Contact relationships between the Askvoll group and the basement gneisses of the Western Gneiss Region (WGR), Sunnfjord, Western Norway

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The Askvoll group, comprising a thick mylonitic sequence, is situated between the Caledonian nappes and the underlying Western Gneiss Region (WGR) and defines the Kvamshesten Detachment Zone on the south side of the Devonian Kvamshesten basin. The tectonostratigraphy of the Askvoll group is subdivided into three units: the upper Gjervika Unit comprises quartzofeldspathic mylonites and marbles; the middle Vikaneset Unit consists of metasediments, greenschists, flaser gabbros, plagiogranites and amphibolite bands; and the lower Kumle Unit comprises metapsammite and garnet mica schist with lenses of garnet amphibolites. The WGR consists of migmatitic and granitic gneisses which are interfolded with amphibolites, metagabbros and metapsammites. The peak metamorphic assemblages preserved in the detachment zone are characteristic of amphibolite facies metamorphism and are observed in both the basement and the Askvoll group. Eclogites have been observed in the gneisses further to the east showing high-grade metamorphism of the basement. Progressive retrogression to low greenschist-facies metamorphism accompanied penetrative shear deformation and mylonitization of the Askvoll group. The contact between the WGR and the Askvoll group is characterized by a change in lithology and structural style along a broad zone, in part associated with the Kumle Unit that truncates the isoclinally folded rocks of the basement. The Gjervika Unit and the Vikaneset Unit are interpreted to be an allochthonous cover sequence to the underlying basement, whereas the Kumle Unit could be part of either the supracrustals in the basement or the lowermost part of the Askvoll group. The deformation and retrograde metamorphism, which are assigned to the orogenic collapse, occurred prior to the deposition of the Middle Devonian basins (380 Ma) and have overprinted and obliterated older tectonic fabrics.

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The later stage of the Caledonian Orogeny can be divided into two distinctly different tectonic phases: (1) a compressional phase related to the Silurian continent–continent collision, and (2) a subsequent extensional phase of Devonian age. The compressional phase gave rise to a series of nappes emplaced onto the Baltic Shield. The tectonometamorphic evolution and complex tectonostratigraphy established during the compressional phase have been studied in detail and are relatively well constrained (e.g. Roberts & Gee 1985, and references therein). The extensional phase, on the other hand, has been recognized only in recent years, mainly as a result of increased knowledge about kinematics and shear sense indicators associated with shear zones (Simpson & Schmid 1983; Lister & Snoke 1984; Passchier 1984; White et al. 1986), and the recognition of orogenic collapse as an important process following the buildup of the orogenic welt (Molnar & Tapponnier 1978; Dewey 1989, and references therein). The recognition of large low-angle normal faults with large displacements in the Basin and Range Province of the Western USA (Davis 1983; Davis & Lister 1988; Davis et al. 1986; Wernicke 1985; Wernicke & Burchfiel 1982; Reynolds & Spencer 1985; Lister & Davis 1989) was a breakthrough in our understanding of the processes involved in orogenic extensional collapse.

Western Norway, where sedimentary basins of Middle Devonian age are juxtaposed on lower crustal rocks with approximately the same mineral cooling ages, represents a key area for the study of extensional tectonics in the Caledonides (Fig. 1). The Devonian sedimentary basins, traditionally interpreted as molasse basins (Fig. 1), occur in contact with the Caledonian nappes as well as the underlying Precambrian basement of the Western Gneiss Region (WGR) (Bryhni 1963; Bryhni & Skjerlie 1975; Kildal 1970; Steel et al. 1985). The boundary between the WGR and the overlying allochthonous rocks is defined by major shear zones comprising mylonitic and cataclastic rocks (Hossack 1984; Norton 1986, 1987; Chauvet & Séranne 1989; Chauvet & Brunel 1988; Swensson & Andersen 1987, 1990). Several models have been proposed for the development and structural modification of these Devonian basins which involve strike-slip movements (Steel 1976; Steel & Gloppen 1980) and thrust faulting (Bryhni & Skjerlie 1975). The present model for the development of the Devonian basins involves large-scale low-angle normal faulting (Bryhni 1963; Nilsen 1968; Hossack 1984; Norton 1986, 1987; Séranne & Séguret 1987; Chauvet & Brunel 1988; Chauvet & Séranne 1989; Chauvet et al. 1987). The present contribution concentrates on the relationships between the KDZ, where it occurs in the Askvoll group, and the WGR in the Atløy–Askvoll area of Sunnfjord (Fig. 1). The major problem in this area is the relationship between the

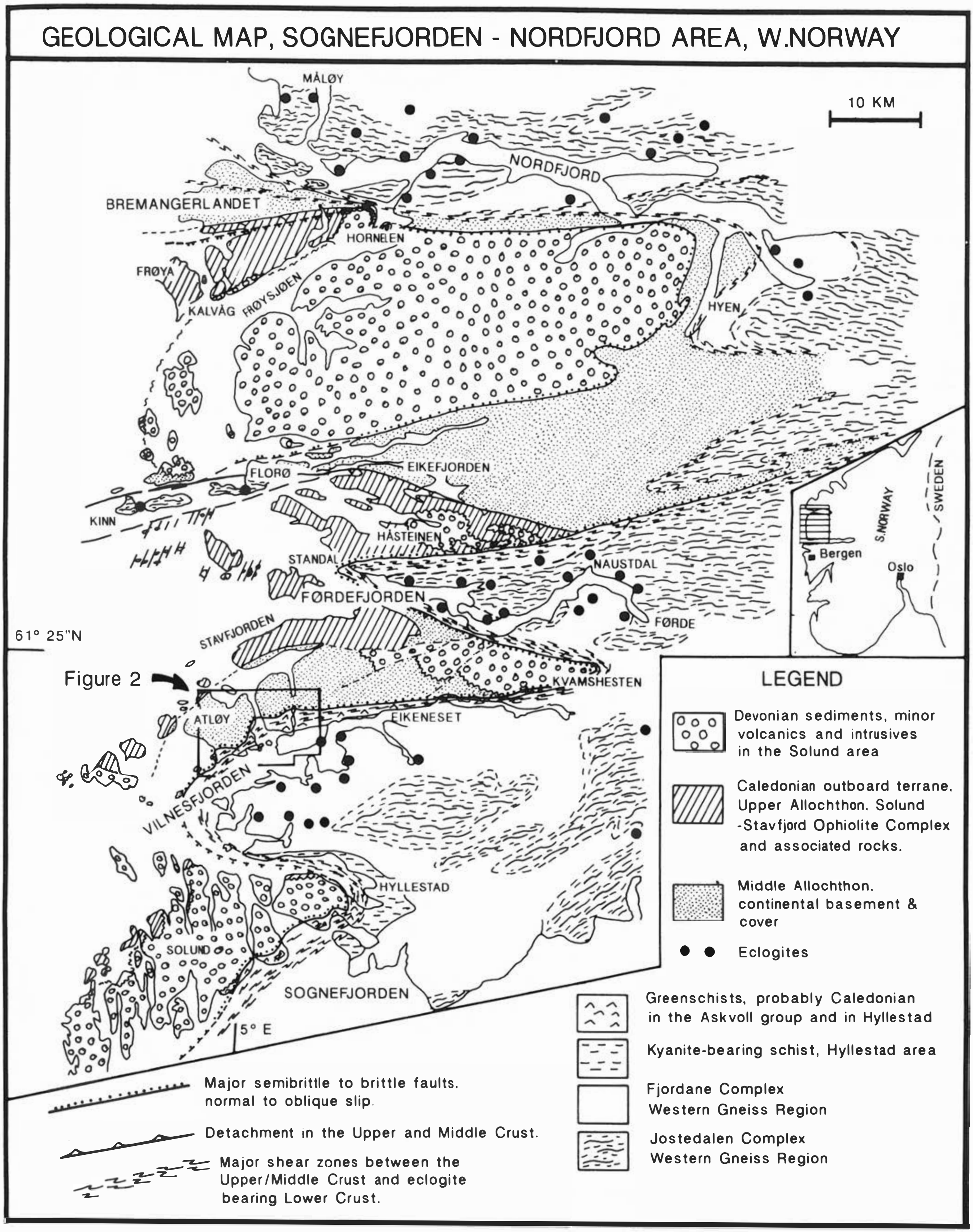


Fig. 1. Simplified geological map of Western Norway between Sognefjord and Nordfjord, modified after Andersen & Jamtveit (1990).

metasediments and metavolcanics of the Askvoll group and the paragneisses and orthogneisses of the WGR. We propose a Palaeozoic age for the mafic sequence of the Askvoll group which could be related to the early rifting phase, i.e. the opening of the Iapetus Ocean (Skjerlie 1969; Furnes et al. 1976). The deformation of the Askvoll group is characterized by progressive deformation during retrograde conditions from amphibolite facies to lower greenschist facies. This evolution is accompanied by down-to-the-west movement of the hanging wall along the KDZ, related to the extensional collapse of the Caledonian Orogenic welt in the Early Devonian (Norton 1986; Chauvet & Séranne 1989; Andersen et al., in prep).

Geological setting

The Precambrian gneisses of the Western Gneiss Region (WGR) constitute the heterogeneous autochthonous basement for the allochthonous Caledonian rocks and Devonian sediments. The Devonian sediments occur in four intracratonic basins (the Hornelen Basin, the Håsteinen Basin, the Kvamshesten Basin and the Solund Basin) (Fig. 1) (e.g. Steel et al. 1985).

The WGR represents the root zone of the Caledonian Orogen, and a metamorphic zonation, from amphibolite facies in the east (Krill 1985) to eclogite facies in the west (Skjerlie 1969; Griffin et al. 1985; Griffin & Qvale 1985; Bryhni 1989), emphasizes the deep crustal section displayed by these rocks. Pressure estimated from basement rocks in the Sunnfjord area ranges from 12 to >16 kbar (Krogh 1980; Andersen & Jamtveit 1990). Further to the north, however, pressures as high as 25–30 kbar at temperatures of 750–800°C have been recorded (Jamtveit 1987; Smith & Lappin 1989). Bryhni (1966) subdivided the WGR into two complexes: the Jostedalen Complex and the Fjordane Complex. The Jostedalen Complex is dominated by massive migmatitic and granitic gneisses dated at around 1500–1800 Ma (Bryhni 1966; Abdel-Monem & Bryhni 1978; Tørudbakken 1982; Griffin & Mørk 1981). The structurally overlying Fjordane Complex is heterogeneous, comprised of supracrustal sequences, mafic to ultramafic rocks, anorthosites and granitic–syenitic rocks (Bryhni 1989; Skjerlie & Pringle 1978; and others). Both the Jostedalen and Fjordane complexes contain eclogites in pods and lenses. In the Førdefjorden area, eclogites appear to be most common in the Fjordane Complex (Bryhni 1966; Bryhni & Grimstad 1970; Bryhni 1989). The eclogite-facies metamorphism is Caledonian (Griffin & Brueckner 1980) and the ages are in the range 410 to 420 Ma (Kullerud et al. 1986, and references therein). The WGR was decompressed almost isothermally to amphibolite-facies metamorphism at around 390–400 Ma (Kullerud et al. 1986; Andersen & Jamtveit 1990), most likely related to the extensional phase and associated footwall uplift.

The allochthonous Caledonian rocks in Sunnfjord comprise a series of thrust nappes, including Precambrian gneisses (The Dalsfjord Suite) and cover rocks (Høyvik and Herland Group), which is overlain by the Solund–Stavfjord Ophiolite Complex and the Sunnfjord Melange formed during obduction of the ophiolite (Brekke & Solberg 1987; Andersen et al. 1990; Furnes et al. 1990). The Devonian sediments rest partly with unconformity and partly with tectonic contact against the Caledonian rocks. The contacts with the eclogite-bearing rocks are, however, everywhere tectonic (Skjerlie 1969; Steel et al. 1985, and references therein; Swensson & Andersen 1987; Swensson 1990; Swensson & Andersen 1990).

The major shear zones that separate the allochthonous rocks and the Devonian sediments from the deep crustal rocks of the WGR are characterized by both mylonitic and cataclastic rocks, whereas mylonites dominate in the footwall and the cataclasites in the hanging wall (Brekke & Solberg 1987; Swensson 1990; Swensson & Andersen 1990; Chauvet & Séranne 1989). The main shear zone was named the Måløy Fault by Hossack (1984) and Nordfjord–Sogn Detachment by Norton (1986). In the present study, Nordfjord–Sogn Detachment (NSD) is preferred. Both Hossack (1984) and Norton (1986) suggested that NSD was a low-angle normal fault developed during major extension associated with the collapse of the Caledonian orogen during Late Silurian–Early Devonian times. During this event, low grade rocks of the Caledonian nappes were juxtaposed on the high grade metamorphic rocks of the WGR along the NSD. This model was demonstrated by microtectonic study of the Middle Devonian sediments and the basement in the Solund area by Séranne & Séguret (1987), Séguret et al. (1989) and Chauvet & Séranne (1989). The NSD comprises several segments (Swensson & Andersen 1990), of which the Kvamshesten Detachment Zone (KDZ) will be discussed here (Fig. 1). The KDZ segment of the NSD can be traced around the southern, eastern and northern margins of the Kvamshesten Basin (Fig. 1), affecting rocks of different tectonostratigraphic levels from east to west (Swensson & Andersen 1990). In the Atløy area (Fig. 1), the KDZ transects the Askvoll group, resulting in a sequence of heterogeneous and highly deformed rocks structurally overlying the gneisses of the WGR (Skjerlie 1969; Andersen et al. 1990; Brekke & Solberg 1987). The term 'Askvoll group' was introduced by Skjerlie (1969) and this term is retained but used informally, as it is uncertain to what extent it represents a coherent stratigraphic unit. The 'Askvoll group' has been interpreted as representing a metasedimentary and metavolcanic sequence deposited on the Baltic continental basement during the opening of the Iapetus Ocean (Skjerlie 1969; Furnes et al. 1976). The mylonites of the KDZ are truncated by the Dalsfjord Fault (DF), characterized by a breccia and fault gouge zone separating the mylonites of the footwall from the cataclastic rocks of the hanging wall (Swensson 1990; Andersen & Jamtveit 1990; Swensson & Andersen 1990).

The present study discusses three alternative contact relationships between WGR and the mylonites of the

Askvoll group: (1) the Askvoll group is the original cover to the underlying Precambrian basement, (2) it is a para-autochthonous to highly allochthonous composite unit emplaced during the Caledonian Orogeny, or (3) it is a highly deformed, phyllonitic part of the basement (Fig. 1). In addition, the internal tectonostratigraphy and tectonometamorphic evolution of the mylonites in the Atløy–Askvoll area will be discussed.

Lithological description

The basement gneisses (WGR)

The gneisses in the area studied form a westerly plunging antiform with a core of orthogneisses and an outer rim of paragneisses (Fig. 2). The antiform is best observed on SE Atløy, where the core comprises deformed migmatitic and granitic gneisses with lenses and boudins of amphibolites, metagabbros and zones of phyllonitic amphibolites (Fig. 2). A characteristic feature of these lithologies is plagioclase crystals with an outer rim of albite. Amphiboles in the mafic rocks are commonly replaced by biotite and chlorite. The mineral assemblages indicate that amphibolite-facies parageneses are replaced by greenschist-facies assemblages. Mafic lenses with preserved eclogite-facies assemblages occur east of the area shown in Fig. 2. Most minerals have undulose extinction. On the mainland, south of Askvoll (Fig. 2), the basement comprises mainly banded migmatitic and granitic gneisses. The gneisses are highly deformed and the mylonitic foliation is folded by isoclinal and sheath folds on centimetre and metre scale (Fig. 3A). Mafic rocks occur mainly as green phyllonitic horizons and metagabbro lenses. At Dorhella (Fig. 2), the gneisses are folded in open to slightly overturned asymmetric folds with northwesterly vergence (Fig. 3B).

The antiformal core at Atløy is bounded by a series of garnet-amphibole-bearing mica schists, metagabbros, augen gneisses, amphibolites and garnet-bearing metapsammites (Fig. 2). This is best observed in the coastal exposures from Brørvika to west of Garvika, where slices of augen gneiss have been interfolded or imbricated with metagabbros, amphibole–plagioclase gneisses and metapsammites. The minerals of the paragneisses are characteristic of amphibolite-facies conditions which in part have been extensively retrograded. Retrogression is shown by a replacement of garnet and amphibole by chlorite in the mafic rocks, indicating lower greenschist-facies retrograde metamorphism (Fig. 4). The metapsammite occurring between the imbricated and interfolded paragneisses and the orthogneisses (Fig. 2) has been mapped from Leirvågvika to Garvika around the antiformal crest and further to the east. It has not been possible to map the metapsammite northwest of

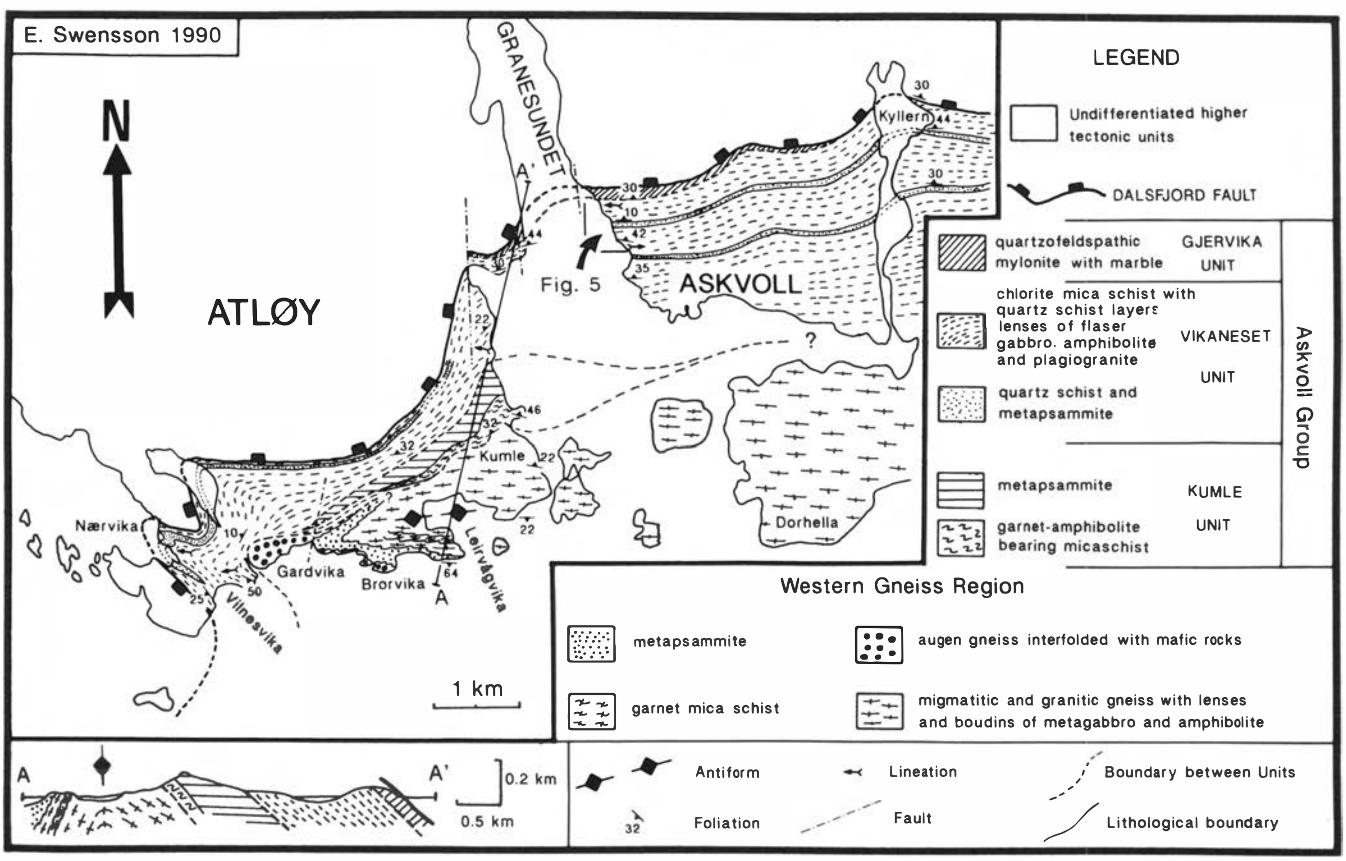


Fig. 2. Geological map of the Atløy–Askvoll area (see Fig. 1 for location). All further UTM coordinates refer to mapsheet Askvoll, no. 1117IV.

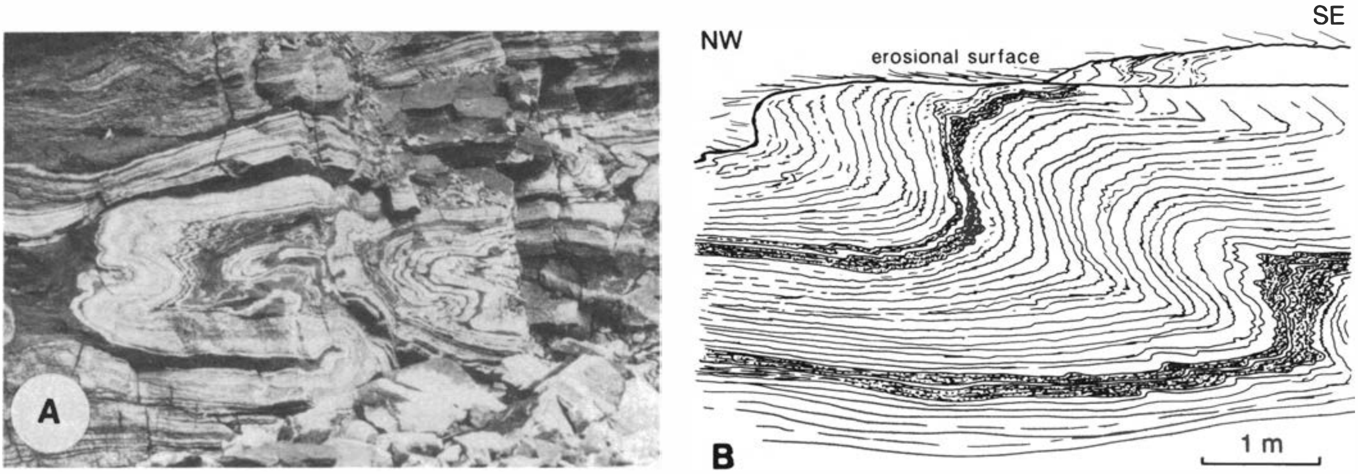


Fig. 3. (A) Intensely folded migmatitic gneiss of the WGR on the mainland south of Askvoll. Width of section is 3 m (UTM: 902–069). (B) Overturned fold in the migmatitic gneiss viewed in a NW–SE section on the mainland at Dorhella (UTM: 903–052).

Leirvågvika due to lack of exposures, but apparently it wedges out towards the lower part of the Askvoll group north of Leirvågvika (Fig. 2). Between the metapsammite and the migmatitic gneiss core observed west of Leirvågvika, garnet-mica schists are found (Fig. 2). The mica schist horizon is only exposed in the southern limb of the antiform and it is not clear whether it is continuous around the crest of the antiform. The boundary between the metapsammite and the underlying rocks is folded with foldaxes ca. 270/20–40 and axial plane 273/74.

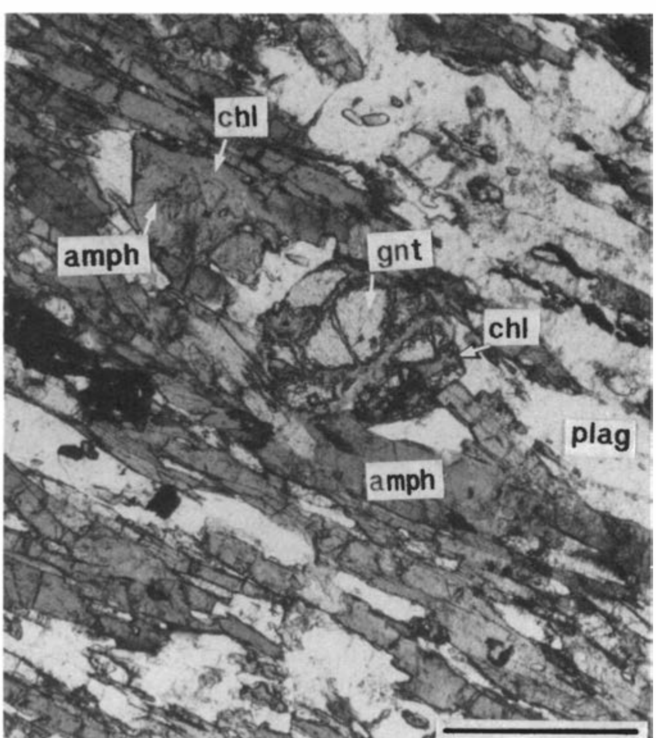


Fig. 4. Photomicrograph of garnet–amphibole-bearing metagabbro from the area between Garvika and Brørvika. Garnet (gnt) and amphibole (amph) are in part replaced by chlorite (chl) (UTM: 857–053). Scale bar: 0.5 mm.

Rocks assigned to the Askvoll group

The Askvoll group comprises mylonitic to phyllonitic rocks of variable composition. It is dominated by a sequence of mafic chlorite-mica schist with horizons of marble and quartz–feldspathic schists, possibly of psammitic origin (Fig. 2). Due to a high content of feldspar, however, an igneous origin for these rocks cannot be ruled out. This will be discussed later, but in the present description the term metapsammite is used. The Askvoll group has been subdivided into three units: the upper Gjervika Unit, the middle Vikaneset Unit and the lower Kumle Unit (Figs. 2 and 5).

The Gjervika Unit comprises quartzofeldspathic mylonites and marbles, and has a structural thickness of approximately 25–50 m. It is best developed in the coastal areas on both sides of Granesundet (Fig. 5), and thins out laterally towards both east and west, where it is truncated by the Dalsfjord Fault (Fig. 2). The quartzofeldspathic mylonites are intensely folded and contain thin layers (< 1.0 cm) of more micaceous material (Fig. 6A). The quartz-feldspar bands (1–5 cm thick) comprise dynamically recrystallized quartz, quartz ribbons, deformed and rotated feldspar porphyroclasts, together with minor amounts of chlorite, biotite and pyrite (Fig. 6B). The micaceous layers contain muscovite, chlorite and plagioclase, with traces of sphene and pyrite (Fig. 6B). On the eastern side of Granesundet, the lower contact of this unit is defined by a 1–2 m thick bluish grey marble horizon (Fig. 5). This layer contains thin bands (< 0.5 cm) enriched in muscovite, plagioclase, quartz and pyrite, alternating with thicker horizons of calcite and possibly dolomite. The calcite grains are normally recrystallized, although some larger grains (> 0.1 mm) have undulose extinction with deformation lamellae and bands. The boundary between the Gjervika Unit and the Vikaneset Unit is marked by a change in lithology from quartz-rich mylonites to mylonites dominated by chlorite and mica (Fig. 5).

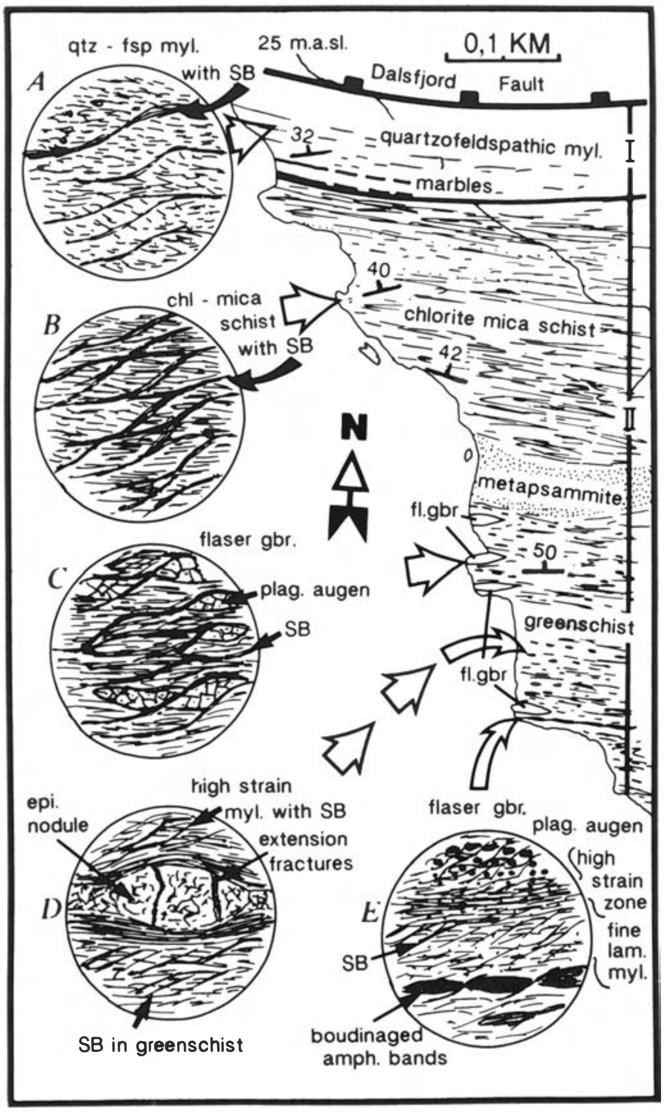


Fig. 5. Detailed geological map of Gjervika Unit (I) and Vikaneset Unit (II), eastern side of Granesundet. Shear bands (SB) are developed in all lithologies. Displacement is towards the west (see Fig. 2 for location). Circle diameter is 15 cm in A, B and C and 25 cm in D and E. Abbreviations: qtz-fsp myl = quartzofeldspathic mylonite, SB = shear band, chl = chlorite, epi = epidote, amph = amphibolite, lam myl = laminated mylonite, plag = plagioclase, fl gbr = flaser gabbro.

The Vikaneset Unit comprises green to grey mylonitic and phyllonitic chlorite mica schists with distinct horizons of quartz-rich schist. The structural thickness of this unit is more than 1 km in the Granesundet area, but decreases towards the W. (Fig. 2). The chlorite mica schist and greenschists contain thin layers of light coloured quartzofeldspathic layers (0.1–4 m thick) (Fig. 7A). The green mylonites have a mineral assemblage characterized by chlorite, epidote, plagioclase and biotite, with various amounts of amphibole, quartz, muscovite and garnet (Fig. 7B and C). Undulose extinction is abundant and quartz grains are normally dynamically recrystallized. Extensive alteration of hornblende to actinolite during the early mylonitization can be observed in the upper part of the sequence. A still later retrogression to chlorite is extensive throughout the sequence (Fig. 7B). Locally, more massive layers and boudins are found within the highly foliated green and grey mylonites. These comprise amphibolites and saussuritized gabbroic lenses in which relict igneous textures are locally preserved. Light coloured bands of deformed plagiogranites are also preserved. Epidote nodules and lenses commonly occur as competent inclusions in the mylonites. These epidote inclusions range in size from 1 cm to more than 20 cm, and form together with the larger bodies (several metres across) of plagiogranites, flaser gabbros and amphibolites, the probable remnants of different igneous protoliths comprising greenstones, gabbros and trondhjemitic dikes.

The quartz-rich schist can be mapped continuously from Vilnes on Atløy towards Granesundet. It outcrops 20 to 40 m below the Dalfjord Fault (Fig. 2). The schist is composed of quartz, microcline, muscovite, plagioclase and epidote, with traces of sphene, pyrite, garnet and biotite (Fig. 8A). The microcline grains have polysynthetic twinning, and observation of perthite may indicate an igneous origin. The quartz grains have undulose extinction with the development of low-angle grain boundaries. Evidence of dynamic recrystallization has not been recognized. The penetrative deformation is also shown by stretched feldspar porphyroclasts and bent muscovite (Fig. 8A). The contact between the quartz-rich schist and the surrounding mafic sequence is sharp and parallel with the foliation (Fig. 8B).

The boundary between the Vikaneset Unit and the Kumle Unit in the east is defined by a change from chlorite mica schist in the former to metapsammitic rocks and garnet-amphibolite-bearing mica schist in the latter (Fig. 2). Identification of the boundary is problematic in the west as the Kumle Unit apparently thins out in a westerly direction. The Kumle Unit comprises a metapsammitic horizon and coarse-grained garnet–amphibolite-bearing mica schist which can be mapped from Granesundet in the east towards Leirvågvika (Fig. 2). The metapsammitic horizon can be followed from Granesundet in the east to Garvika in the west, where it thins out (Fig. 2). The horizon has a maximum structural thickness of 350 m consisting of quartz, plagioclase, muscovite and epidote with traces of sphene, garnet, chlorite and pyrite (Fig. 9A). Local high strain zones on microscale indicate that small-scale deformation was heterogeneous (Fig. 9B). The structural thickness of the garnet–amphibolite-bearing mica schist is reduced from the coastal exposures at Granesundet (200 m) to north of Kumle (50 m) (Fig. 2). Further to the west the unit is assumed to wedge out north of Leirvågvika. The mineral assemblage includes muscovite, quartz, garnet, biotite, amphibole, plagioclase and epidote, with traces of sphene, chlorite and pyrite (Fig. 10). Garnet porphyroclasts up to 2 cm across have been observed. The mica schist contains abundant asymmetric lenses and boudins of medium to coarse-grained garnet amphibo-

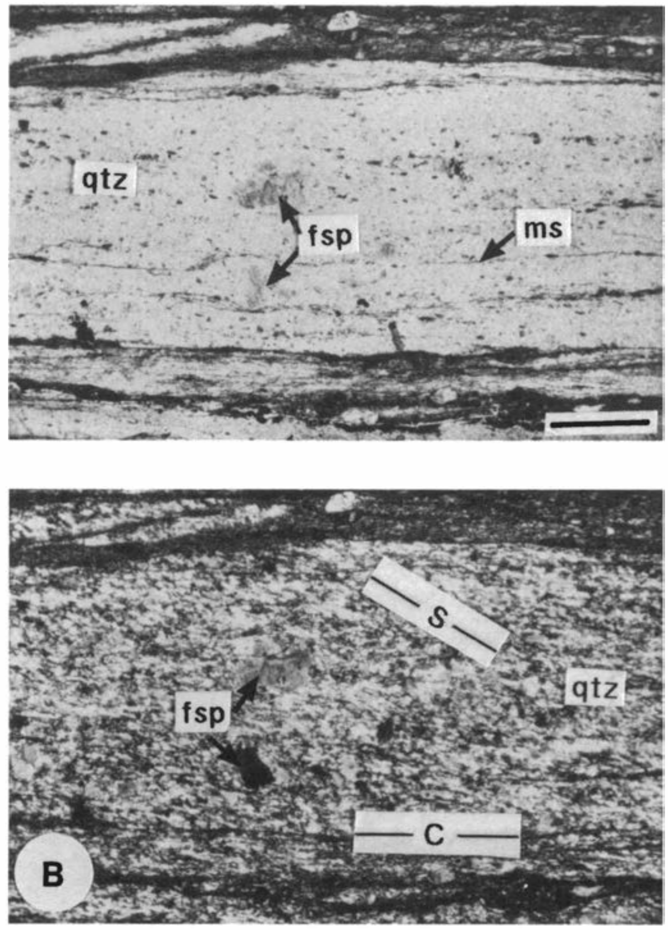


Fig. 6. (A) N–S section of intensely folded quartzofeldspathic mylonite with a northerly dipping axial surface (north is to the right). Foldaxes plunge gently towards the west (UTM: 876–090). Width of section is 35 cm. (B) Photomicrograph of quartzofeldspathic mylonite from 5 m below the Dalsfjord Fault at the western side of Granesundet. Layers of dynamically recrystallized quartz (qtz) have a preferred orientation (S) to the main foliation (C). Deformed feldspar clasts (fsp) occur within the layer together with mica seams (ms). Displacement is to the west (left). Scale bar: 0.5 mm.

lites, which probably represent highly attenuated mafic dikes.

In the Askvoll area, on the eastern side of Granesundet (Fig. 2), only the Gjervika Unit and the Vikaneset Unit have been recognized. There is a change in the Gjervika Unit in the Askvoll area (Fig. 2), where the quartzofeldspathic mylonite has a higher feldspar content than those observed at Atløy. At Kyllern (Fig. 2), only the Vikaneset Unit has been recognized. Here, the upper quartz schist has a structural thickness of less than 10 m and is interfolded with calcite-rich horizons (0.5–5 cm thick). The mineral assemblage is comprised of quartz, muscovite, microcline, plagioclase and tourmaline, with traces of sphene, epidote and zircon. Tourmaline has not been observed in the rocks on Atløy, which differs from the quartz schists in the Askvoll area in the east by their higher content of microcline and epidote. Lack of exposures in the farmland and forested areas east of Granesundet makes it difficult to map the lower part of the Askvoll group and the contact to the orthogneisses in the basement in detail. Further to the east, at Eikeneset (Fig. 1), a coarse-grained garnet-bearing mica schist similar to the one in the Kumle Unit occurs near or within the WGR.

The nature of the contact between the Askvoll group and WGR

The contact between the basement gneisses and the Askvoll group is exposed only locally on Atløy. A new road section north of Kumle (Fig. 2) exposes a highly sheared contact between the quartzofeldspathic schist of the basement and the deeply weathered and phyllonitic garnet-amphibolite-bearing mica schist of the Kumle Unit. The foliation is orientated 285/46N, the contact is orientated 226/32NW, whereas the foliation in the underlying foliated gneisses is orientated 200/15NW, indicating a structural discordance between the Kumle Unit and the basement gneisses at this locality. Further to the west, at Garvika (Fig. 2), a chlorite mica schist and greenschist of the Vikaneset Unit rest directly upon rocks of the underlying gneisses, and the characteristic garnet-amphibolite-bearing mica schist of the Kumle Unit is missing. The contact in this area can only be inferred from difference in lithology and structural style between the basement and the overlying Vikaneset Unit. The structures in the basement are characterized by large-scale isoclinal folds and imbrication affecting several lithological layers in the tectonostratigraphy. The Askvoll

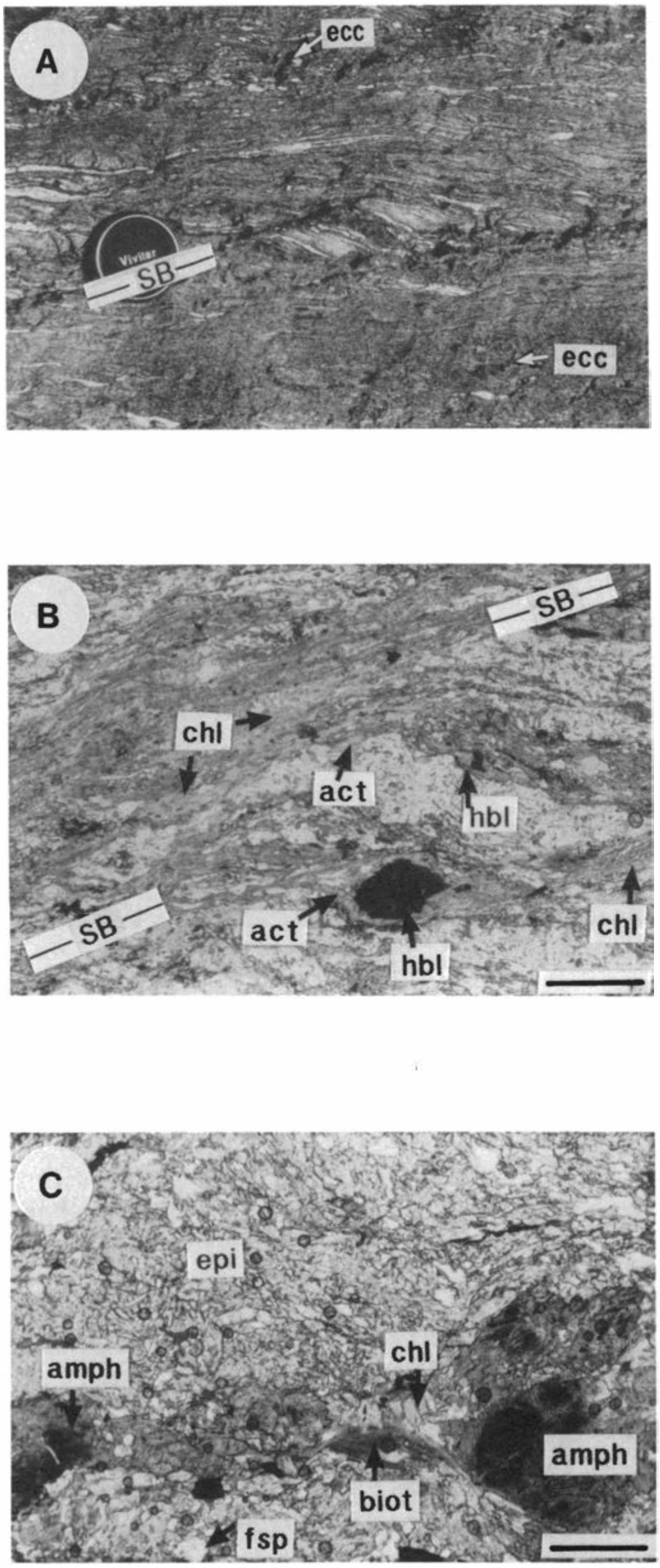
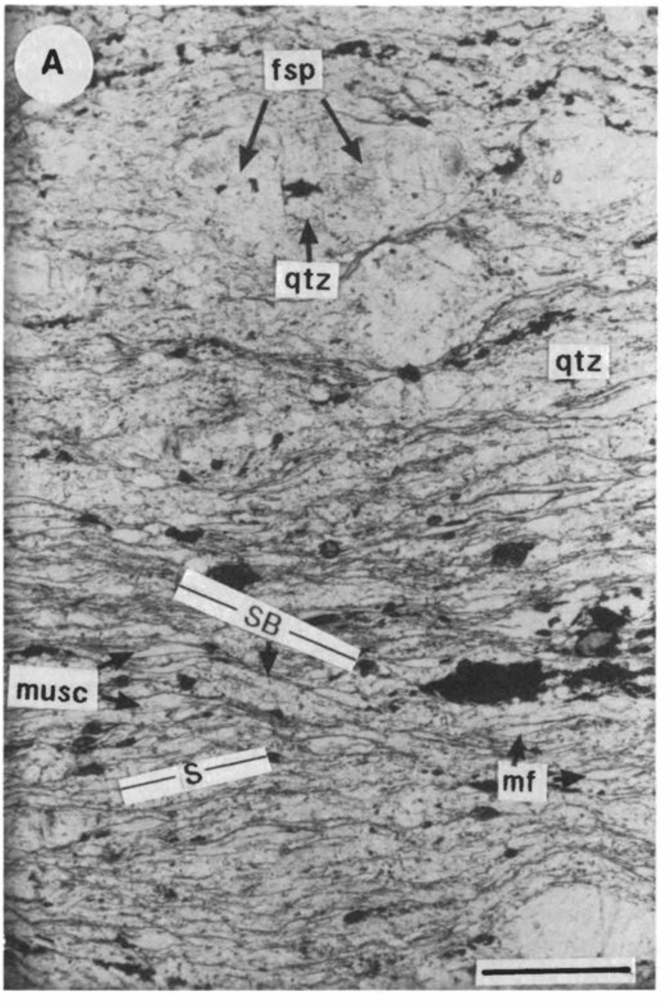


Fig. 7. (A) Shear bands (SB) and extensional crenulation cleavage (ecc) in the mafic sequence form the upper part of the Vikaneset Unit, western side of Granesundet. Displacement is to the west (left). Width of section is 50 cm (UTM: 876–087). (B) Photomicrograph of the chlorite mica schist, Vikaneset Unit western side of Granesundet. Hornblende (hbl) has been retrogressed to actinolite (act) with further retrogression to chlorite (chl). Shear bands (SB) are defined by both actinolite and chlorite. West is to the left (UTM: 872–078). Scale bar: 0.5 mm. (C) Photomicrograph of possible protolith comprising: epidote (epi), amphibole (amph), biotite (biot), chlorite (chl) and feldspar (fsp) (UTM: 872–078). Scale bar: 0.5 mm.

group is also characterized by isoclinal folding, but here the folding is mainly intrafolial and does not affect the boundaries between different lithologies to the same degree. Between the interfolded and imbricated metapsammite in the basement and the metapsammite of the Kumle Unit lies a chlorite mica schist which thins out towards the east between the metapsammite and the garnet-amphibolite-bearing mica schist of the Kumle Unit. The map (Fig. 2) shows that the metapsammite in the basement can be traced around the antiform, and that it is apparently truncated along the northern limb of the antiform by the overlying Vikaneset and Kumle Units, indicating the presence of a tectonic slide at this contact. It is not possible to observe the truncation in the field due to lack of exposures. Further to the west, towards Vilnesviken, the contact is characterized by a zone of interfolded augen gneiss, amphibolites and metapsammites in contact with the chlorite mica schist of the Vikaneset Unit of the Askvoll group.

Structures

A detailed structural analysis of the area is not the object of the present study. However, a few important observations relevant for discussion of the basement cover problem are given. The detailed structural geology of the mylonitic sequence of Kvamshesten Detachment Zone will be presented elsewhere. One aspect of major importance is the abundant occurrence of shear bands in all of the different lithologies (Fig. 7A). The shear bands strike generally NNE–SSW with a moderate to steep dip towards WNW and have a normal sense of movement (Fig. 7A). Generally, they postdate the mylonitic fabric, but are themselves associated with ductile deformation involving dynamic recrystallization of quartz and retrogression of amphibole and biotite to chlorite, which defines the slip surfaces (Fig. 7B). There is a significant change in the orientation of the foldaxes and foliations from the basement into the Askvoll group (Fig. 11). In the Askvoll group the foldaxes generally have an E–W trend with a westerly plunge of 5–15°. Poles of the foliations plot along a N–S great circle with a maxima of poles in the south (Fig. 11A). The great circle is a result of the late mesoscopic folds, syn-genetic with the mapped large-scale fold on SE Atløy (Fig. 2). In contrast, azimuths of foldaxes from the basement plot more randomly, generally with a gentle plunge (<35°) (Fig. 11B). There is an increase in preferred orientation of the foldaxes from the basement gneisses into the Kumle Unit and the Vikaneset Unit. The stretching lineations have an E–W to ENE–WSW trend with a gentle plunge towards east or west (Fig. 11C) and are defined by stretched and recrystallized quartz and stretched feldspar. This trend is also observed in the upper part of the basement gneisses, but it is not so well defined in the structurally lower parts of the migmatitic and granitic gneisses.



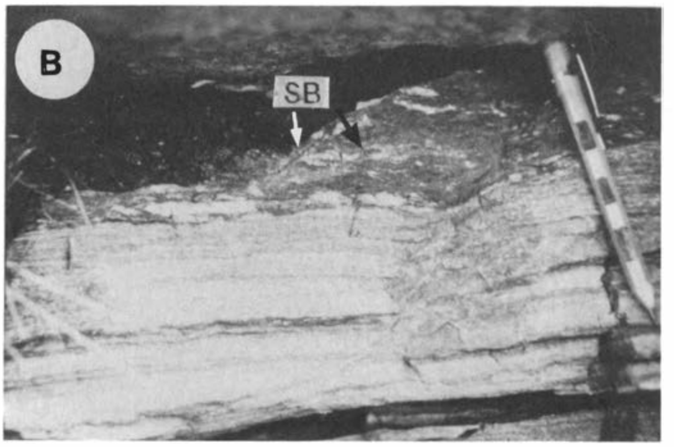
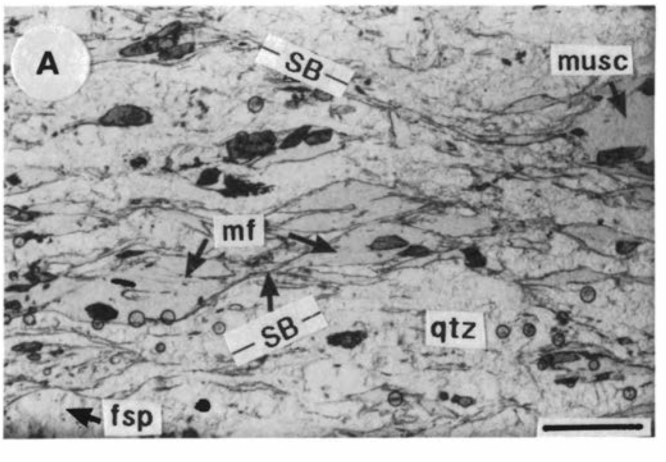


Fig. 8. (A) Photomicrograph of quartz schist (Vikaneset Unit) with stretched feldspar (fsp), mica-fishes (mf), quartz (qtz) and shear bands (SB). The foliation (S) has been rotated due to the listric nature of the shear bands. West is to the right (UTM: 836–054). Scale bar: 0.5 mm. (B) Upper boundary between the chlorite–mica schist (upper) and quartz schist (lower) north of Vilnesvika. Mesoscopic shear bands (SB) can be observed in the chlorite–mica schist, indicating displacement towards the west (left) (UTM: 835–053). Pencil for scale.

Discussion

Three alternative relationships between the Askvoll group and the underlying rocks can be suggested: (1) The Askvoll group represents the original cover to the underlying Precambrian basement, (2) it represents a para-autochthonous to highly allochthonous composite unit with an internal tectonostratigraphy emplaced during the Caledonian Orogeny, or (3) it is a highly deformed, phyllonitic part of the basement.

The most prominent feature relevant for this discussion is the marked difference in lithologies on either side of



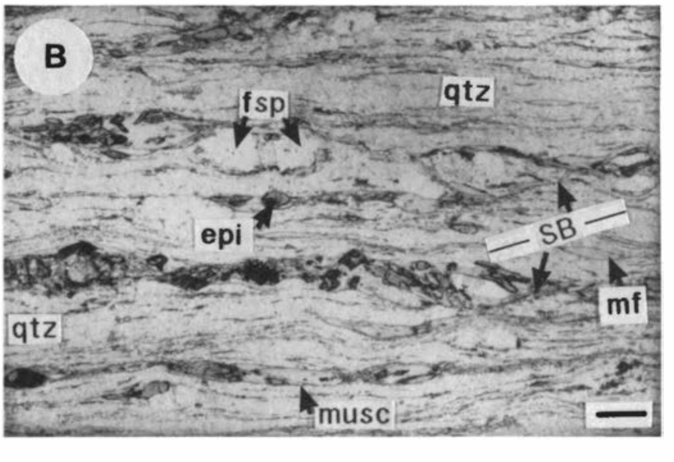


Fig. 9. (A) Photomicrograph of the metapsammite (Kumle Unit) showing mica-fishes (mf) and shear bands (SB). Recrystallized quartz (qtz) and stretched feldspar clasts (fsp) together with muscovite (musc) occur as lenses bounded by shear bands (UTM: 874–072). Scale bar: 0.5 mm. (B) Photomicrograph from the same sample as Fig. 11b. Stretched feldspar clasts (fsp) and boudinaged muscovite (musc) occur together with high strain zones of recrystallized quartz (qtz). Shear bands (SB) are abundant. Scale bar: 0.5 mm.

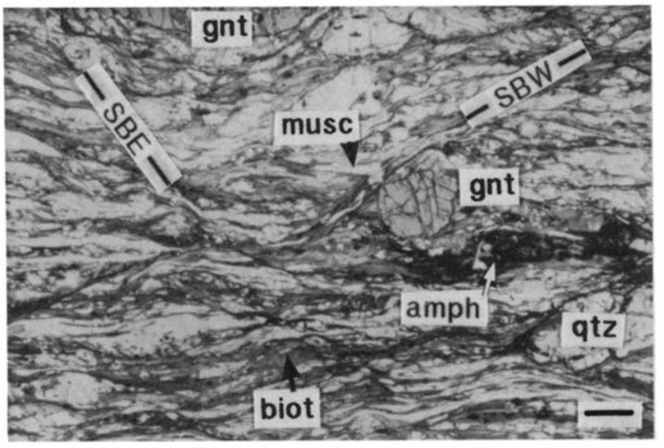


Fig. 10. Photomicrograph of the garnet–amphibolite-bearing mica schist, lower Kumle Unit. Fractured garnets (gnt) occur together with amphibole (amph), muscovite (musc), biotite (biot), and quartz (qtz). Shear bands dip towards the east (SBE) and west (SBW) (UTM: 875–068). Scale bar: 0.5 mm.

the Kumle Unit. The lithologies above the Kumle Unit are dominated by mylonitic chlorite schists, greenschists and quartz-rich schists or metapsammites, with intensely sheared boundaries between the different lithologies. They also contain remnants of an igneous complex of greenstone, gabbro and trondhjemites. The underlying basement comprises migmatitic and granitic gneisses, metagabbro, with infolded isoclines of metapsammites and garnet mica schist. Isoclinal folds are also common in the Askvoll group, but mainly as intrafolial folds. There is also a difference in foldaxis orientation between the basement and Askvoll group. In the basement the foldaxes are oriented more randomly than in the overlying rocks, where these structures have a highly preferred orientation (Fig. 11A and B). This could indicate that the lower rocks were affected only to some extent by the deformation. The change in foldaxis orientation shows that the upper and middle parts of the mylonite zone were subjected to intense deformation and mylonitization during westward translation of the structurally higher units. Similar observations were made by Chauvet & Séranne (1989) in the Hyllestad–Solund area.

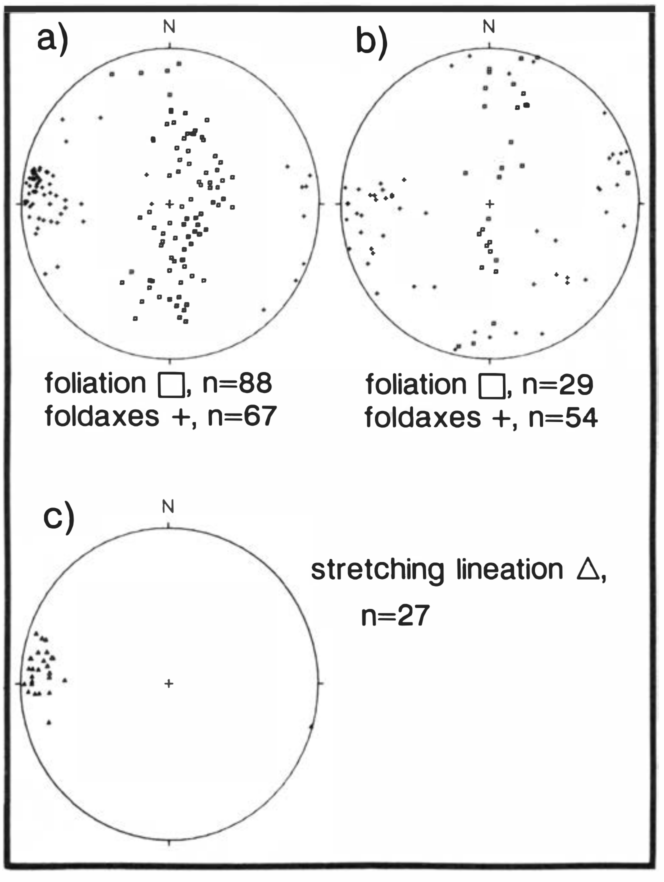


Fig. 11. Equal-area stereographic projections (Schmidt nett, lower hemisphere) of: (a) foliation and foldaxes in the Askvoll group, (b) foliation and foldaxes in the WGR, and (c) stretching lineation in the Askvoll group.

The Kumle Unit, with metapsammite and coarse-grained garnet-amphibolite bearing micaschist, is quite different from the overlying mafic mylonites, but is very similar to the rocks observed in tight folds in the upper part of the basement. The metapsammite in the basement is also locally associated with a garnet-amphibole-bearing mica schist (Fig. 2, Leirvågvika area). It is clear that the mica schist and metapsammite of the Kumle Unit have been translated westward along a late shear zone, and that the Kumle Unit is structurally separated from the mica schist and metapsammite which overlies the gneisses near Leirvågvika (Fig. 2). The similarities in lithology, mineral assemblages and textural development between the Kumle Unit and the metasediments which are infolded and imbricated with the gneisses suggest a common origin for these metasedimentary rocks. If this correlation is correct, it is likely that the metasediments originally constituted a sedimentary cover to the gneisses, and they could be interpreted as part of the late Proterozoic cover rocks on the gneisses (Fjordane Complex by Bryhni 1966, Skjerlie 1969, Krill 1985). It has not been possible, however, to verify this interpretation by observation of preserved primary depositional basement cover relationships. Hence, it is therefore not possible to exclude the Kumle Unit as part of the Askvoll group.

The lithological and compositional differences between the upper parts of the Askvoll group (Vikaneset and Gjervika Units) and the basement indicate that the rocks in the upper part of the Askvoll group could not have been derived from the underlying basement as a result of mylonitization. Generally the basement is rich in quartz and feldspar, which is in contrast to the mica, chlorite and amphibole-dominated rocks in the mafic sequence in the Askvoll group. A different origin for this mylonitic sequence is therefore suggested. Some of these lithologies clearly have a sedimentary origin, such as the marbles and the tourmaline-bearing metapsammite east of Granesundet. Furnes et al. (1976) argued for a volcanic origin for the mafic sequence and geochemical analysis shows that some of these rocks have a tholeiitic and andesitic composition. They suggested that the Askvoll group was a sedimentary and volcanic sequence.

The origin of the quartz-rich schists and metapsammitic horizons of the Vikaneset Unit on Atløy remains enigmatic. They may have been developed either from sandstones or by intense deformation of granitic to granodioritic intrusives; however, no intrusive relationships have been observed.

The observed metamorphic assemblages in the Askvoll group indicate a peak metamorphism at the amphibolite-facies conditions. Contemporaneously with the deformation and the development of the mylonitic fabric, hornblende recrystallized to actinolite, indicating a decrease in P and T. Continuous deformation was accompanied by a decrease in metamorphic grade, from amphibolite-facies to greenschist- and lower greenschist-facies metamorphism, indicated by a massive chloritization of the mafic rocks (Winkler 1979). This is in accordance with observations made by Chauvet & Séranne (1989) in the Hyllestad–Solund area. Minerals in the Askvoll group, especially quartz, commonly have undulose extinction, indicating continuous deformation and limited annealing of the deformed fabrics. The basement rocks also have early mineral assemblages of amphibolite-facies metamorphism. Eclogites have not been observed in the studied area, but are observed within the basement further east and on the south side of Vilnesfjorden (Fig. 1). Retrogression of the basement is most penetrative in its upper part, where both garnet and amphibole are partly to completely replaced by chlorite (Fig. 4). This indicates that no significant metamorphic break existed between the basement and the overlying Askvoll group during the mylonitization. Both rock units consisted of amphibolite-facies minerals in the early stages of the mylonitization. The regional amphibolite-facies metamorphism in the WGR has been dated to around 400 ± 10 Ma (Rb–Sr whole rock and mineral ages, also including K–Ar, Ar–Ar, Sm–Nb and U–Pb data, Kullerud et al. 1986, and references therein), which gives a maximum age for the earliest fabric presently recognized in the Askvoll group. After this metamorphism, all rocks were subjected to the same retrograde metamorphic evolution. By this time the entire Askvoll group acted as a cover to the basement. A variety of structures and textures which form the tectonite fabric in the mylonites demonstrate down-to-the-west movement of the hanging wall (Norton 1986; Swensson & Andersen 1987, 1990; Chauvet & Séranne 1989). This is also constrained by the penetrative WNW–ESE orientation of the stretching lineation with a dominantly westerly plunge (Fig. 11C), and the stretched feldspar porphyroclasts in the quartzo-feldspathic mylonites. Textures such as shear band slip surfaces defined by actinolite and chlorite, and dynamically recrystallized quartz, show that the shear deformation in the Askvoll group was contemporaneous with the retrogression from the amphibolite-facies to lower greenschist-facies metamorphism. The same structural development has been proposed by Chauvet & Séranne (1989) for the evolution of the shear zone on the eastern side of the Solund Devonian basin. From the above, the Askvoll group could either represent an original cover to the underlying basement or an allochthonous rock sequence emplaced during the compressional phase of the Caledonian Orogeny. One major problem regarding this interpretation is the lack of structures within the Askvoll group showing that it participated in the eastward thrusting and imbrication which took place during the compressional event. Only structures indicating westward movement of the hanging wall are observed in the mylonites. This indicates that the older tectonic fabric was either totally overprinted by the later extensional event, or the Askvoll group was little affected by deformation during the compressional phase and was first activated during the back-gliding of the nappes related to the orogenic collapse.

Further to the south, in the Hyllestad area (Fig. 1), rocks similar to the Askvoll group are situated between the Solund Devonian basin and eclogite-bearing basement gneisses (Kildal 1970). This sequence comprises a lower part with garnet kyanite-bearing pelitic and quartzitic schists and an upper part with greenschists, marbles and limestones, which are interpreted as being part of the allochthons. The kyanite schist overlies eclogite-bearing gneisses of the WGR, but exhibits high-pressure assemblages consistent with eclogites in the WGR. The upper part could be equal to the Askvoll group, and does not contain high-pressure assemblages (Pinardon et al. 1990).

Assuming that the correlation between the Askvoll group and the upper part of the rock sequence in Hyllestad is correct, the Askvoll group, at least the upper parts (the Gjervika and Vikaneset Units) have many similarities with the eugeoclinal rocks of West Norway, and thus represent allochthonous cover to the underlying Precambrian basement. The question remains whether the lowermost sedimentary rocks, i.e. the metapsammite and coarse-grained garnet-amphibolite-bearing mica schist of the Kumle Unit was part of this allochthonous unit, or whether it constituted an original cover to the gneisses. Furthermore, the tectonostratigraphy in the Askvoll–Atløy area is quite similar to the sequence described by Krill (1980) in the Oppdal area. The upper part of the Askvoll group (the Gjervika Unit and the Vikaneset Unit) could be equivalent to the Tronget Unit (Krill 1980), which comprises biotite–chlorite phyllite and schist, metavolcanics and metasediments of possible Lower Palaeozoic age. The Kumle Unit could be correlated with the Blåhø Unit (Krill 1980) comprised of garnet-mica schist, amphibolites and serpentinite also of possible Lower Palaeozoic age. The underlying rocks, i.e. the metapsammite and garnet-amphibole-bearing mica schist, which we have assigned to be part of the WGR, could be the equivalents to the Risberget, Åmotsdal and Lønset Unit (Krill 1980) and of Proterozoic age, and part of the autochthonous and parautochthonous basement. Similarities between the lithologies in these two areas indicate that the Askvoll group is an allochthonous sequence, possibly part of the Middle Allochthon tectonically emplaced upon the Lower Allochthon and the Parautochthonous rocks during the compressional phase of the Caledonian Orogeny. The later phase with crustal extension and the development of the KDZ and the DF reworked and thinned the Caledonian tectonostratigraphy dramatically, making regional correlations difficult.

Based on the tentative correlation between the rocks of the Hyllestad, Oppdal and Askvoll areas (Gjervika Unit and Vikaneset Unit), the Askvoll group may represent allochthonous rocks emplaced during the compressional phase of the Caledonian Orogeny. The Askvoll lithologies may have been a major thrust zone during the emplacement of the Upper and Middle Tectonic units (Brekke & Solberg 1987; Andersen et al. 1990), which was later reactivated as a large-scale extensional shear zone associated with retrograde metamorphism during the late-orogenic collapse.

Conclusions

1. The Askvoll group comprises three tectonostratigraphic units: the Gjervika Unit (upper), the Vikaneset Unit (middle) and the Kumle Unit (lower).
2. The Gjervika Unit and Vikaneset Unit of the Askvoll group probably represent eugeoclinal allochthonous rocks with respect to the Kumle Unit and WGR.
3. The Kumle Unit may represent an original sedimentary cover sequence to the orthogneisses of the WGR (belonging to the Fjordane Complex) or be the lowermost part of the Askvoll group and part of the allochthon.
4. Compressional structures related to the emplacement of the Caledonian nappes have been completely overprinted by mylonitization during the orogenic extensional collapse.
5. The extensional movements were accompanied by footwall uplift which caused retrogression from amphibolite- to low-greenschist-facies metamorphism. This is in agreement with the conclusions drawn by Chauvet & Séranne (1989) for the Solund area.
6. The Askvoll group and the upper part of the WGR have a common tectonometamorphic development during later stages of the extensional collapse.

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