate from the Gulfjellet Ophiolite has been dated (U-Pb, zircon) at 489 ± 3 Ma, and a tonalitic island-arc type intrusion at 482+6/-4 Ma (Dunning & Pedersen 1988). The lower part of the Holdhus Group contains an Ashgill fauna (Kolderup & Kolderup 1940), and the higher part of the Ulven Group a Lower Llandovery fauna (Reusch 1882, Ryan & Skevington 1976).

The scope of this paper is to separate the rocks of the Minor Bergen Arc into lithostratigraphic units, and to present a description of the various rock types and their tectonometamorphic development.

The Minor Bergen Arc

The rocks of the Minor Bergen Arc (MiBA) show many similarities to rocks of the Major Bergen Arc (MaBA), but the strain is generally higher in the MiBA and thus primary features are more obscured. Part of the MiBA was described by Reusch & Kolderup (1902) and Kolderup & Moncton (1911) who interpreted the rocks as altered gabbros, minor volcanics (hornblende schists) and pelitic and psammitic metasediments, in addition to granitic gneisses of magmatic origin. Kolderup & Kolderup (1940) also mentioned a green conglomerate and marble, both strongly deformed, which they correlated with similar-looking Upper Ordovician metasediments in the southern part of the MaBA.

The rocks are now subdivided into three complexes, based on lithological differences and field occurrences. The *Nordåsvatn Complex* comprises metasedimentary and meta-igneous rocks, the *Storetveit Group* is a metasedimentary cover to rocks of the Nordåsvatn Complex, and the *Gamlehaugen Complex*, comprising mylonitic gneisses and quartzites, may represent a strongly deformed continental basement-cover couplet.

The Nordåsvatn Complex

The Nordåsvatn Complex comprises a heterogeneous complex of polyphasally deformed amphibolites and trondhjemites (generally meta-igneous rocks) and mafic mica schists (metasediments).

Mica schists

The mica schists constitute a major heterogeneous, mappable unit within the MiBA. A polyphasal structural history is evident, and flattened pods of vein-quartz, rodded vein-quartz and dykes are transposed into the composite L-S fabric. The mylonitic nature of the mica schists is recognized by a well-developed S or L-S fabric, grain-size reduction, syn-kinematic mineral growth and several sets of foliations (S-C structures; cf. Lister & Snoke 1984).

Garnet-amphibole-mica schists (Fig. 2) account for the major part of mica schists in the Nordåsvatn Complex. Garnet and amphibole may be present in concentrations up to 25% each. Amphiboles are usually parallel-aligned, but garben textures are locally found. Some garnets and amphiboles show indications of syn-kinematic growth. Calcareous layers or zones are common in the garnet-amphibole-mica schists. Meta-cherts form white to pink bands a few cm thick, intercalated with amphibole-rich layers. Impure parts of the cherts contain bands rich in small spessartine-rich garnets (Fig. 3) and magnetite.

Fig. 2. Mica schist of the Nordåsvatn Complex, Kyrkjetangen (Plate 1). Note shear bands indicating sinistral shear (overthrusting to the east).

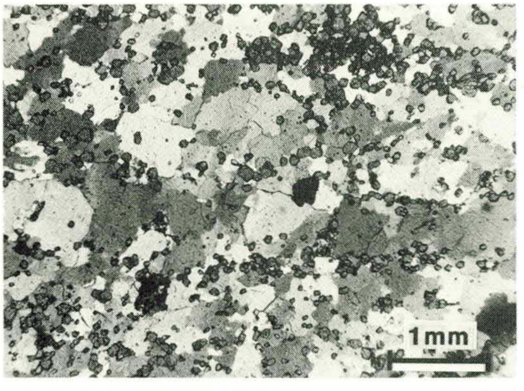

Fig. 3. Bands of small spessartine-rich garnets in impure chert layer, Nordåsvatn Complex, southern part of Marmorøyen (Plate 1).

Fig. 4. Tectonic clast of greenstone in tectonic melange, Nordåsvatn Complex, Kyrkjetangen. The greenstone is foliated, folded and refolded, being enveloped by the foliation in the mica schist matrix.

Tectonic melange

A tectonic melange locally occurs where the garnet-amphibole-mica schists contain fragments of adjacent rock-types. Tectonic clasts are seen at outcrop-scale, generally chaotically scattered. The melange is best exposed in the Marmorøyen area, at Kyrkjetangen (Plate 1) and at Bjorøy (SW of Plate 1).

The size of the fragments within the mica schists ranges from a few cm to several m. The fragments are mostly amphibolites and greenschists and locally saussurite gabbro and metasediments. Most fragments contain an internal foliation oblique to the external foliation which wraps around the fragments (Fig. 4). The greenschist/amphibolite fragments occasionally show complex internal structures, such as refolded foliations, while the foliation in the mica schist matrix envelops the clasts (Fig. 4). The tectonic nature of the melange is also indicated by the occurrence of fragments which can be shown to be boudins and isolated fold hinges.

Meta-igneous rocks

The meta-igneous rocks of the Nordåsvatn Complex are dominated by mafic rocks, generally amphibolitic varieties, and constitute nearly one half of the Complex. Trondhjemitic bands and serpentinites occur in smaller amounts within the amphibolites and mica schists.

Mafic rocks (amphibolites)

Amphibolitic rocks occur in linear zones or belts of 1m to some 100m in thickness. The rocks are generally in contact with the mica schists, but also with mylonitic rocks of the Gamlehaugen Complex (Plate 1). The zones thin out along strike or interfinger with the mica schists. The amphibolitic rocks have a pervasive foliation and nematoblastic textures, whilst primary igneous textures or relationships are scarce. In the field, the amphibolitic rocks may be separated into fine- and coarse-grained varieties.

Metre- or decimetre-thick, fine-grained amphibolites are generally interpreted as deformed and metamorphosed basic dykes and sills, or lava flows. Magmatic cross-cutting relationships have been obliterated due to high strains and transposition. Fine-grained amphibolites may also be mylonitized gabbros, and in that case porphyroclasts of larger amphiboles are

Fig. 5. Metagabbro with compositional layering interpreted as primary layering, preserved between zones of highly strained (mylonitic) gabbro. Nordåsvatn Complex, west of Paradis (Plate 1).

commonly found. Some bands and lenses of greenstones are found which probably represent metavolcanites. The greenstones contain epidote nodules up to several cm in diameter. Amphibole is commonly present in the greenstones, but epidote and saussuritized plagioclase dominate. Coarse-grained amphibolites are interpreted as deformed saussurite gabbros, except where the large amphiboles clearly are syn- to post-kinematic. The primary sub-ophitic gabbro texture is locally preserved, but primary pyroxenes are not found. The gabbro complex, made up of isotropic gabbro, layered gabbro and gabbroic dykes and gabbro pegmatites, is best preserved in the Gamlehaugen-Marmorøyen area (Plate 1). Primary layering occurs locally (Fig. 5), flaser gabbros are common, and locally the gabbros are altered to more fine-grained amphibolites.

Granitoids

Leucocratic bands, most of them milky white, are common in the amphibolitic rocks and occur to some extent also in the mica schists. The bands may vary from some mm up to a few metres across. Modal analyses (Fossen 1986) indicate a trondhjemitic composition, but a few bands contain K-feldspar and are thus more granitic. Many of the bands may be traced continuously for several tens or hundreds of metres, and show mylonitic fabrics. The plagioclase is generally near An_{20}, but saussuritization indicates a higher primary Ca content. While quartz has recrystallized completely, some plagioclase porphyroclasts may show primary twinning.

Ultramafic rocks

Partly or completely serpentinized ultramafic rocks are found as small bodies within mica schists or saussurite gabbros in the Nordåsvatn Complex (Kolderup & Kolderup 1940). Small bodies are altered to talc schist, while the largest (50m broad) body in Bergviken (Plate 1) contains olivine grains which are partly altered to serpentine minerals.

Interpretation of the Nordåsvatn Complex

The mica schists of the Nordåsvatn Complex are generally thought to represent metasediments (pelites and semipelites). Most of the mica schists are mafic, with abundant amphibole. This indicates a mafic provenance, like the meta-igneous rocks of the Nordåsvatn Complex. Deposition in an area influenced by mafic volcanic activity is shown by the presence of intercalated greenstones and fine-grained amphibolites. Meta-chert, magnetite- and Mn-rich metasediments and possible amphibole-rich metasediments are recorded. Similar metasediments are well known from dismembered ophiolite fragments in western Norway, e.g. from the Torvestad Group (Solli 1981) and from the Gulfjellet Ophiolite (Ingdahl 1985, Thon 1985a, Fossen & Ingdahl 1987), as well as from other ophiolites. Hence, mica schists of the Nordåsvatn Complex show similarities with metasediments in the upper part of an ophiolite pseudo-stratigraphy.

The tectonic melange is interpreted as a product of boudinage, transposition, repeated folding and subsequent shearing of a layered sedimentary and igneous complex during D2 (Scandian). The possibility that the melange originally was an olistostrome cannot, however, be totally ruled out. Similar rocks and structures have been described from the Os area (Ingdahl 1985), the Osterøy area (Henriksen 1979, fig. 38-39) and the Lindås area (Bøe 1978) in the MaBA, where they also are interpreted to have developed during the Scandian orogenic phase. The amphibolitic rocks are interpreted as deformed and altered basaltic lavas, gabbroic plutonic rocks and basaltic/gabbroic dykes. Elements of an ophiolite pseudo-stratigraphy are found, e.g. the (dismembered) ultramafic zone (ultramafic bodies), the gabbroic zone and the lava zone. Sheeted dyke complexes are probably also present. The mafic mica schists and intercalated volcanic rocks most likely represent the upper part of an ophiolite pseudo-stratigraphy, whereas the trondhjemitic/granitoid dykes may correspond to oceanic plagiogranites or island-arc type intrusion of similar type as in the Gulfjellet Ophiolite Complex (Furnes et al. 1982).

Chemical analyses from the Nordåsvatn Complex are scarce, but some greenstones (metabasalts) from Natlandsfjellet (Plate 1) have been analyzed for REE's by Furnes et al. (1982). The REE patterns are comparable with those from the Gulfjellet Ophiolite Complex (Thon 1985a), suggesting an influence of island-arc magmatism. The effect of the intense recrystallization, metamorphism and deformation on the geochemical results is not known (e.g. Furnes et al. 1982) and the data should be interpreted with care. However, the lithological similarities with rocks of the Gulfjellet Ophiolite Complex are striking, and an interpretation of at least most of the rocks of the Nordåsvatn Complex as representing a strongly dismembered ophiolite complex is favoured.

The Storetveit Group

In the MiBA the rocks of the Storetveit Group occur as a thin (‹100m), continuous zone within the Nordåsvatn Complex. The best outcrops are found in the Nordåsvatn area (Plate 1), but Quaternary and Recent cover makes it impossible to trace the zone to the north and northwest (Plate 1). The Storetveit Group consists of two formations, the Paradis Formation (green conglomerate) and the Marmorøyen Formation (marble). The rocks of the Marmorøyen Formation always occur in association with the Paradis Formation, while the latter in some cases occurs alone.

The Paradis Formation

This formation comprises a major part of the Storetveit Group, and consists of green, polymict conglomerate. The conglomerate is always strongly deformed, and the foliation is commonly seen to be tightly folded (Fig. 6) and locally refolded. At Marmorøyen (Plate 1) the formation reaches its maximum structural thickness of 50 m, but the high strains indicate that the primary thickness may have been considerably different from that observed today.

Fig. 6. The conglomerate of the Paradis Formation, Storetveit Group. The pebbles were strongly deformed by D2 strains prior to being folded during D3. Axial planes of F3 folds dip gently to the right (east). South of Paradis (Plate 1).

The conglomerate generally appears to be clast supported, although amphibolitic clasts may be difficult to distinguish from the amphibole-rich matrix. Some of the less-deformed pebbles show sub-angular shapes, but the initial shape is usually obscured. The grainsize varies from 1 mm up to 30cm (long axes), with pebble sizes dominating. There are three common types of pebbles in the Paradis Formation: (a) Granitoid clasts, commonly trondhjemitic. These form the largest clasts, and are easily recognized by their white colour. Oblate shapes are common, being oriented parallel with the foliation although the shape may vary. (b) Light green epidote-rock clasts. As they are more competent than the matrix, these clasts are enveloped by the foliation. Greenstones rich in epidote-nodules are the probable source rocks for the epidote clasts. (c) Amphibolitic clasts. These clasts, together with the amphibole-rich matrix, give the conglomerate a general dark green colour. The amphibolitic clasts are the least competent ones, and were deformed along with the matrix. Both the amphiboles in the matrix and those within the clasts are metamorphic (syn- to post-M2).

In some places blocks of amphibolite occur in the conglomerate (Fig. 7). The blocks may have been tectonically emplaced, but more likely they represent primary clasts. Bedding has not been found within the conglomerate. Lack of bedding, indications of angular clasts, the poor sorting or absence of such, and the probable presence of large blocks indicate a short transport, probably related to deposition in a tectonically active area.

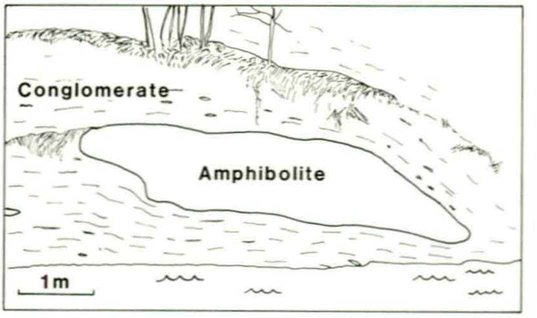

Fig. 7. Block of amphibolite in conglomerate, Paradis Formation, Storetveit Group. East of Marmorøyen (Plate 1).

The Marmorøyen Formation

This formation consists of a metamorphosed and strongly deformed limestone (marble) and a calcareous garnet-amphibole-mica schist which occurs in contact with the marble. In most places the marble is less than 2m thick; at Marmorøyen, however, it is 35-40 m in thickness. The marble is tectonically repeated, and the unusual thickness at Marmorøyen is probably due to its location in the hinge-zone of an isoclinal fold. The marble generally displays tones of dark grey to white, but also shows pinkish or weakly blue-green colours. Most primary structures are obscured in the completely recrystallized limestone. Possible crinoid ossicles have been reported (Kolderup & Moncton 1911, Kolderup & Kolderup 1940, A. Thon, pers. comm.), indicating an Ordovician or younger age. A metamorphic banding occurs, usually defined by thin bands enriched in epidote-group minerals. Such bands reveal complex isoclinal folding and refolding.

At Storetveit (Plate 1) the marble contains fragments of garnetiferous greenstone which may derive from the substrate, tectonically emplaced into the limestone. Alternatively, the greenstone may represent a mafic sediment or indicate volcanism during deposition of the limestone. At Søvikneset (Plate 1) the marble is in contact, and locally intercalated, with a thin, calcareous, garnet-amphibole mica schist. This mica schist may be part of the Marmorøyen Formation as there is no sharp break or clear tectonic contact between the marble and the mica schist.

Relationship to the Nordåsvatn Complex

The presence of a primary unconformity between the Nordåsvatn Group and the assumed younger Storetveit Group is suggested by the fact that all conglomerate clasts in the Paradis Formation are rock-types also found in the meta-igneous part of the Nordåsvatn Complex. The latter is therefore likely to have served as a source for the pebbles in the Paradis Formation. A comparison with similar rocks of the MaBA (below) and other areas in western Norway (Thon 1985b) indicates that the relationship between the Storetveit Group and ophiolitic rocks of the Nordåsvatn Complex was of depositional character. A sheared primary contact is inferred between the conglomerate of the Paradis Formation and the ophiolitic rocks to the west in the Marmorøyen area (Plate 1) (Fossen 1986).

Stratigraphy and correlation

The original stratigraphy of the Storetveit Group has been obscured, way-up criteria have not been found, and assumed primary contacts have been masked by high strains. However, similar metasediments in the MaBA (the Holdhus Group, Færseth et al. 1977, Ingdahl 1985 and in press) are better preserved and may serve as an object of correlation. The Moberg Formation (Ingdahl 1985 and in press) of the Holdhus Group shows lithologi-

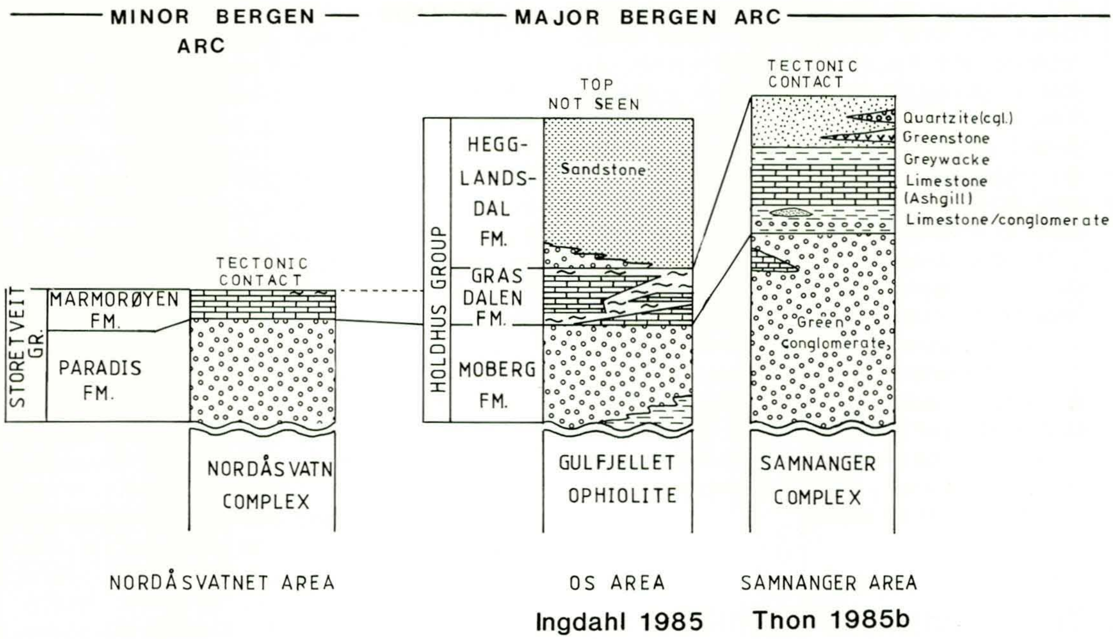

Fig. 8. Stratigraphic correlation of the Storetveit Group (MiBA) with the Holdhus Group (MaBA).

cal characteristics similar to those of the Paradis Formation. An unconformity has been described between the Gulfjellet Ophiolite and the Moberg Formation (Kvale 1960, Naterstad 1976, Sturt & Thon 1976 Ingdahl 1985, 1986 and in press). Thin, discontinuous layers of non-fossiliferous marble are locally found within the Moberg Formation (Færseth et al. 1977). Above the Moberg Formation, fossiliferous limestones of Ashgill age (Reusch 1882, Kolderup & Kolderup 1940) are present in the Grasdalen Formation. The Marmorøyen Formation may be correlated with either the Grasdalen Formation or the intra-Moberg Formation marble (Fig. 8), but the continuity of the Marmorøyen and Grasdalen Formations, and the possible occurrence of crinoid ossicles, indicate a correlation with the Grasdalen Formation as the most probable.

Very similar lithologies in both the older (Nordåsvatn Complex and Gulfjellet Ophiolite/ Samnanger Complex) and the younger series (the Holdhus and Storetveit Groups) favours a correlation. This correlation has already been indicated by Kolderup & Kolderup (1940) and is supported by the present work.

Deformation structures

The rocks of the Nordåsvatn Complex and the Storetveit Group have both suffered polyphase deformation during a phase of deformation which is correlated with the Scandian event. A pervasive mylonitic fabric which developed during this event was more or less contemporaneously folded, refolded and ruptured. All structures formed during this event are therefore termed D2 structures, being succeeded by a family of folds (F3) with consistent vergence and orientation, and post-dating the deposition of sediments of the Storetveit Group. The main, metamorphic, compositional foliation (S2) is therefore used as a reference surface, while D1 (S1) is restricted to deformation structures apparently pre-dating the main event (D2). For simplicity, D2 (M2) is used for structures (metamorphism) formed during the main Scandian event in the Nordåsvatn Complex, Storetveit Group and Gamlehaugen Complex, although D1 deformation is believed to be restricted to rocks of the Nordåsvatn Complex.

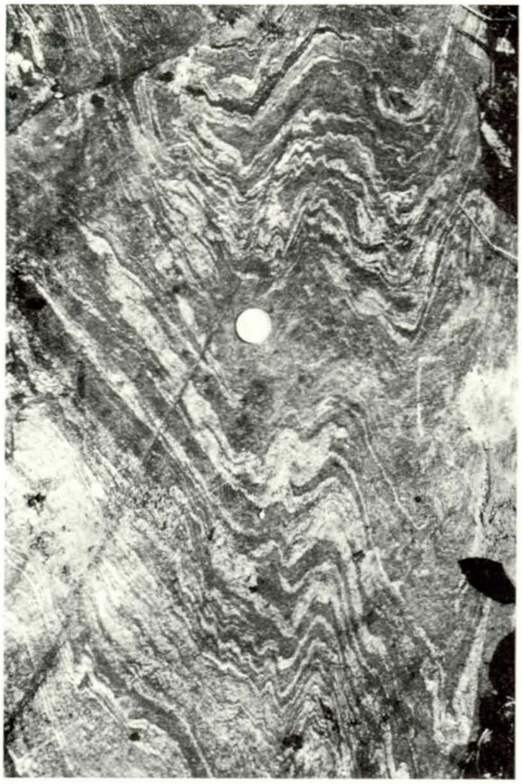

Fig. 9. Trondhjemitic bands in strongly foliated amphibolite, Nordåsvatn Complex, showing type 3 (Ramsay 1967) interference pattern due to refolding during D2. Fjellsiden, NE of St. Lungegårdsvatnet (Plate 1).

Earliest structures (D1) and ambiguous structures

There is no clear evidence for a separate event of deformation which predates the late Caledonian event (D2) because of the complexity and intensity of the latter, but the fact that possible D1 structures are more or less restricted to rocks of the Nordåsvatn Complex may indicate that D1 predates deposition of the sediments of the Storetveit Group. The earliest deformation structures seen in the rocks of the Nordåsvatn Complex are, on the microscopic scale, internal fabrics (inclusion trails) in porphyroblasts (porphyroclasts) of garnet, amphibole and locally plagioclase. The internal fabrics are straight or curved and of a more fine-grained nature than the matrix (Fossen 1988b). Locally, such fabrics are restricted to an inner core of zoned garnets. Curved inclusion patterns may represent either the growth of the porphyroblast over a former crenulation cleavage or syn-kinematic porphyroblast growth. Straight inclusion patterns which are oblique to the matrix foliation may be an S1 foliation preserved from transposition and reworking by porphyroblast overgrowth. Alternatively, these microstructures may have formed progressively during the D2 event. Inclusion patterns oblique to the matrix foliation are also found in the mica schist of the Marmorøyen Formation and in greenstone fragments within the marble. The greenstones may, however, be tectonically derived from rocks of the Nordåsvatn Complex.

Also on the mesoscopic scale, pre-D2 structures have been so intensely reworked that they are only represented as transposed elements in the composite D2 surface, inseparable from the D2 structures. Intrafolial folds, transposed fold hinges and folded foliations have previously been regarded as D1 elements in the MaBA (Færseth et al. 1977, Henriksen 1979) though similar structures developed in the younger Holdhus Group (Sivertsen 1975, Ingdahl 1985). In the MiBA the D2 strains are so large and pervasive that such structures may have formed progressively during the D2 event.

Ambiguous structures are also found within the tectonic melange. An internal, locally folded foliation is present within some of the tectonic clasts of the melange, oblique to the enveloping S2 foliation (Fig. 4). The internal foliation may commonly be traced towards the edge where it rotates to become parallel with the enveloping foliation. Locally, the internal foliation is cut by the younger, enveloping foliation. Similar structures from the MaBA are interpreted as D1 structures (internal foliation) reworked by D2 deformation (Osterøy; Henriksen 1979, p. 68-69), but also as D2 structures (Os; Ingdahl 1985) as the internal foliation in the tectonic clasts may represent an early expression of the progressive D2 event. The problem is analogous to that of the interpretation of poikiloblastic porphyroclasts as discussed above and below. Thus, from a structural point of view there are some indications of a pre-D2 deformational event, but neither the microscopic nor the macroscopic evidence is unambiguous.

Scandian structures (D2)

The structural development of the D2 event is complex and may be called polyphasal, al-

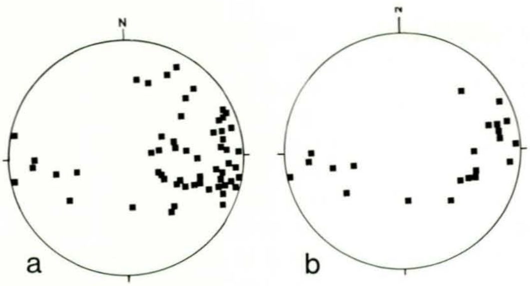

Fig. 10. Stereographic projection of D2 fold axes (a) in the Nordåsvatn Complex and Storetveit Group, and (b) in the Paradis Formation at one locality (1x1m) at Marmorøyen (Plate 1).

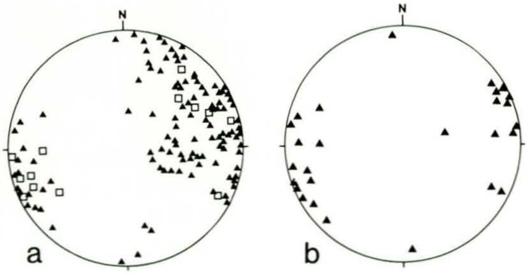

Fig. 11. Stereographic projection of D2 linear structures in the Nordåsvatn Complex (filled triangles) and the Storetveit Group (open squares) (a) from several localities in the MiBA, and (b) from the southern part of Marmorøyen (Plate 1).

though it is interpreted as progressive rather than separated into distinct phases. The following progressive evolution seems to have taken place: (1) F1 folding of the rocks into tight or isoclinal folds of major and minor scale. Transposition of earlier structures into the axial planes. (2) Slip and shearing, initially along the limbs of the F2 folds with extensive formation of mylonitic fabrics. (3) Progressive folding and refolding associated with contemporaneous shearing.

Major F2 folds are not detected, but it is inferred that rocks of the Storetveit Group are preserved within a strongly modified (sheared) synformal structure (Fossen 1986). Mesoscopic and microscopic folds are seen in the garnet-amphibole-mica schists of the Nordåsvatn Complex, and the geometric configuration of deformed quartz veins locally visualizes tight to isoclinal folds in the mica schists which otherwise would be difficult to recognize.

The D2 folding of mylonitized metagabbros and trondhjemites may be spectacular (Fig. 9), and non-cylindrical folds have axes which vary from being strike-parallel to normal to the main foliation (Fig. 10). F2 folds in the amphibolites and the Storetveit Group are separated from F3 folds by their higher metamorphic grade (see below), smaller interlimb angle and the orientation of fold axes and axial planes.

Heterogeneous deformation during D2 produced local shear zones which transgress the general, mylonitic D2 fabric at low angles, and, as a result, angular disconformities of tectonic origin are abundant. Flinty ultramylonitic mica schists developed locally at a late stage, and cut the general mylonitic fabric at high angles NNE of Natlandsfjellet (Plate 1) (Fossen 1986).

Linear elements such as quartz rods, elongated pebbles (Storetveit Group) and mineral lineations are common. Their orientations are somewhat scattered even on a local scale (Fig. 11b), partly due to anastomosing shear zones and refolding, but most are sub-horizontal or have a northeasterly dip (Fig. 11).

Boudinage of amphibolites and granitoids within the mica schists is common and, together with folding, is regarded as an important process during the formation of the tectonic melange in the Nordåsvatn Complex.

Later deformation

A series of asymmetric folds with a consistent easterly-directed vergence (Fig. 12, profile B-B) affect all the D2 structures in all lithologies of the MiBA (Fossen 1986) as well as in the UGC and the Rundemanen Formation where they are designated F2 (Fossen 1988a). Axial planes dip gently away from the core of the arc, and the sub-horizontal or gently-plunging fold axes are parallel with the trend of the arc (Fossen 1986). The consistency of these structures throughout the area suggests that these folds formed during a separate phase of deformation, designated D3. The possibility has been suggested that the F3 folds are parasitic to a major monoclinal fold (Fossen 1986, 1988a).

An even later phase of deformation (D4, =D3 in the Rundemanen Fm, Fossen 1988a) cau-

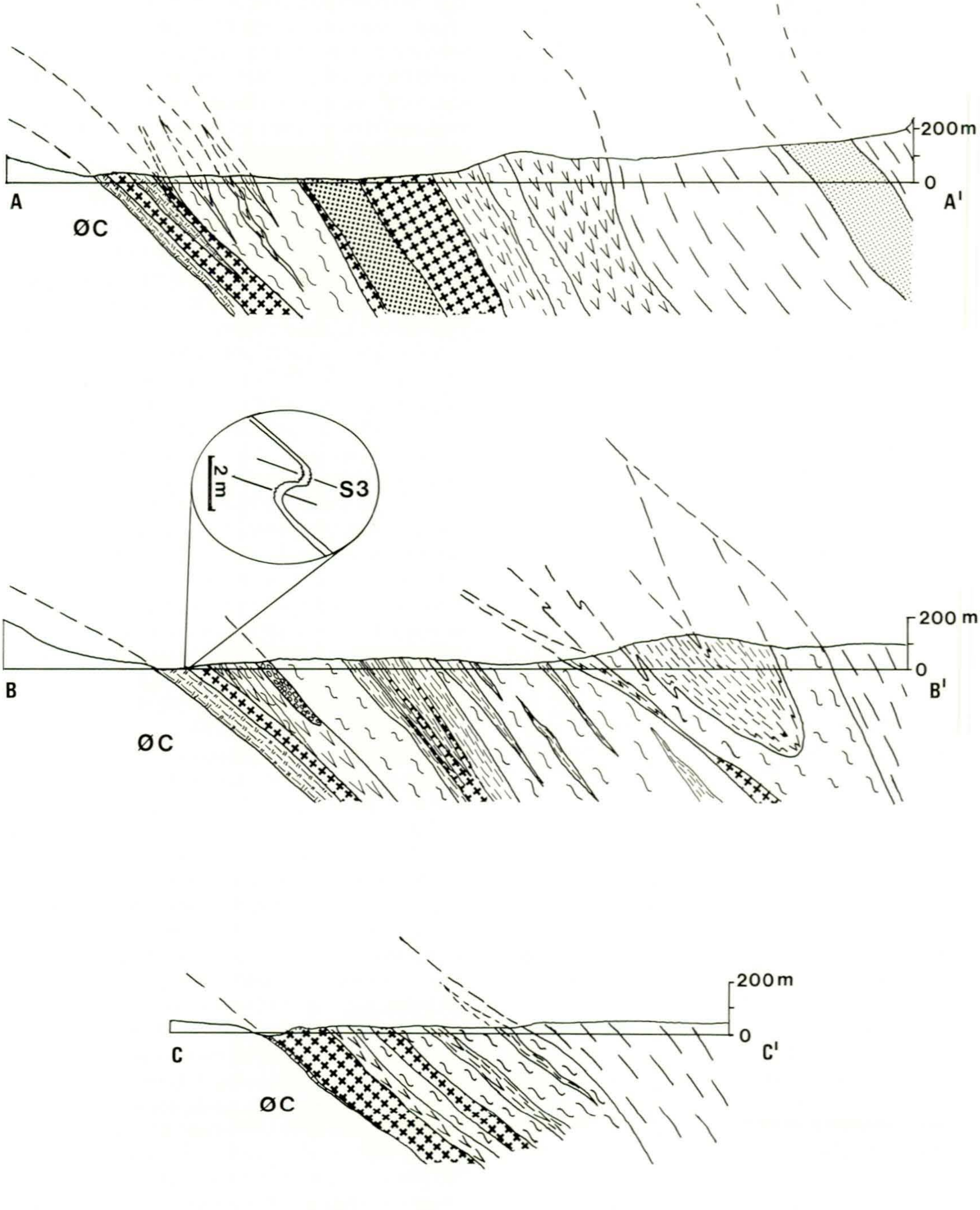

Fig. 12. Profiles through the Minor Bergen Arc. For locations, see Plate 1. ØC=Øygarden Complex

sed the formation of kink-like folds with easterly-plunging axes and sub-vertical axial planes. This deformation was not very pronounced, and is related to the formation of the arcuate structure of the Bergen Arc System (Fossen 1986).

Metamorphic development

The earliest metamorphism (M1)

Intense recrystallization and mineral growth occurred during D2 (M2), and a sign of any earlier (M1) metamorphism is only expected to be found in porphyroclasts. However, porphyroclasts also formed from M2 porphyroblasts during D2, and microchemical analyses have been used in an attempt to separate the two metamorphic events.

Large porphyroclasts of amphibole from metagabbro and gabbro-pegmatite, which may represent altered primary pyroxenes, were unstable during M2. A marked compositional contrast is seen between the M1 and M2 amphiboles (Fig. 13, Fossen 1986, 1988b) where the compositions of the early, large (M1) amphiboles indicate the biotite zone (Turner 1981) of the greenschist facies. The M1 amphiboles are not found in rocks of the Storetveit Group, indicating that the M1 metamorphism is restricted to rocks of the Nordåsvatn Complex.

Some of the garnets within the mica schists of the Nordåsvatn Complex show a chemical break between the core and the rim. The break commonly coincides with a microtextural break (Fossen 1988b), and the more spessartine-rich core may indicate a lower metamorphic grade during its growth than during the growth of the almandine-rich rim. The coinciding textural and chemical break may support this view. Alternatively, the garnet may have grown at various stages during one prograde event (multi-zoned garnets support this view). Clear evidence is not found for either of the interpretations.

Minerals formed during D2 (M2)

Garnet-amphibole-plagioclase-mica is a typical M2 paragenesis, indicating that at least the garnet zone was reached.

As mentioned above, garnets may have formed both during M1 and M2, and their porphyroclastic appearance makes classification difficult. Syn-tectonic garnets of possible M2 age show rotational inclusion trails, common in both mica schists and amphibolites. An outer rim free of inclusions is locally present. Garnets with straight inclusion patterns are also present, though the inclusion trails commonly curve near the edges (Fig. 14). This is interpreted as interkinematic growth of the inner part during a local break in the deformation, and syn-kinematic growth of the rim during renewed deformation. Sieve garnets, where inclusions have the grain-size of the matrix, are regarded as M2 garnets, and are formed where quartz is in excess relative to mica. The inclusions may be randomly oriented or forming structures as described above. The garnets in the mica schists show a grossular content of about 17-25%, indicating a calcareous sediment. Almandine dominates with 50-65%, the spessartine content is 5-25%, while pyrope represents 3-15%. Garnets in chert-bearing metasediments are more spessartine-rich (30-50%) and less almandine-rich (30-45%) (Fossen 1986).

Most metamorphic amphiboles in the Storetveit Group and the Nordåsvatn Complex grew during M2. While M1 amphiboles are ferroan-pargasitic hornblende to magnesio-hornblende, the M2 amphiboles generally are of the alumino-calcic amphiboles of ferroan-pargasitic type (Fossen 1986) (nomenclature after Leake 1978). The difference in composition indicates a higher metamorphic grade during M2 than during M1, as indicated from Fig. 13. Uppermost greenschist facies metamorphism is indicated for M2, possibly reaching the lowermost amphibolite facies (staurolite zone, Turner 1981) at the peak. Very little zoning is found in the amphiboles, indicating growth or recrystallization during peak metamorphism. M2 amphiboles define a mineral lineation or a (re)folded S2 fabric in the amphibolites. Amphiboles also overgrow D2 folds and refolds, and these amphiboles have a composition similar to amphiboles defining the refolded foliation. Hence, the local D2 folding and refolding occurred during the peak of M2. Amphiboles in the mica schists are in most places porphyroclastic, but their compositions are similar to those in the amphibolites and in the Storetveit Group (Fig. 13). Hence, an M2 age is likely also for these amphiboles.

Plagioclase and albite from mica schists of the Nordåsvatn Complex and from the Storetveit Group show compositions from An_{01} to

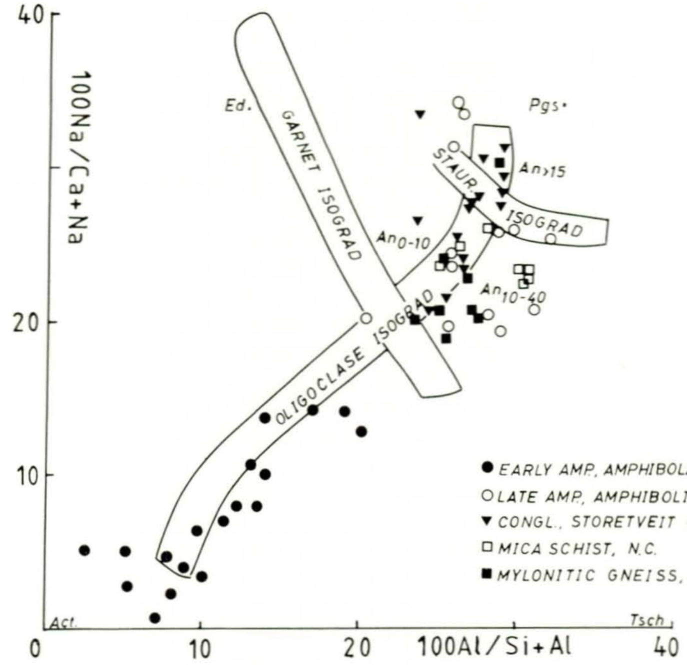

Fig. 13. Formula proportion variation diagram showing amphibole compositions from different rocks of the MiBA. Diagram from Laird & Albee (1981).

An_{40} (Fossen 1986). The possibility that relict plagioclases of pre-D2 age occur should not be neglected, but the intense recrystallization during D2 and the apparently lower grade during D1 indicate that most plagioclase grains are of D2 age. The coexistence of albite and plagioclase is expected in the transition from upper greenschist facies to lower amphibolite facies (Turner 1981) which is the metamorphic grade indicated during M2.

The composition of white mica is shown to be P-T dependent (Velde 1969), but it is also dependent on the composition of the host rock and on factors which are not fully understood. Nevertheless, the composition of white micas from mica schists of the Nordåsvatn Complex (Fossen 1986, 1988a) compares with those formed in the uppermost part of the greenschist facies in other parts of the world (Miyashiro 1973). It is concluded that the compositions of garnets, amphibole, plagioclase/albite and white mica indicate that the M2 deformation was of uppermost greenschist facies, possibly into lowermost amphibolite facies locally. Medium pressure is indicated during M2 from amphibole compositions (Fossen 1988b). However, deformation proceeded after peak metamorphism, causing zones of retrogression, commonly enriched in chlorite, and generating a porphyroclastic texture in many M2 porphyroblasts.

Later metamorphism

During D3 and D4 little recrystallization took place. Mechanical rupture of hornblende and bending of platy silicates occurred, and polygonization of mica is locally seen. Only chlorite clearly overgrows D3 structures. The apparent stability of white mica during D3 and D4 indicates that the deformation took place under middle to lower greenschist facies conditions.

The Gamlehaugen Complex

The Gamlehaugen Complex is the name assigned to strongly-deformed mylonitic orthogneisses and metasediments of psammitic and subordinate pelitic character that occur as slivers or zones within the Minor Bergen Arc (Plate 1). The zones divide rocks of the Nordåsvatn Complex into nine distinct tectonic units. Gneiss and metasediments always occur together, commonly showing internal repetitions. The close association between these metasediments and the gneiss, and their dissimilarities

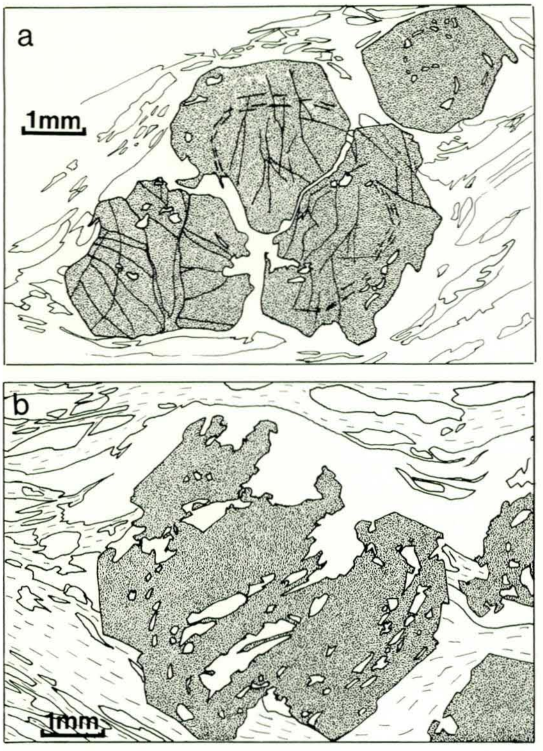

Fig. 14. Garnets from amphibole-garnet-mica schist, Nordåsvatn Complex. (a) Cracked garnet of uncertain age with inclusion dust indicating former crystal faces of the garnet, enveloped by the matrix foliation. (b) Undeformed M2 garnet with inclusion trails and relatively sharp edges.

to rocks of the Nordåsvatn Complex and the Storetveit Group indicate that the rocks of the Gamlehaugen Complex represent a detached continental basement-cover sequence tectonically emplaced into rocks of the Nordåsvatn Complex.

The gneiss zones

Gneisses occur in at least eight zones which vary in thickness up to a maximum of 450 m. (Plate 1). Though most are rather extensive they thin out along strike as well as in the vertical direction. The zones are generally concordant with the arc structure, but low-angle, tectonic disconformities with various rocks of the Nordåsvatn Complex are found, e.g. near Gamlehaugen (Plate 1, Fig. 12).

On outcrop scale the gneisses vary from protomylonitic augen gneiss to ultramylonite. The augen gneiss typically contains feldspar augen (about 1cm) in a darker matrix. Banded gneiss consists of white to reddish granitoid bands of former pegmatites and granitoid dykes alternating with darker mica-rich bands. The granitoid bands are commonly complexly folded and sheared.

Ultramylonitic gneiss is common in the Landås area, and is difficult to separate from other ultramylonites in the MiBA. It may be a problem to separate mylonitic varieties of the gneiss from mylonitized metasediments, although the mylonitic quartz-rich metasediments generally have a lighter colour than the mylonitic gneiss. On outcrop scale it is also difficult to separate thin (3m broad) gneissic bands from strongly-deformed granitoids in the Nordåsvatn Complex. The lithologies of the gneisses closely resemble those of mylonitized parts of the Ulriken Gneiss Complex and the Øygarden Gneiss Complex immediately to the east and west (Plate 1). In the feldspar augen, relict textures such as perthite structures, partly or fully developed microcline patterns, and untwinned K-feldspar and myrmekite are found which are similar to those observed in the UGC. Biotite, white mica, albite/plagioclase and in some cases garnet and amphibole constitute the remaining mineralogy.

Metasediments

Like the gneisses, the metasediments form relatively continuous zones which locally split and die out along the strike (Plate 1). The zone from Dragefjellet across Store Lungegårdsvatnet to Landås is the thickest (200m). The zones parallel the arc structure. Schistose quartzite or quartz schist are most common, but more pelitic varieties occur among quartzite and quartz-schists in the westernmost zone (Plate 1). Flaggy quartz schists are also present, where micaceous bands alternate with quartzitic bands (Fig. 15). Feldspar occurs in some of the quartz-rich metasediments, indicating the presence of meta-arkose. The very high strain has, however, obliterated the sedimentary structures, and only the compositional layering and petrography may indicate that the rocks were metasediments deposited as sands with some silty beds. While (ultra)mylonitic psammites are locally difficult to separate from the gneisses, pelitic

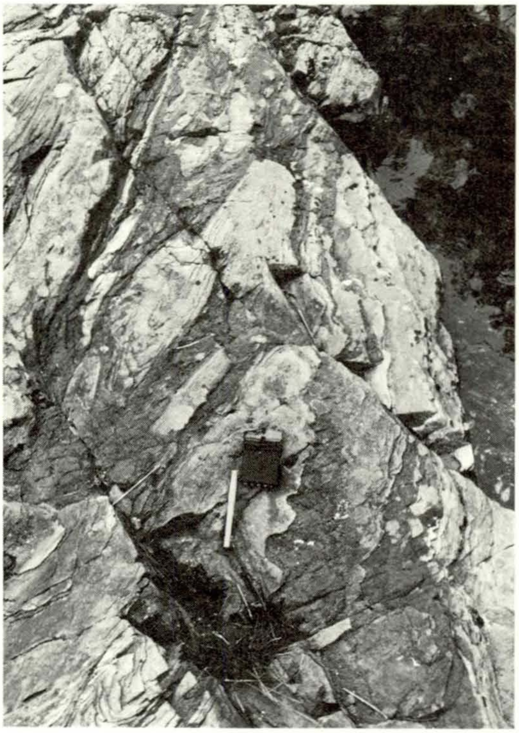

Fig. 15. Isolated fold hinge of psammite in pelite (mica schist), Gamlehaugen Complex, testifying to high D2 strains. The compositional banding probably reflects primary bedding. Island west of Marmorøyen and north of Søvikneset.

varieties show similarities with mica schists of the Nordåsvatn Complex. The latter is, however, of more mafic and calcareous composition with abundant amphibole and garnet, while garnet and amphibole are nearly absent in metasediments of the Gamlehaugen Complex. Garnets do occur, however, in the (semi)-pelitic varieties of the Gamlehaugen Complex, which otherwise consist of quartz, mica, albite/plagioclase, K-feldspar and some tourmaline, biotite and epidote.

Deformation and metamorphism

The mylonitic fabric in the rocks of the Gamlehaugen Complex indicates very high strains, and all contacts are mylonitic. Tight to isoclinal folding is seen in the metasediments (Fig. 15) as well as in the banded gneisses, and fold axes tend to parallel the rodding and mineral lineation. The latter generally have an E-W trend (Plate 1) which is the regional trend in the western Bergen area (Kvale 1960, Weiss 1977, Fossen 1986). The intense deformation which led to the mylonitic fabric in both the gneisses and the metasediments is followed continuously into rocks of the Nordåsvatn Complex and the Storetveit Group, and hence is the Scandian event which is designated D2 in the Nordåsvatn Complex. Any earlier deformation structures would have been obliterated or obscured by this deformation.

Uppermost greenschist facies close to the amphibolite facies was reached during M2, as determined from the composition of late, syn-kinematic metamorphic ferroan pargasite to ferroan-pargasitic hornblende (Fig. 13). No indications of earlier metamorphism or deformation are found. The asymmetric folds (F3) which fold the mylonitic fabric in the area are well developed within the Gamlehaugen Complex, and show the same geometrical features as in the Nordåsvatn Complex, Storetveit Group (above), the Rundemanen Formation (F2 in that formation) and the Ulriken Gneiss Complex (Fossen 1986, Fossen 1988a).

Interpretation of the Gamlehaugen Complex

The lithological differences between rocks of the Gamlehaugen Complex and other rocks of the MiBA are marked. The close association between the gneisses and metasediments may indicate that they were separated by a depositional contact prior to the Caledonian deformation. The gneiss slices are likely to be reworked Precambrian basement gneisses, and the gneisses and metasediments are interpreted as a continental basement-cover couplet which was detached and strongly deformed and imbricated into rocks of the Nordåsvatn Complex. A similar relationship is found between the Ulriken Gneiss Complex and its sedimentary cover, the Rundemanen Formation, and it seems likely that the Gamlehaugen Complex represents its highly deformed and detached equivalent.

Conclusions

Three rock units, the Nordåsvatn Complex, the Storetveit Group and the Gamlehaugen Complex, constitute the Minor Bergen Arc. The Storetveit Group, which consists of green polymict conglomerate (the Paradis Formation) and limestone (the Marmorøyen Formation) is interpreted as a metasedimentary cover to assumed ophiolitic rocks of the Nordåsvatn Complex. The latter contains metagabbro, amphibolite, greenstone and greenschist and is interpreted as a dismembered ophiolite fragment intruded by granitoids. Mica schists and minor cherts in this complex may be part of the cap rock to the ophiolite, though mica schists of other origin may be present. Rocks of the Nordåsvatn Complex are correlated with Early Ordovician rocks of the Gulfjellet Ophiolite Complex and assumed Cambro-Ordovician rocks of the Samnanger Complex. The Storetveit Group is correlated with the lower part of the Holdhus Group of the MaBA, suggesting a Late (or possibly Middle) Ordovician age.

The Gamlehaugen Complex consists of entangled psammitic metasediments and mylonitic gneisses. It is suggested that these rocks represent a continental basement-cover relationship which was detached and obliterated by Caledonian deformation and metamorphism. The Gamlehaugen Complex may thus be correlated with the Rundemanen Formation and the Ulriken Gneiss Complex to the east.

All the rocks of the Minor Bergen Arc are highly strained, and mylonitic fabrics are pervasive throughout the rocks. The intense deformation and common repetition of both oceanic and continental rocks is interpreted as imbrication during Caledonian overthrusting onto Baltica. A Silurian-Early Devonian (Scandian) age of the thrusting and imbrication is indicated by the assumed Late Ordovician Storetveit Group which was involved in the imbrication and mylonitization. Ambiguous structures are inclusion patterns in porphyroclasts and strong foliations in tectonic clasts in the Nordåsvatn Complex. These structures may be the remnants of a pre-Scandian orogenic event, but could also be the result of complex D2 deformation. It is, however, likely that earlier deformational structures are present but difficult or impossible to separate from the pronounced D2 structures. Pre-Scandian, Ordovician deformation has been demonstrated near the Krossnes Granite in the MaBA (Fossen & Austrheim 1988), but also here relict structures of the Ordovician event are inseparable from the Scandian structures where radiometric constraints are not available. Nevertheless, in the MiBA (and the MaBA) it is clear that the Scandian deformation was the most important. The metamorphic grade during the Scandian event reached the transition greenschist facies-amphibolite facies at its peak, but heterogeneous deformation proceeded during retrograde conditions. Amphibole analyses indicate a similar Scandian metamorphic grade in rocks of the Nordåsvatn Complex, the Storetveit Group and the Gamlehaugen Complex.

Indications of an earlier Caledonian metamorphism are found in mafic meta-igneous rocks of the Nordåsvatn Complex. A lower metamorphic grade is indicated for this metamorphism (lower-middle greenschist facies), which may be related to an island arc event during an earlier orogenic stage.

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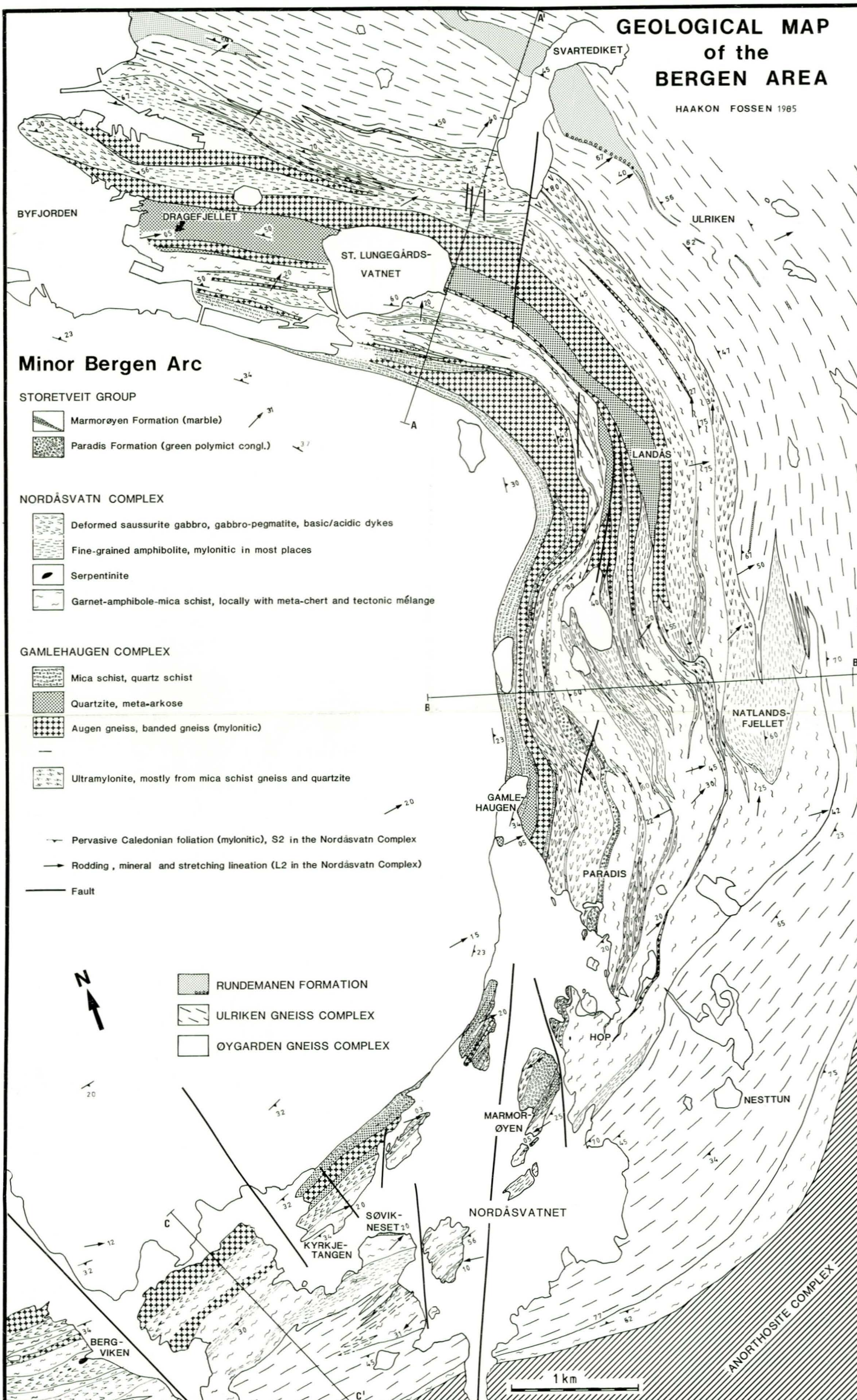
Appendix

The stratigraphical nomenclature introduced in this work, i.e. the Nordåsvatn Complex, Storetveit Group, Paradis Formation, Marmorøyen Formation and the Gamlehaugen Complex, has been accepted by the Norwegian Committee on Stratigraphy, and these units are to be regarded as formal names.



GEOLOGICAL MAP
of the
BERGEN AREA
HAAKON FOSSEN 1985
Minor Bergen Arc
STORETVEIT GROUP
Marmorøyen Formation (marble)
Paradis Formation (green polymict congl.)
NORDÅSVATN COMPLEX
Deformed saussurite gabbro, gabbro-pegmatite, basic/acidic dykes
Fine-grained amphibolite, mylonitic in most places
Serpentinite
Garnet-amphibole-mica schist, locally with meta-chert and tectonic mélange
GAMLEHAUGEN COMPLEX
Mica schist, quartz schist
Quartzite, meta-arkose
Augen gneiss, banded gneiss (mylonitic)
Ultramylonite, mostly from mica schist gneiss and quartzite
Pervasive Caledonian foliation (mylonitic), S2 in the Nordåsvatn Complex
Rodding, mineral and stretching lineation (L2 in the Nordåsvatn Complex)
Fault
RUNDEMANEN FORMATION
ULRIKEN GNEISS COMPLEX
ØYGARDEN GNEISS COMPLEX
N
1 km
BYFJORDEN
DRAGEFJELLET
ST. LUNGEGÅRDS-
VATNET
SVARTEDIKET
ULRIKEN
LANDÅS
NATLANDS-
FJELLET
GAMLE-
HAUGEN
PARADIS
HOP
NESTTUN
MARMOR-
ØYEN
NORDÅSVATNET
SØVIK-
NESET
KYRKJE-
TANGEN
BERG-
VIKEN
ANORTHOSITE COMPLEX
A
A'
B
B'
C
C'