Interpretation of kinematic indicators along the northeastern margin of the Bergen Arc System: a preliminary field study

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The Fensfjorden Fault separates the Bergen Arc System and the Devonian conglomerates of the Fensfjorden Basin from the Western Gneiss Complex. Detailed mapping of kinematic indicators along the northeastern margin of the Bergen Arcs reveals a distinct pattern. In the upper part of the section, a zone of sinistral movement indications is observed. In contrast, indications of dextral movements are observed in the lower part of the section and along the Fensfjorden Fault, related to a stretching lineation trending about 295° and plunging about 20°W. The dextral movements are tentatively correlated with the regional late Caledonian 'top-to-west' movements associated with the formation of the Devonian basins of western Norway. It is suggested that the zone of dextral kinematic indicators represents the southern continuation of the Nordfjord–Sogn Detachment.

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Introduction

The Bergen Arc System is composed of five rock units of different lithologies and metamorphic grade, with tectonic contacts which show an arcuate outcrop pattern surrounding Bergen (Kolderup & Kolderup 1940). The contacts between the main rock units have been interpreted as thrusts by most authors (e.g. Færseth et al. 1977; Sturt & Thon 1978) resulting from a polyphasal deformation history during the Caledonian Orogeny. The Caledonian orogen in Scandinavia resulted from the convergence of Laurentia and Baltica in late Ordovician to early Devonian times. During the main orogenic phase (late Silurian/early Devonian), a nappe wedge was established with transport direction mainly towards the SE over the margin of Baltica (Sturt et al. 1975; Sturt & Thon 1978; Roberts & Sturt 1980). Late/post orogenic extensional tectonics are thought to have led to the formation of Devonian basins in western Norway, including the Fensfjorden Basin in the northern part of the Bergen Arc System (Hossack 1984; Norton 1986; Séranne & Seguret 1987; Andersen & Jamtveit 1990). Recent data presented by Fossen (1992) suggest that 'top-to-west' extensional tectonics had a more regional significance in South Norway. 'Top-to-west' sense of movement has also been confirmed in shear zones of the Øygarden Complex, the westernmost unit of the Bergen Arc System (cf. Rykkelid & Fossen 1992).

An important feature of the late/post Caledonian extension of western Norway is the Nordfjord–Sogn Detachment which is a complex, low-angled normal-sense shear zone (Hossack 1984; Norton 1986, 1987). The hanging wall of this shear zone (upper plate) consists of a Precambrian basement with a late Precambrian to Silurian sedimentary cover, the Solund–Stavfjord Ophiolite Complex and Devonian clastic sediments (Andersen et al. 1990). The deformation of these is characterized by extensional reactivation of contractional shear zones and fabrics under progressively more brittle conditions (Osmundsen & Andersen 1994). The footwall to the detachment (lower plate) comprises the 'Caledonized' Precambrian basement of the Western Gneiss Complex (WGC),[1] characterized by polyphase Caledonian deformation and metamorphism, including an early phase of eclogite formation (Milnes et al. 1988). The extension of the lower plate is, according to Andersen & Jamtveit (1990), characterized by inhomogeneous non-coaxial deformation superimposed on the earlier fabrics. The extensional nature of the detachment is supported by investigations of kinematic indicators. Stretching lineations have plunges between W and NW, and asymmetric structures indicate non-coaxial progressive deformation as the hanging wall of the Nordfjord–Sogn Detachment was displaced westward to northwestward relative to the footwall (e.g. Chauvet & Séranne 1989; Andersen & Jamtveit 1990; Swensson & Andersen 1991).

The Fensfjorden Fault (Fig. 1) is a major brittle structure which marks the northeastern margin of the Bergen Arc System towards the WGC. In the outer parts

[1] We use the term Western Gneiss Complex (WGC) in favour of the more traditional but vaguer 'Western Gneiss Region' to indicate that we are referring to a specific tectonic unit. This unit has particular characteristics, which have been described in detail along the Sognefjord section (Milnes et al. 1988) and which are found in the whole area south of Sognefjord (Fig. 1). North of Sognefjord, other units appear which are tectonically distinct (e.g., the Lavik Mafic Complex, Fig. 1), but there is as yet no consensus on the location of the main tectonic boundaries – which is possibly why the geographic term 'region' is still favoured by some authors.

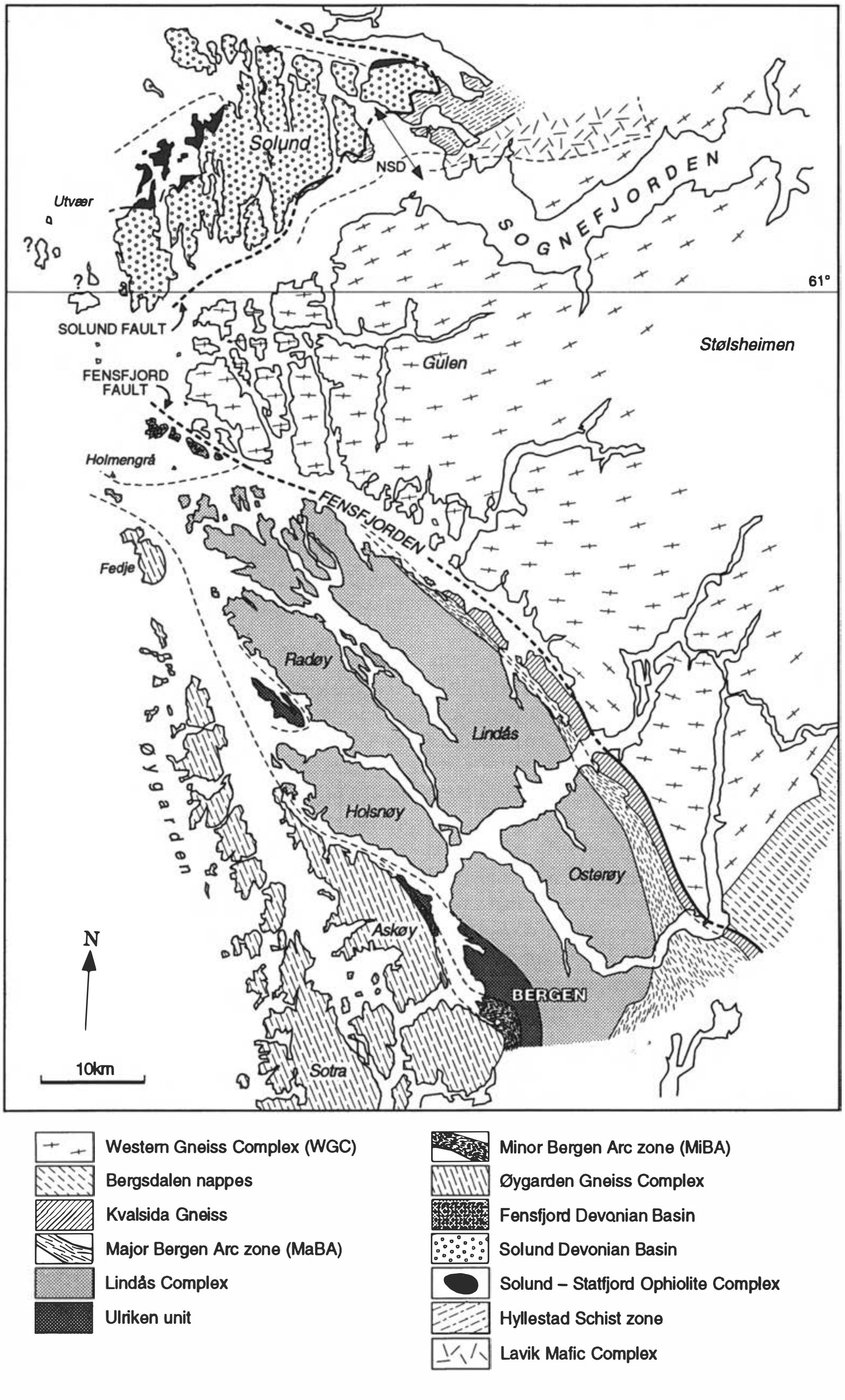


Fig. 1. Simplified geological map of the northern part of the Bergen Arc System. Location of the investigated area is framed (see Fig. 2). NSD shows the approximate extent of the Nordfjord–Sogn Detachment.

of Fensfjorden, the fault separates the Devonian sediments of the Fensfjorden Basin from the WGC, and to the southeast it truncates the Bergsdalen Nappes. Dextral movements along the zone containing the Fensfjorden Fault have recently been indicated in more regional papers by Séranne et al. (1991) and Fossen (1992). This zone is interpreted by Fossen (1992) to be part of a curved large-scale extensional shear zone, transecting and extending the Caledonian Orogen during a late/post-orogenic phase, and has also been suggested to represent the southward continuation of the Nordfjord–Sogn Detachment as defined by Norton 1987 (e.g. Milnes et al. 1988). The zone containing the Fensfjorden Fault follows Fensfjorden to a large extent, but continuous profiles are exposed on Osterøy (Henriksen 1979) and at the neck of the Lindås Peninsula. The latter is the main focus of the present work (framed in Fig. 1). In time, more detailed investigations will be carried out and the area will be extended along the Fensfjorden. This article is only a presentation of some preliminary results based on recent field work.

Main rock units

The WGC is the lowermost tectonostratigraphic unit along the western coast of South Norway. Radiometric age determinations indicate two pre-Caledonian tectonothermal events within the WGC, one middle Proterozoic (1750–1450 Ma) and one late Proterozoic (900–1000 Ma) (Kullerud et al. 1986; Milnes et al. 1988). Eclogites within the WGC show Caledonian ages in the range of 400–450 Ma (e.g. Krogh et al. 1974; Griffin & Brueckner 1980, 1985; Mearns & Lappin 1984). Superimposed on the eclogites is amphibolite facies metamorphism dated at 390–400 Ma (e.g. Andersen & Jamtveit 1990; Chauvet & Dallmeyer 1992). In the investigated area, the WGC is mostly composed of banded, migmatitic and augen gneisses of granitic composition with local quartzites and amphibolites. No eclogites have been described in the vicinity of the Fensfjorden.

The Kvalsida Gneiss, as defined in its type area on Osterøy, is a heterogeneous unit consisting of banded gneisses with granulite facies relics, amphibolites, metagabbros, granitic gneisses meta-anorthosites and quartzites (Henriksen 1979). In the investigation area, this unit has been mapped as norite, mangerite and mangerite syenite (Kolderup & Kolderup 1940). The Kvalsida Gneiss shows zones of strongly foliated mylonitic rocks around lenses of underformed protolith and all transitions between these two end members.

The major Bergen Arc Zone (MaBA) is best known from the southern part of the Bergen Arc System, where it consists of a dismembered ophiolite complex (Gullfjellet Ophiolite Complex – Thon 1985) dated at 489 ± 3 and 489^{+6}_{-2} (Dunning & Pedersen 1988) and an associated imbricated zone (Samnanger Complex – Færseth et al. 1977). The ophiolite complex is unconformably overlain by conglomerates, limestones and phyllites of Ashgillian to Llandoverian age (Holdhus and Ulven Groups – Færseth et al. 1977; Ryan & Skevington 1976). In the southeast the MaBA is an 8–10 km broad zone which becomes dramatically thinner northwestwards across Osterøy. In the studied area, north of Osterøy (framed in Fig. 1), the thickness of the MaBA is less than 1 km, and we correlate the strongly sheared rocks with the Samnanger Complex of Færseth et al. (1977). Based on lithological and structural relationships, the unit can be divided into two parts. The lower part is composed of mica schists with quartz lenses, showing variably sized lenses and fragments of amphibolite and psammite. The upper part comprises similar lithologies characterized by a higher metamorphic grade with abundant garnet and amphibole. The amphibole often develops as characteristic 'garben-schist' structures.

The rocks of the Lindås Complex are of anorthositic to gabbro-anorthositic, noritic and mangeritic composition (Kolderup & Kolderup 1940). Two major events have influenced these rocks, a Precambrian (Grenvillian) event involving magmatic activity, deformation and granulite facies metamorphism, followed by Caledonian reworking localized to shear zones (Austrheim & Griffin 1985). The majority of the Caledonian shear zones show amphibolite facies mineralogy (Andersen et al. 1991), but some zones preserve ecolgite facies assemblages (Austrheim & Griffin 1985; Austrheim 1987), stable at 700°C and >18 kbar (Jamtveit et al. 1990). Several generations of granitic/trondhjemitic veins (Kolderup & Kolderup 1940) probably of both Precambrian and Caledonian age intrude the Lindås Complex.

Coarse, polymict conglomerates similar to the Devonian clastics on Solund, further north, are preserved on islands in outer Fensfjorden, between the WGC and the Lindås Complex (the Fensfjord Devonian Basin, Kolderup 1926).

Structural geology

A map showing the main rock units across the investigated area is presented in Fig. 2. The contacts between the main rock units have strike of about 160° and a dip of 40–60° towards WSW. The contacts between the Lindås Complex and the MaBA, and between the MaBA and the Kvalsida Gneiss are characterized by ductile deformation, and the different units are separated by mylonitic zones. Profiles through these contacts are best exposed along the shores, and normally show a gradual transition across the rock boundaries. In contrast, the Fensfjorden Fault, which in this area marks the contact between the Kvalsida Gneiss and the WGC, is a complex zone characterized by both ductile and, later, extensive brittle deformation. The fault zone has a significant topographic effect, marked by a depression and by an escarpment on the Kvalsida Gneiss side. Within the zone, slices of garnet-mica schist occur which are oriented with a strike of 140°,

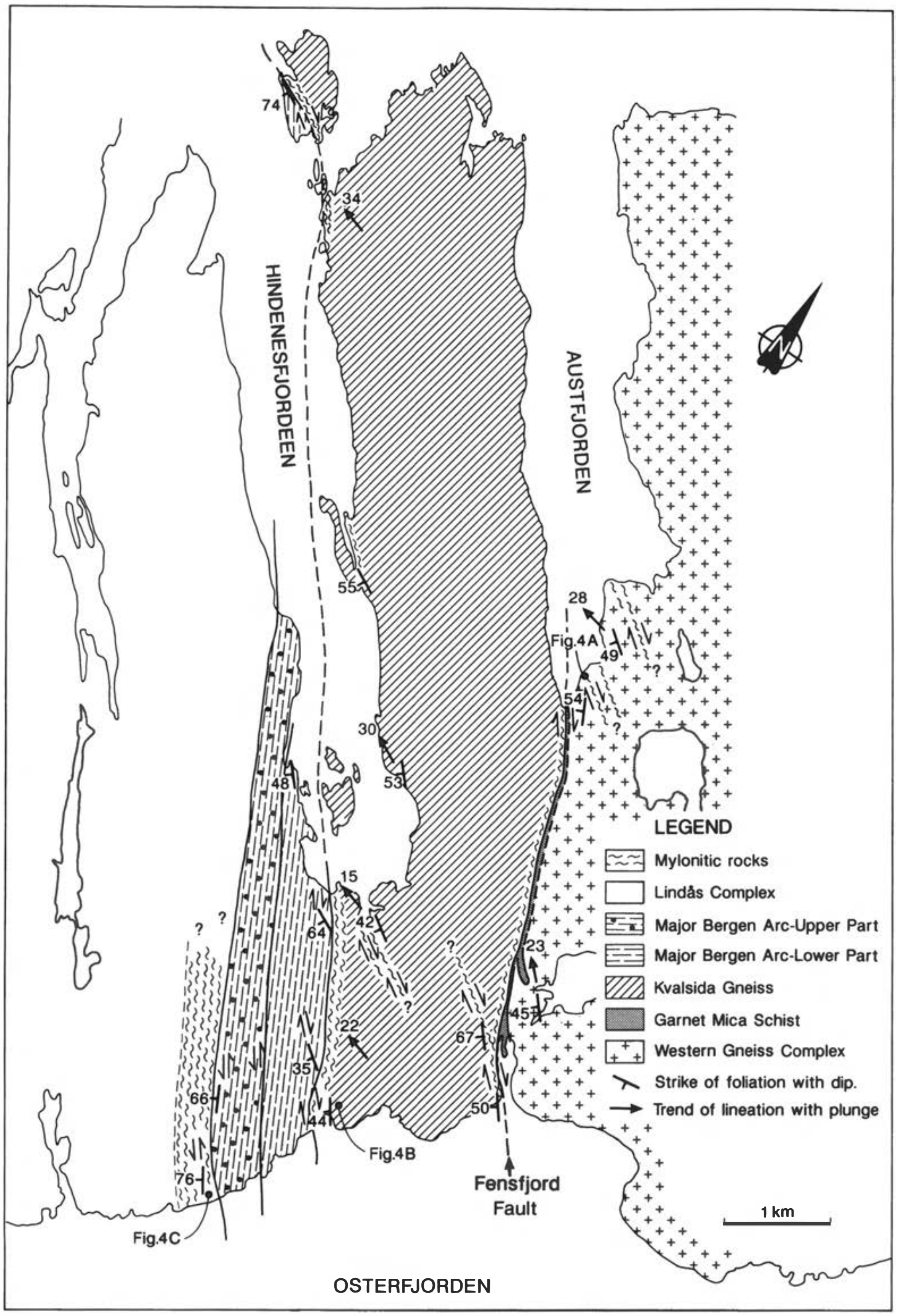


Fig. 2. Geological map of the neck of the Lindås Peninsula. Arrows indicate the sense of shear.

i.e. 20° oblique to the main rock boundaries. The maximum observed thickness of these slices is ca. 100 m. One of these slices wedges out along a mylonitic shear zone within the WGC, and fragments of gneissic rock are found within the slices.

Measurements of foliation (schistosity in the MaBA Zone, mylonitic foliation and gneiss banding in the other units) show a marked degree of parallelism and a rather constant orientation across the investigated area. The mean strike is about 140°, i.e. about 20° oblique to the main rock boundaries. The mean dip is 50°–60° towards SW. Northeast and southwest of the mapped area the foliation becomes more flat-lying: the investigated area seems to represent the steep limb of a large-scale monoclinal structure.

A strong stretching lineation is developed on the foliation surfaces within the WGC and the Kvalsida Unit trending approximately 295° and plunging 20° towards

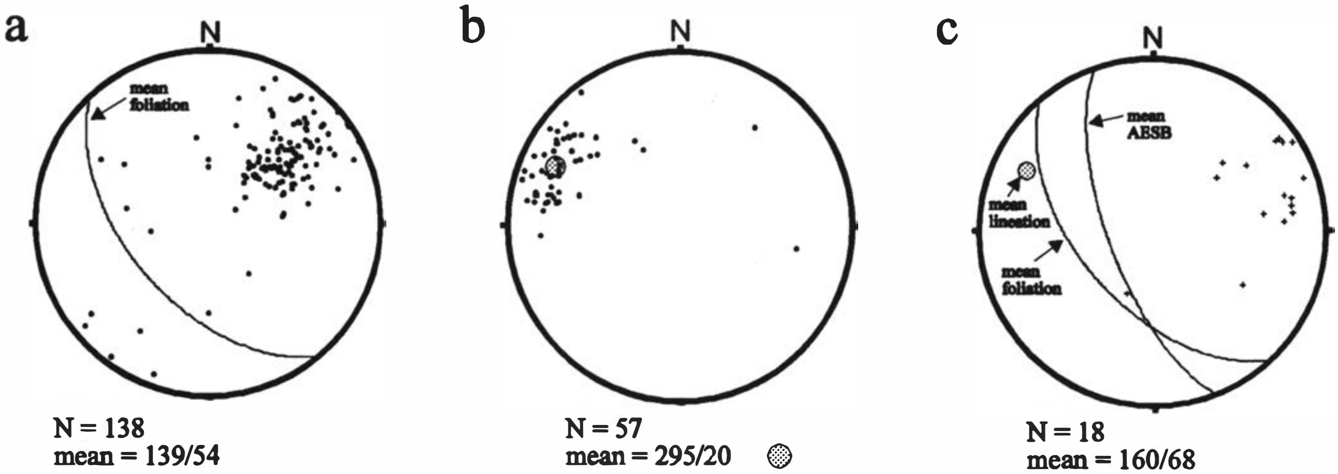
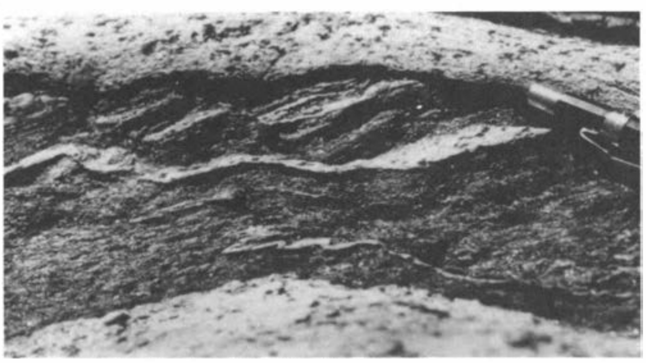
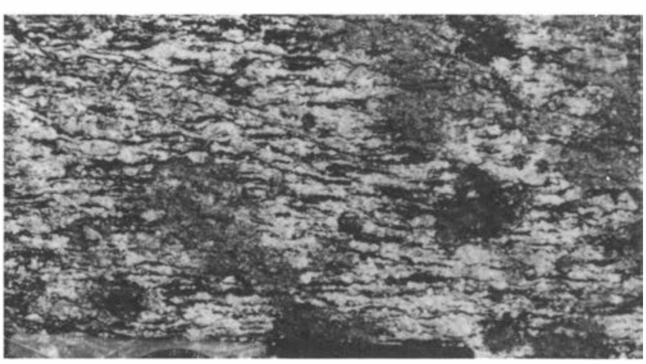


Fig. 3. Stereogram of structural data from the WGC and the Kvalsida Gneiss. (a) Poles to foliation; (b) stretching lineations; (c) poles to asymmetric extensional shear bands (AESB). Means of foliation and asymmetric extensional shear bands are plotted as large circles. Means of lineations as open circle. (Mean value after right-hand rule. Equal area projection, lower hemisphere.)


4a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4c

WNW (Fig. 3b). Ductile, mylonitic shear zones are developed within the WGC and the Kvalsida Unit oriented parallel to the average foliation. Detailed mapping of asymmetric small-scale structures has been carried out to evaluate the sense of shear associated with these shear zones. The most common shear sense indicators observed are asymmetric extensional shear bands, often associated with backrotated foliation segments (Hanmer & Passchier 1991), and the majority of these indicate a dextral sense of shear (Figs. 4a & 4b). These structures are normally best developed in the marginal parts of the shear zones, at an angle of 20° to the mylonitic foliation in the central part (Fig. 3). The intersections between the mean orientation of the foliation and the asymmetric extensional shear bands are approximately perpendicular to the stretching lineation (Fig. 3c). This indicates that the orientation of the stretching lineations and the origin of the asymmetric extensional shear bands are controlled by the same shear deformation. Asymmetric folds indicate the same dextral sense of shear. Porphyroclasts do not normally show a well-developed asymmetry, but in those cases when an asymmetry can be observed, a dextral sense of shear is indicated by both σ- and δ-porphyroclasts (as defined by Passchier & Simpson 1986). Asymmetric extensional shear bands indicating dextral sense of shear are also observed along the Fensfjorden Fault both in the slices of garnet-mica schist and in the

Fig. 4. (a) Asymmetric extensional shear bands with associated back-rotated foliation segments localized to a mica-rich layer within a mylonitic shear zone in the WGC. The structures show an orientation which indicates dextral movement. (Subhorizontal outcrop. NW is to the right.) (b) Photo of asymmetric extensional shear bands in the marginal part of a ductile shear zone, Kvalsida Unit, showing an asymmetry indicative of dextral movement. (Subhorizontal outcrop. NW is to the right.) (c) Discordant aplitic dykes in the marginal mylonites of the Lindås Complex deformed by later non-coaxial. Orientation of both the folded and the stretched dyke relative to the shear plane indicates sinistral sense of shear. (Subhorizontal outcrop. NW is to the right.)

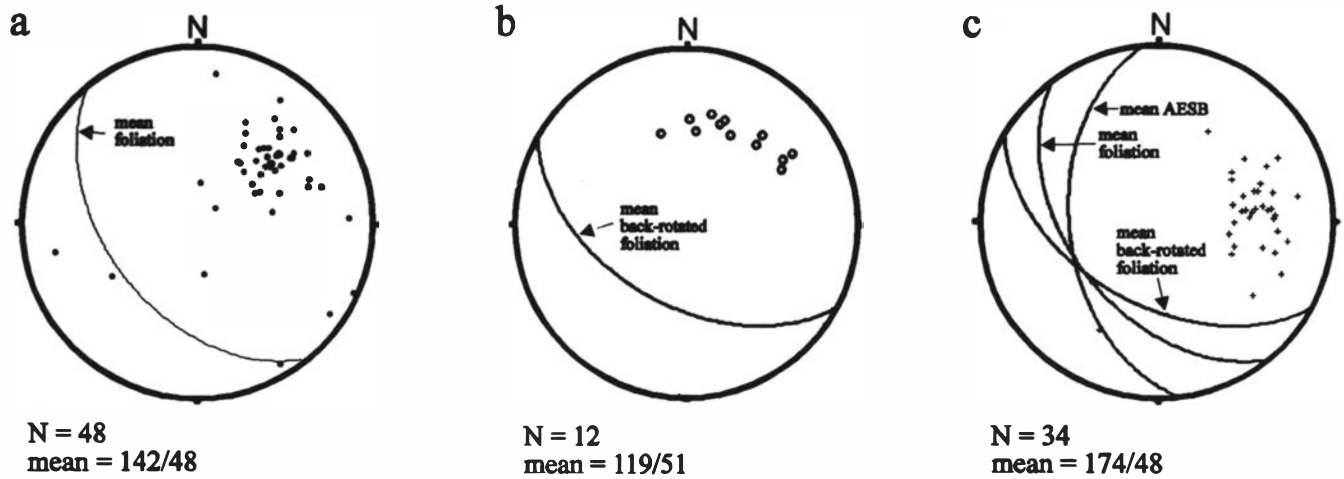

Fig. 5. Stereogram of structural data from the lower part of MaBA. (a) Poles to foliation; (b) poles to back-rotated foliation; (c) poles to asymmetric extensional shear bands (AESB). Mean of foliation, back-rotated foliation and asymmetric extensional shear bands are plotted as great circles. (Mean value after right-hand rule. Equal area projection, lower hemisphere.)

mylonites of the Kvalsida Gneiss. They are also found associated with the mylonitic contact between the MaBA and the Kvalsida Gneiss.

The MaBA lithologies consist mostly of mica schists, which are incompetent rocks compared to the overlying and underlying gneisses. The lower part of the MaBA is characterized by kinematic indicators which show an asymmetric geometry indicative of dextral movements. Asymmetric extensional shear bands are common within this zone (Fig. 5c), and they are oriented at an angle of 20°–25° to the mean foliation (Fig. 5a). Locally, foliation segments are back-rotated (Hanmer & Passchier 1991) 15°–20° relative to the mean foliation (Fig. 5b). The mean orientation of the foliation, back-rotated foliation and the asymmetric extensional shear bands intersect almost at the same point (Fig. 5c). The intersections have a SW trend in contrast to the more south-trending intersection in the WGC and Kvalsida Gneiss (Fig. 3c). The vergence of asymmetric folds also indicates a dextral sense of movement.

The upper part of the MaBA (amphibole/garnet-mica schist) is structurally characterized by asymmetric features indicating a sinistral sense of shear. Asymmetric extensional shear bands are less common here than in the lower part, but, where observed, the asymmetry is the opposite. Other structures indicating sinistral movements are asymmetric boudins and folds.

No detailed structural investigation of the mylonites along the contact between the Lindås Complex and the MaBA has yet been carried out. However, the mean orientation of the mylonitic foliation has a strike of 150° and a dip of 70° towards WSW with a subhorizontal stretching lineation developed on the foliation surfaces. Aplitic dykes intrude the sheared rocks discordantly at different angles to the mylonitic foliation. These dykes have been deformed by later non-coaxial strain with the orientation of shortened and elongated dykes indicating a sinistral sense of shear (Fig. 4c). Elongated dykes show asymmetric boudins and shortened dykes show asymmetric folds, and both are consistent with sinistral movements. These sinistral movements are the latest movements recorded in the mylonites that mark the boundary between the Lindås Complex and the MaBA.

Some preliminary conclusions

A summary of the observed kinematic indications is presented in a generalized block diagram in Fig. 6. Indications of dextral movements are observed along the Fensfjorden Fault trace and in shear zones in the WGC and Kvalsida Gneiss. The movement direction is quite well constrained by the fact that the mean stretching lineation on the foliation surfaces is perpendicular to the intersection between the mean orientation of the foliation and the asymmetric extensional shear bands (Fig. 3c). The gentle plunge of the stretching lineation, however, indicates a component of normal movement across this

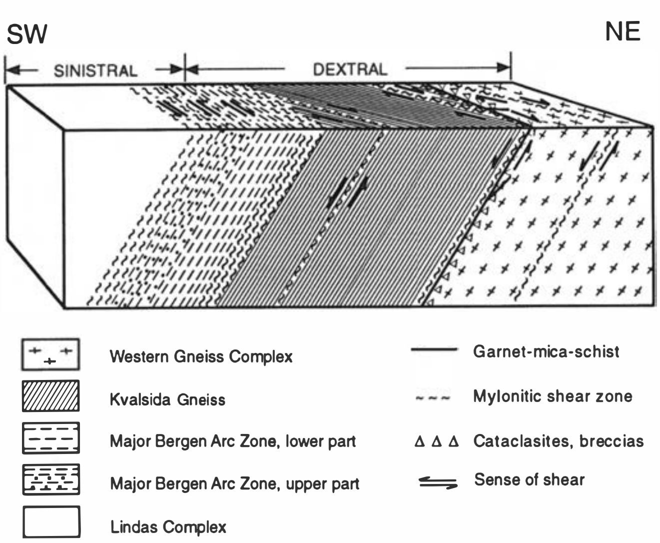

Fig. 6. Generalized block diagram across the investigated area. Arrows indicate the sense of shear.

zone which finds its expression in the development of the large-scale monoclinal structure. Since the Fensfjorden Fault and the shear zones dip southwestward, these movements are 'top-to-west'.

The present orientation of the zone containing the Fensfjorden Fault and the indications of dextral normal movements suggest a transtensional setting for the coarse conglomerates of the Fensfjord Basin. Investigations in progress along the Fensfjorden and within the Fensfjorden Basin will give more information about the origin of this basin.

The MaBA, composed mainly of mica schist, seems to represent an incompetent unit squeezed between the more competent, gneissic Lindås Complex and the Kvalsida Gneiss. A major amount of shear strain is expected to be recorded in this zone. Along the contact with the Kvalsida Gneiss and within the lower part of the MaBA most of the asymmetric structures indicate dextral movements (Fig. 6). This again corresponds to 'top-to-west' movement of the hanging wall.

Following the strike of the Fensfjorden Fault and the zone of dextral kinematics (Figs. 1 & 6) northwestwards, the MaBA has to truncate, to be truncated by, or to merge with the Nordfjord–Sogn Detachment between Fensfjorden and Sognefjorden. We suggest that this zone at least partly represents the southern continuation of the Nordfjord–Sogn Detachment. This suggestion is based on the following arguments: (1) Kinematic indications along this zone indicate dextral movements which represents 'top-to-west'. This is congruent with the sense of shear as found below the Devonian Solund Basin (Chauvet & Séranne 1989). (2) The stretching lineation has the same trend as that associated with the detachment zone below the Solund Basin (Chauvet & Séranne 1989). (3) Both zones separate the WGC in the footwall from allochthonous units and Devonian sedimentary basins in the hanging wall. Following this argumentation the dextral or 'top-to-west' shear sense is interpreted to be related to the late/post-Caledonian extension.

In contrast, indications of sinistral movements are found in the amphibole-garnet-mica schist of the upper part of the MaBA and along the contact between the Lindås Complex and the MaBA. With the present orientation of the Fensfjorden Fault these structures represent 'top-to-the-southeast', and are tentatively interpreted to be remnants from the phase of southeastward thrusting of the Lindås Complex on top of the MaBA. The contacts between the other main rock units probably originated as a thrust during an early stage of the Caledonian Orogeny (Sturt & Thon 1978; Henriksen 1979). The 'top-to-west' movements along this zone thus represent extensional reactivation and obliteration of earlier contractional structures.

A southward continuation of the Nordfjord–Sogn Detachment as the zone of dextral movement implies that the eclogites of the Lindås Complex (Austrheim & Griffin 1985) are in the hanging wall (upper plate), in contrast to the footwall (lower plate) eclogites of the WGC further north. The rapid exhumation of the WGC eclogites has been explained by tectonic exhumation during late/post-Caledonian extension (e.g. Norton 1986; Andersen & Jamtveit 1990). An upper plate position of the Lindås Complex eclogites would suggest that these were exhumed and emplaced in the Caledonian nappe wedge prior to the exhumation of the eclogites in the WGC.

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