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Shear zone structures in the Øygarden area, West Norway

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Abstract

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Investigation of shear-related sheath-like folds from blastomylonitic gneisses in the Øygarden Complex, Norway, shows that the folds have not initiated with fold axes systematically normal to or with another fixed angle to the lineation. Their short limbs do, however, pass from a period of thickening to final thinning as the folds close and the short limbs become inverted.

The formation of the folds appears to be controlled by local geometries within the shear zone, and we suggest three fold-generating mechanisms. In one, the mylonitic foliation curves ahead of a tectonic lens and starts to fold and in another, mesoscopic shear bands with normal fault geometries cut subplanar mylonites and folds are generated by the accretion of material in the evolving gap between the "hangingwall" and the "footwall". The third mechanism involves perturbation of the main foliation by slip along an inclined S-foliation so that shear folds may develop. All the mechanisms involve a rotation of the mylonitic foliation into the compressional field of the instantaneous strain ellipse.

Introduction

The progressive evolution of mesoscopic structures in ductile and semiductile shear zones and mylonites has been described and discussed by a number of authors (e.g. Ramsay and Graham, 1970; Coward, 1976; Berthé et al., 1979; Simpson, 1983; Choukroune et al., 1987). Due attention has been devoted to the studies of fold development and geometries, and more recently also to the occurrence and significance of *S–C* structures (Berthé et al., 1979). However, while much of the previous work on folds has been carried out in ductile shear zones where shear bands and other *S–C* structures are not very common, we have studied fold generation in mid-crustal blastomylonitic gneisses in the Øygarden Complex near Bergen where folds appear to be closely related to such structures. We are concerned with the progressive formation of folds and foliations in the mylonites, their geometries and their implications.

Geologic setting

The Øygarden Complex is located west of Bergen (Fig. 1) and has mylonitic contacts with the allochtonous rocks of the Minor Bergen Arc (Weiss, 1977; Fossen, 1986). The Minor and Major Bergen Arc (Fig. 1) comprise early Ordovician ophiolitic and associated rocks covered by late Ordovician to Silurian sediments which were sheared and imbricated together with mylonized basement slices.

The Øygarden Complex is dominated by gneisses, formed from various assumed Precambrian and Caledonian (Sturt et al., 1975) migmatites and intrusions. Caledonian deformation accounts for most strain presently seen in

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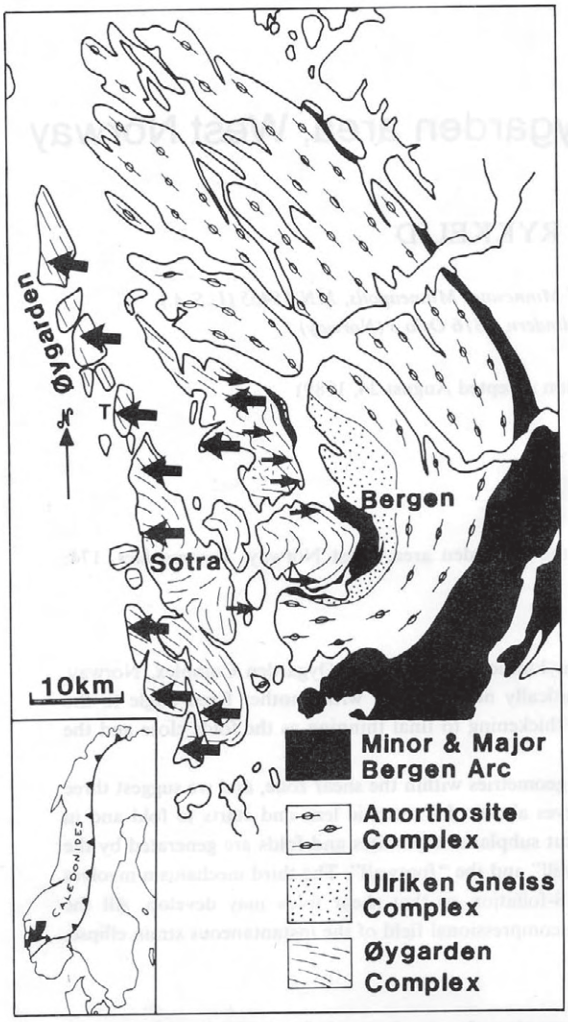

Fig. 1. Simplified geologic map of the Bergen area, modified after Kolderup and Kolderup (1940). The sense of shear in the Øygarden Complex is indicated. Arrows are parallel to the lineation and indicate the shear directions of the top relative to the bottom of a sequence of tectonites. Thick arrows: pre-Scandian sense of shear (deformation studied in this work). Thin arrows: pre-Scandian sense of shear *T*—Toftøy.

these rocks. The complex has been variously sheared throughout, and inhomogeneous strain has resulted in high strain gradients across small areas. The Øygarden Complex has been considered the autochthonous basement over which the allochthonous units of the Bergen Arcs have been thrusted (Kvale, 1960), but Bering (1984) pointed out that the pervasive shear deformation of the complex suggests also an allochthonous status.

The Caledonian deformation in the Bergen area is dominated by the Scandian event which affects the cover sequence to the ophiolitic rocks in the Major Bergen Arcs containing a Llandovery fauna (Reusch, 1882). However, there are indications of earlier Caledonian deformation and metamorphism (Sturt and Thon, 1976; Færseth et al., 1977; Henriksen, 1981; Fossen and Austrheim, 1988; Fossen, 1988b). The strong shear deformation which overprints the migmatitic and intrusive relations in the Øygarden Complex has been interpreted as Caledonian (Askvik, 1971; Bering, 1984) and a number of Caledonian mineral ages (Neuman, 1960; Askvik, 1971; Krogh et al., 1974; Sturt et al., 1975) supports this interpretation. Bering (1984) separated the Caledonian deformation into an early Caledonian ("Finnmarkian") and a later Scandian event. The early Caledonian deformation was accompanied by lower amphibolite facies metamorphism, while the Scandian event resulted in upper greenschist facies parageneses.

The Øygarden Complex

The structures described in this work are formed mostly during the assumed early Caledonian amphibolite facies event which dominates the Øygarden–Sotra area (Fig. 1). This western part of the Øygarden Complex shows some excellent exposures provided by the sea. The deformation was generally semi-ductile with dynamic recrystallization of minerals and the formation of an overall *L–S* fabric, although some discontinuous deformation occurred in the layered tectonites. The lineation is generally a stretching lineation defined by rodded quartz, elongated mineral aggregates, mica streaking and aligned amphiboles and shows a remarkably consistent orientation with gentle plunges towards N90E to N110E. The main foliation, which is commonly protomylonitic or blastomylonitic (classification after Sibson, 1977), is defined by the lithologic layering and aligned platy minerals and mineral aggregates. The deformation is heterogeneous on outcrop scale, and anastomosation of the mylonitic foliation is common. Folds, small-scale compressional imbrication structures and extensional structures are found in the sheared rocks, and various *S–C* structures (Berthé et al., 1979; Lister and Snoke, 1984) are widespread. The asymmetry of the structures in this area uniformly indicates a top-to-the-west sense of shear, parallel to the stretching lineation (Fig. 1). The later Scandian greenschist facies shearing is developed towards the Minor Bergen Arc where the associated asymmetric structures indicate top-to-the-east sense of shear. A late Caledonian phase of folding resulted in asymmetric tight to open folds with sub-horizontal axial plane crenulation cleavages which fold the mylonitic fabric near the contact with the Minor Bergen Arc (D_2 of Fossen, 1988a and D_3 of Fossen and Ingdahl, 1987). A later event caused large-scale, easterly-plunging open folds with vertical axial planes (D_3 of Fossen, 1988a, D_5 of Bering, 1984). The arcuate structure of the Bergen Arcs formed during this event, and these folds are well developed in the Øygarden Complex where the large, open structures (Fig. 1) have mesoscopic, parasitic buckle-folds. However, this folding event caused no inversion of lithologies which could have complicated the determination of shear sense.

Foliations

Several foliations have developed during the shearing in the Øygarden Complex. The foliations are microscopically defined by parallel aligned, platy minerals separating domains or aggregates of quartz and feldspar. An *S* foliation which probably parallel the *X–Y* plane, is developed where strain is low to moderate. In the high strain zones the *S* foliation is (sub)parallel to transposed earlier structures, forming a blastomylonitic layering/foliation. This mylonitic foliation is a composite surface similar to Berthé et al.'s (1979) *CS* surface.

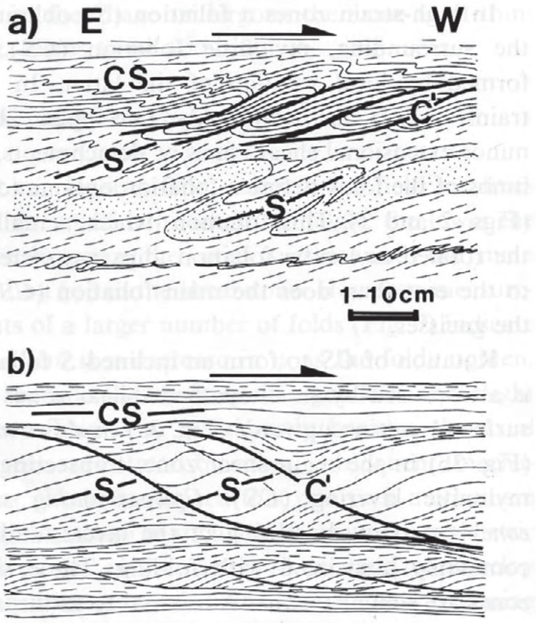

Fig. 3. General sketch of two types of tectonites found in the Øygarden Complex. a. Compressional type with folds and imbrication structures. b. Extensional type showing extensional *S–C* structures.

An inclined *S* foliation is locally defined by recrystallized minerals which have their long axes oblique to the main foliation or banding (*CS*). The minerals, commonly micas and quartz, formed by growth subparallel to the *X–Y* plane of the strain ellipsoid of a certain strain increment (cf. Lister and Snoke, 1984).

Another inclined mineral foliation is the axial planar foliation locally associated with the folds described below.

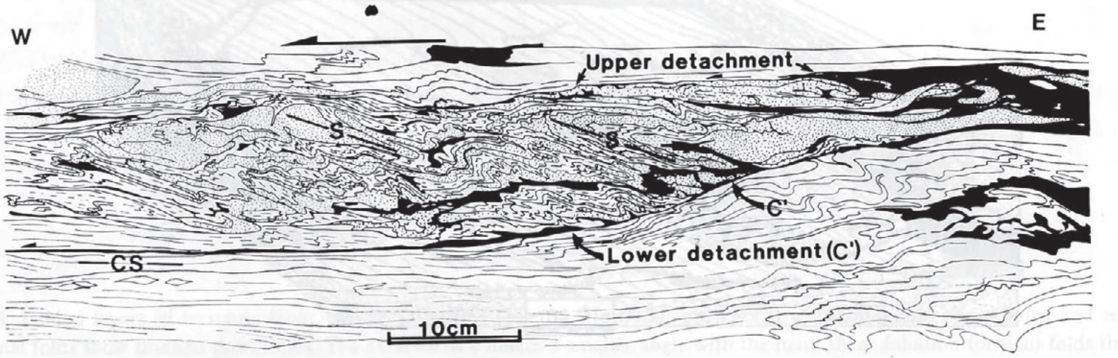

Fig. 2. Fold train developed above an extensional detachment fault developed at top of slightly older folds (third mechanism). Redrawn from photograph from Toftøy, Øygarden (Fig. 1). The section is parallel to the lineation and normal to the foliation.

In high-strain zones a foliation (*S*) oblique to the surrounding, mylonitic foliation (*CS*) has formed by local rotation of the latter. In fold trains, which are commonly developed above minor extensional shear zones or detachments, the limbs of the folds define a foliation oblique to *CS* (Figs. 2 and 3). This foliation, which actually is the rotated mylonitic foliation, dips more steeply to the east than does the main foliation (*CS*) in the gneisses.

Rotation of *CS* to form an inclined *S* foliation is also caused by small synthetic shear zones (*C′* surfaces) cutting upwards (Fig. 3a) or downwards (Fig. 3b) in the main shear zone, transecting the mylonitic layering (*CS*). *Upward-cutting shear zones* result in shortening of the layers, and are commonly associated with folding. These shear zones are similar to what is referred to as thrust or *P* shears (Tchalenco, 1968; Mandl et al., 1977) in Riedel-type experiments and are also reported from simulated halite shear zones (Shimamoto, 1989) and evaporitic layers involved in thrust tectonics ("reverse-fault type shear bands" of Marcoux et al., 1987). The shear zones or small "thrusts" climb in the transport direction, i.e. to the west.

Downward-cutting shear zones are extensional features, also called shear bands (e.g. White, 1979), extensional crenulation cleavages (Platt, 1984), extensional or normal fault type shear bands (Marcoux et al., 1987), and their associated structures have been called asymmetric or rotational boudins (Platt and Vissers, 1980; Gaudemer and Tapponnier, 1987; Lacassin, 1988). They correspond to R-type Riedel shears. In Øygarden such shear zones frequently occur on variable scales. Some are ductile shear zones, while others are narrow zones which transect the mylonitic foliation and looks like extensional faults at a distance. Their microscopic fabric is, however, defined by alligned, platy minerals, so that indications of cataclastic flow would have been obscured by metamorphic recrystallization. These shear zones show "normal fault" geometry (Fig. 3b), and we therefore apply the terms "hanging wall" and "footwall" for the rocks at each side of such extensional shear zones. The extensional shear zones (*C′*) cut down in the direction of transport (Fig. 3b), i.e. to the west in the study area.

There are several indications that the various small shear zones formed more or less coevally during the mylonitization in the study area: (a) they are restricted to certain layers in the tectonites, particularly micaceous and well foliated sequences; (b) the structures are more or less systematically repeated along these sequences, and the small shear zones curve to become part of the mylonitic *CS* foliation; (c) the metamorphic mineral assemblage along the small shear zones is similar to that of the mylonitic fabric; (d) they indicate a uniform movement direction identical with that of the mylonitic foliation which they affect, and (e) the close relation between the development of the various small shear zones (and folds) to the local shear zone geometry. The latter is described in further detail below.

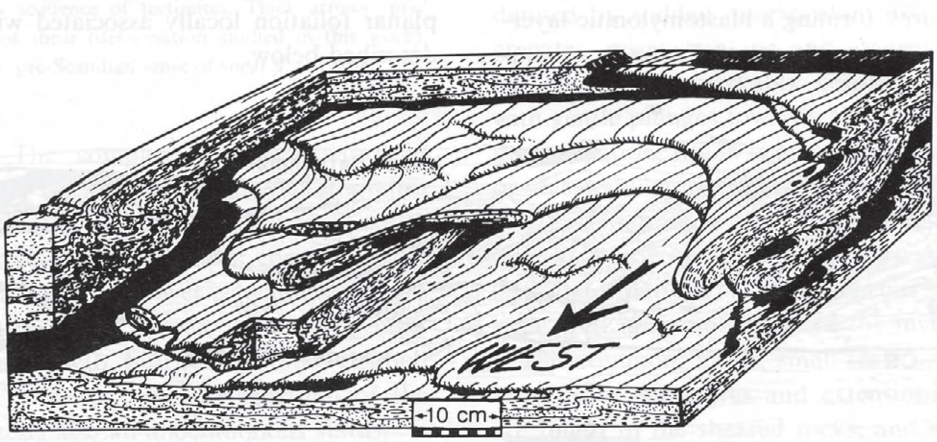

Fig. 4. Illustration of the complex fold geometries that occur in the blastomylonitic gneisses in the Øygarden Complex. Drawn from several photographies from locality at Toftøy, Øygarden (Fig. 1).

Folds

The folds dealt with in this survey are those formed in high-strain zones during the assumed early Caledonian shear movements in the complex. These shear-related folds appear to have complex three-dimensional geometries (e.g. Fig. 4). Analyses of various structural elements of the folds were carried out to get an impression of their geometries and development.

Limb–thickness relations

Two main stages of the development of shear-related folds are recognized in the field: (a) those which show a thickened short limb and b) those in which the short limb is inverted and thinned (Fig. 5). Plotting the field data (Fig. 6) elucidates a simple relation between the interlimb angle and the limb thickness ratio where gentle folds have thickened short limbs, and tight folds have attenuated short limbs (Fig. 5). The relative thickness of the limbs is closely related to the fold history. The folds initially form as open, upright folds which subsequently became overturned and closed. During this process the short limb rotates from the compressional to the extensional field of the instantaneous strain ellipse associated with the shear zone, and hence experienced an early period of thickening and a subsequent period of thinning. After a certain period of thinning the short limb has obtained its original thickness, but is still thicker than the long limb which meanwhile has undergone some thinning. The critical interlimb angle when the two limbs have equal thickness, that is, they have undergone the same total thinning, seems to be about 30–45.

Axial surface relations

It can be seen from some of the field localities that the smaller the interlimb angle, the lower the angle between the axial surface and the main foliation (ϕ) in the shear zone. However, measurements of a larger number of folds (Fig. 7) indicate that there is a decrease in ϕ as the folds tighten, but the correlation is not as good as one might expect. This is at least partly because the axial surfaces are rotated by other, subsequent, mechanisms. We have noticed that one such mechanism is the formation of small-scale compressional listric shear zones or "thrusts" which tend to develop along inverted short limbs that undergo thinning (Fig. 3a). Movements along these shear zones commonly result in rotation antithetic to the main rotation and thus counteract the expected decrease in ϕ as the folds tighten. Where this mechanism plays a prominent part, one observes trains of folds where open through isoclinal folds shows little variation in ϕ-value. However, other processes, like movements along small-scale extensional shear zones and local geometric effects within the anastomosing shear zones, also complicate the relation between ϕ and the interlimb angle.

Fold axes relations

Figure 8a shows how folds initiate oblique to the lineation, and subsequently develop very com-

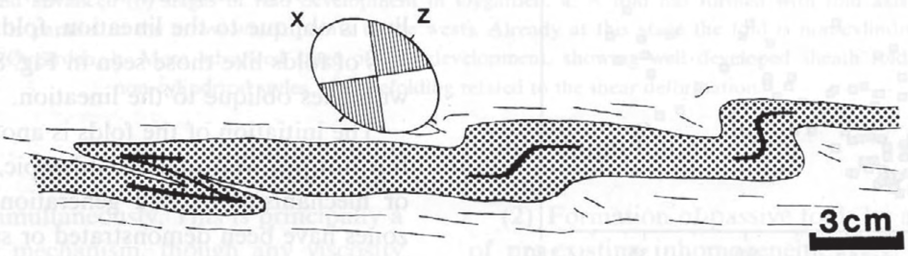

Fig. 5. Folded layers in tectonite from Toftøy, Øygarden (Fig. 1). Note that open folds show thickened short limbs and tight to isoclinal folds show thinned short limbs. The axial surface makes a smaller angle with the main shear foliation for tight folds than for open folds at this locality. An incremental strain ellipse is indicated. Note that short limbs of open folds are in the compressional field while those of tight folds have rotated into the extensional field. Redrawn from photograph.

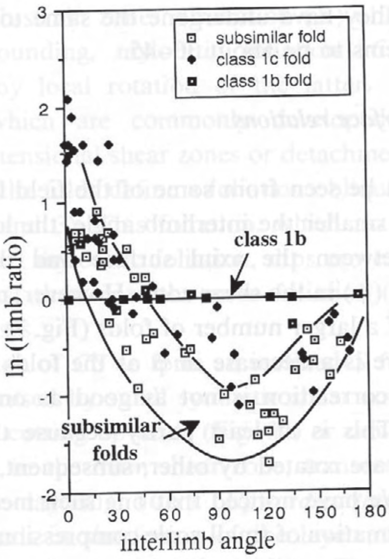

Fig. 6. Interlimb angles plotted against the limb thickness ratio (thickness of long limb/thickness of short limb) from Toftøy, Øygarden. The measured folds have been classified after the classification of Ramsay (1967), and the trends of class lb and subsimilar folds are indicated.

plex sheath-like (Skjernaa, 1989) geometries (Fig. 8b). Field measurements (Fig. 9) indicates that there is no obvious correlation between the fold axis–lineation angle and the interlimb angle, and open as well as close folds display fold axes at various angle to the stretching lineation.

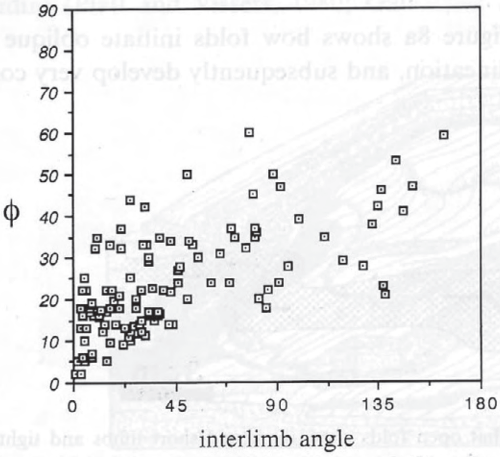

Fig. 7. The angle between axial surfaces and the main shear zone foliation (ϕ) plotted against the interlimb angle from folds in Øygarden (Toftøy).

Discussion of the fold genesis

Many of the folds in the area have strongly non-cylindrical geometries, resembling typical sheath folds (Skjernaa,1989) (Figs. 5, and 9b). It has been demonstrated theoretically (Escher and Watterson, 1974; Cobbold and Quinquis, 1980) and experimentally (Cobbold and Quinquis, 1980) that such folds may form under progressive non-coaxial deformation. These folds form with axes normal to the movement direction, rotating towards parallelism with the lineation along with tightening. Also, their axial surfaces rotate to eventually become subparallel to the main foliation (Sanderson, 1973; Escher and Watterson, 1974; Bell, 1978; Cobbold and Quinquis, 1980). Our observations reveal, however, that this process cannot fully explain the fold geometries in the Øygarden Complex. The poor relation between fold axes–lineation angle and tightness of the fold suggests that folds initiated with axes at various angles to the lineation and movement direction. The presence of shear-related folds with axes formed at various angles to the lineation has been noticed elsewhere (Bell and Hammond, 1984), and may be explained by complex strains related to frontal or lateral tips of shear zones (Coward and Potts, 1983) or shear strain gradients perpendicular to the movement direction (Ridley, 1986). There is also a purely geometric explanation for this: the initial fold hinge orientation depends on the orientation of the layer with respect to the shear plane, and approximates the line of intersection. When the layer is subparallel to the shear plane, small variations in layer orientation have large effect on the intersection line with the shear plane and thus on the hinge orientation. When the intersection line is oblique to the lineation, folds or en echelon sets of folds like those seen in Fig. 8a may develop with axes oblique to the lineation.

The initiation of the folds is another important, but not yet well understood topic. Three models or mechanisms of fold generation in high-strain zones have been demonstrated or suggested in the literature:

(1) Lenses truncated by local shear zones can cause folding in front of lenses (Fig. 10a, b) (Bell and Hammond, 1984) and extensional structures

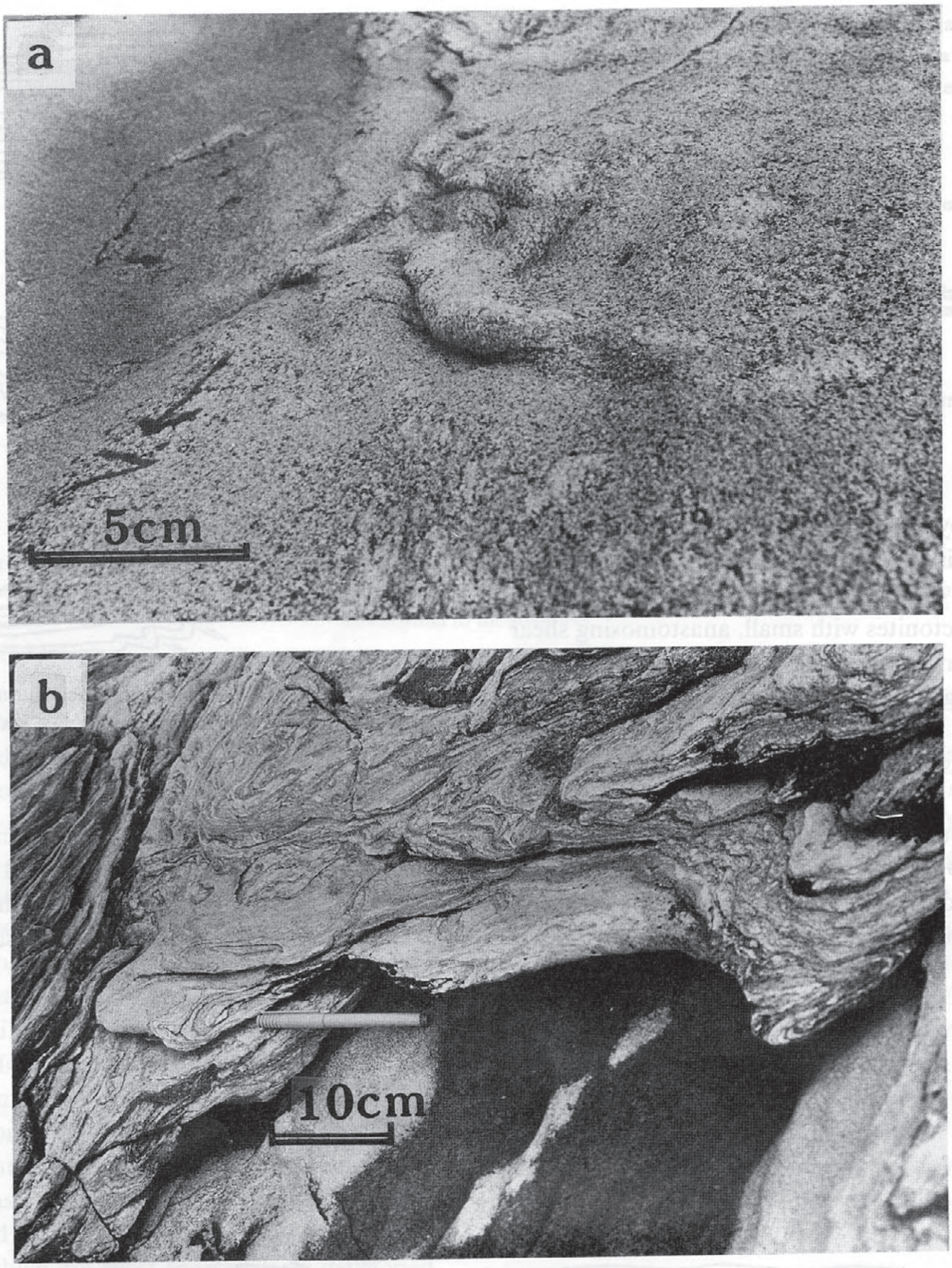

Fig. 8. Early (a) and advanced (b) stages of fold development in Øygarden. a. A fold has formed with fold axis oblique to the lineation (lineation is parallel to the arrow which points to the west). Already at this stage the fold is non-cylindrical. Weathered surface at Toftøy, Øygarden. b. More advanced stage of fold development, showing well developed sheath folds with strongly non-cylindrical styles. Note refolding related to the shear deformation.

behind lenses simultaneously. This is principally a passive folding mechanism, though any viscosity contrast between layers should also lead to buckling as the original foliation plane rotates into the shortening field.

(2) Formation of passive folds by amplification of pre-existing inhomogeneities, e.g. sedimentary structures like ripples or channels, irregular layers etc. (Fig. 10 c, d). Similar folds have been produced in the laboratory (Cobbold and Quinquis,

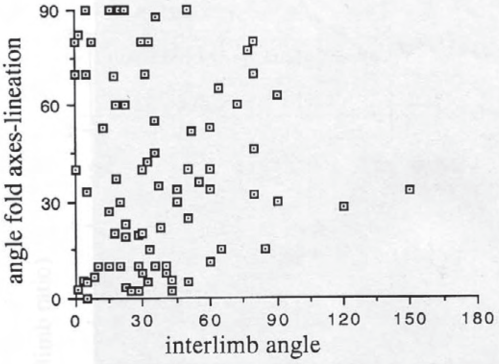

Fig. 9. Interlimb angle plotted against the angle between fold axes and the stretching lineation.

1980) and by computer simulation (Vollmer, 1988), though again, viscosity contrasts would lead to a component of active folding.

(3) In tectonites with small, anastomosing shear zones, shear lenses would form continuously during shearing. The pre-existing foliation within the lenses will not necessarily be parallel to their walls. If this acute angle is counter to the sense of shear, the pre-existing foliation will lie in the instantaneous shortening field and become deformed into a set of asymmetric folds (Fig. 10 e, f) (Ghosh and Sengupta, 1987). This is an active process of folding as opposed to 1 and 2 above, and buckle folds are expected.

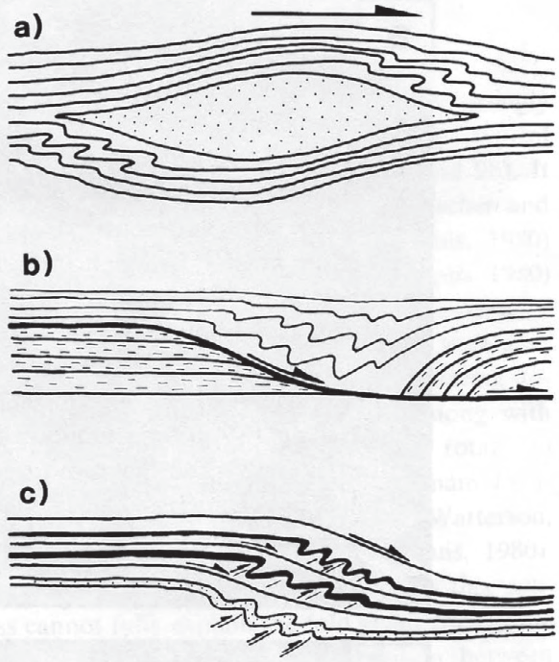

Fig. 11. Three models for fold generation during non-coaxial deformation in the Øygarden Complex. See text for explanation.

In addition comes models which involve non-plane flow (cf. Nicolas and Boudier, 1974). However, many of the structures found in the tectonites in the Øygarden Complex are not satisfactorily explained by the models mentioned above. We

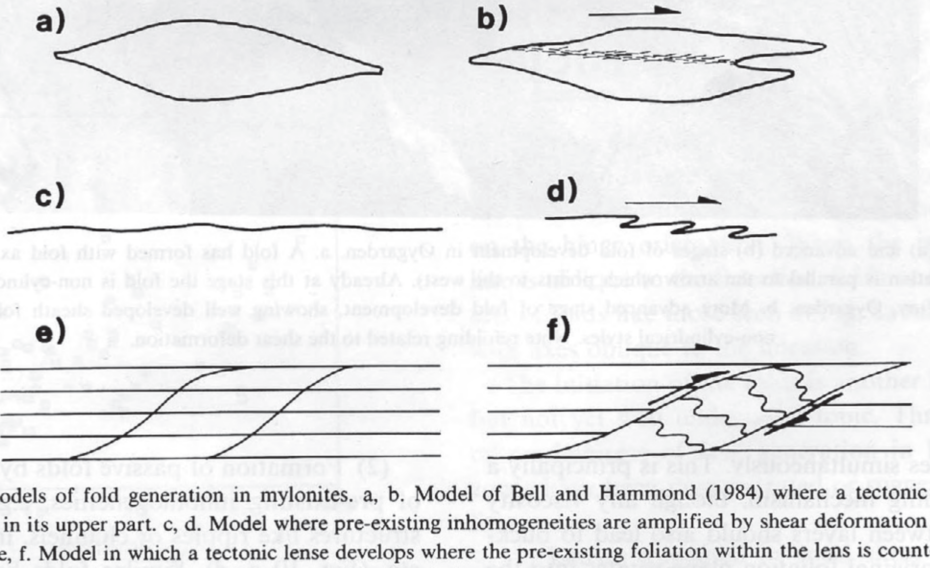

Fig. 10. Three models of fold generation in mylonites. a, b. Model of Bell and Hammond (1984) where a tectonic lense is more intensely sheared in its upper part. c, d. Model where pre-existing inhomogeneities are amplified by shear deformation (Cobbold and Quinquis, 1980). e, f. Model in which a tectonic lense develops where the pre-existing foliation within the lens is counter to the shear direction and hence is folded when the lense deforms (Ghosh and Sengupta, 1987). Section parallel to the lineation and normal to the foliation.

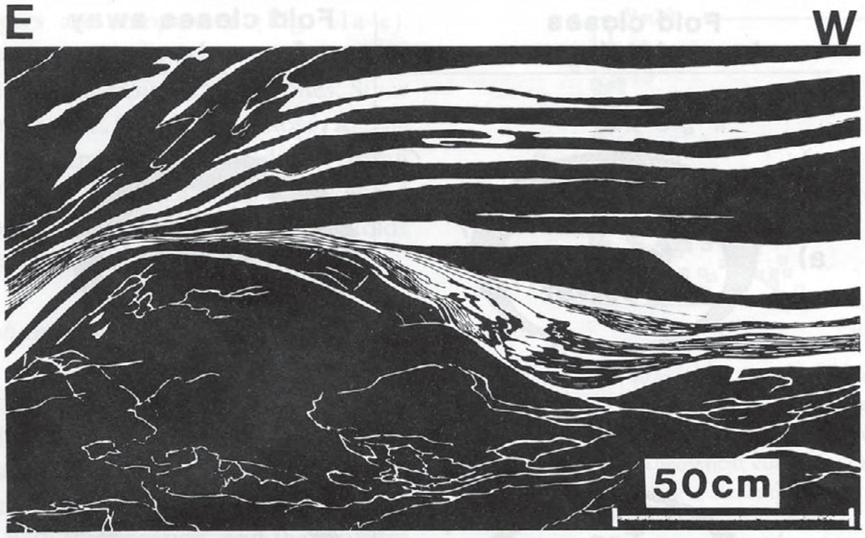

Fig. 12. Inhomogeneously sheared agmatite on Sotra, Øygarden Complex. A sub-horizontal, curving shear zone transects the agmatite in the middle of the drawing. Note that folds are only seen where the shear zone curves downwards. Section parallel to the lineation and normal to the foliation.

have noticed three associated types of structures where the foliation is rotated into the shortening field by three distinct processes.

The first type is related to anastomosation of the mylonitic foliation around lenses of lesser deformed rocks (inhomogeneous shear). Compressional structures typically occur where shear zones dip downwards ahead of tectonic lenses (Figs. 11a and 12), while extensional structures are common where the foliation curves upwards behind the lenses. A laminated or layered mylonitic sequence in the tectonites may be followed in the shear direction until it is rotated forwards ahead of a tectonic lens. At this point the dipping layers develop fold trains and sometimes, small duplex structures which are most spectacularly developed in the lowermost part of the sequence of dipping layers. This results in accretion of material ahead of the lenses. This process has similarities with Hudleston's (1977) model for recumbent folds at the base of glaciers and ice sheets. In Hudleston's model the foliation is passively deformed, whilst in the present model, components of active folding are thought to occur since layers of contrasting viscosities are present.

The second situation is related to the formation of narrow, extensional shear zones or "faults" (C' surfaces) within the mylonites. C' surfaces locally transect the sub-planar layering in the shear zone, and compressional structures are found in the evolving "gap" between the "hangingwall" and footwall" (Fig. 11b). Considerable amounts of material may be accreted in this situation. Layers above the accreted material are planar as the folding and/or imbrication vanish upwards. In the Øygarden Complex the "hangingwall" is locally displaced several meters or tens of meters due to high strains, and identification of the "hangingwall" is not always possible. Remaining is the isolated "footwall" truncated by the listric shear zone, while the "hangingwall" contains a

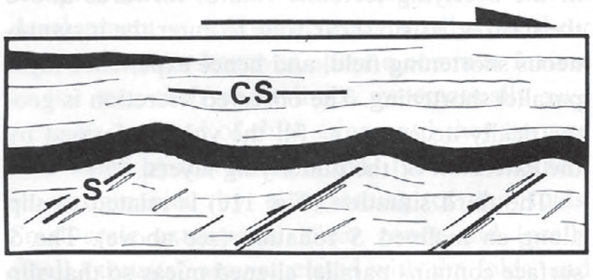

Fig. 13. a. Slip along an S foliation oblique to already existing layering (CS) in a tectonite may cause perturbation of CS, so that ongoing shearing amplifies the open fold into well developed shear folds.

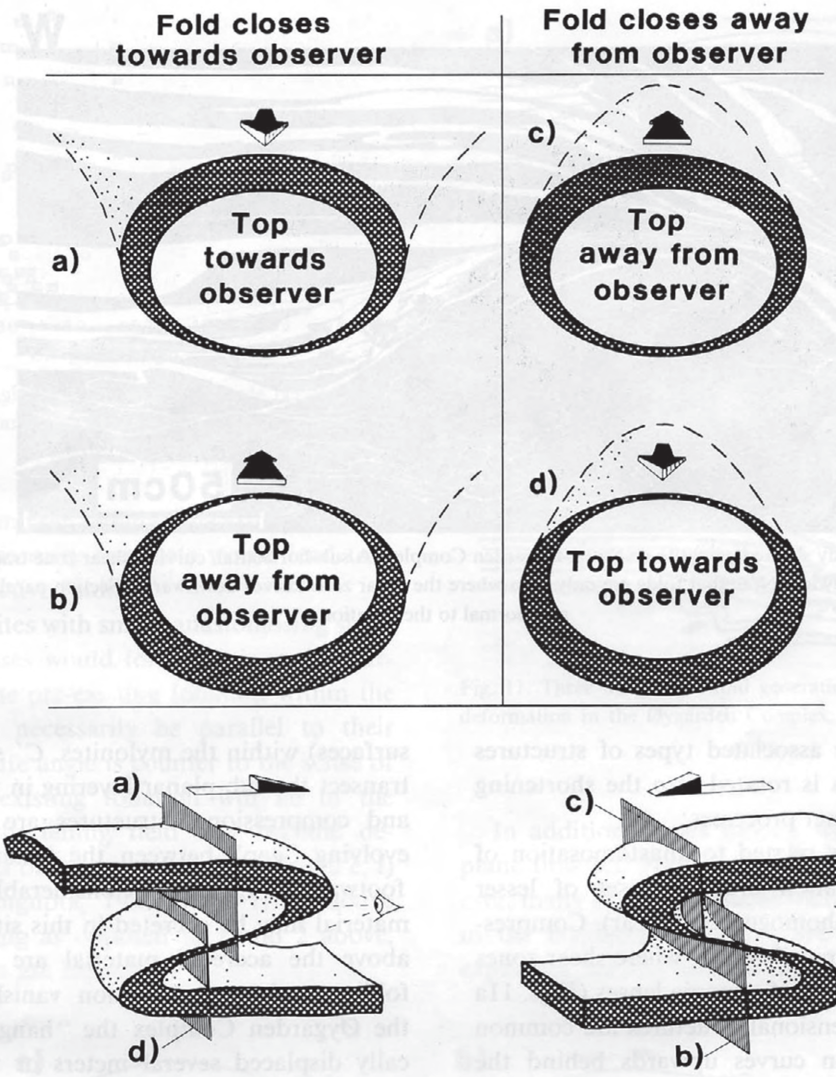

Fig. 14. a–d show sections normal to the movement direction for sheath folds and how the sense of shear can be determined when the short limb is thinned and the direction in which the fold closes is known. Below:sections parallel to the movement direction.

rotated foliation (Fig. 11b). The mylonitic layering in the overlying tectonite rotates forwards above the narrow, listric shear zone to enter the instantaneous shortening field, and hence experience layer parallel shortening. The observed accretion is geometrically necessary to fill the volume formed by the extension of the underlying layers.

The third situation (Fig. 11c) is related to slip along an inclined *S* foliation (see above). The *S* surface contains parallel aligned micas so that slip may occur on discrete surfaces parallel to *S* (Platt, 1984). This slip causes a perturbation of the mylonitic layering (Fig. 13) which will be amplified by the on-going shearing, resulting in shear-related folds. The folds again lead to a perturbation of the overlying flow, so that new folds may evolve ahead of and in front of the folds. This process may propagate and give rise to sequences of tectonites where fold trains are separated by local detachments (slip surfaces) (Figs. 2 and 11c).

The processes responsible for the three types of fold-related structures described above have in common a rotation of the mylonitic foliation into the compressional field of the instantaneous strain ellipsoid. When the foliation or layering dips forward, e.g. ahead of tectonic lenses or a "fault scarp", the layers are compressed (Fig. 11a–c). Otherwise, the layers are thinned and locally affected by small scale extensional shear zones. Since the general, mylonitic foliation is close to the plane of no incremental longitudinal strain (Ramsay, 1967), only small rotations are required before the compressional field is entered and folds and/or small thrusts develop.

Shear-sense deduced from folds

To determine the shear direction from the geometry of the shear folds, sections parallel to the lineation and perpendicular to the foliation were used. The majority of folds have axes which make an angle with the lineation, and the uniform asymmetry of the folds is consistent with top-to-the-west sense of shear. Sections normal to the lineation are rather chaotic, resembling Type 1 interference patterns as defined by Ramsay (1967). However, well developed sheath folds with thinned inverted limbs form eye-folds in this section and may be used as shear-sense indicators if the fold closing direction can be determined. If the fold closes towards the observer, a thinned inverted limb indicates top-towards-observed sense of shear and vice versa (Fig. 14).

Indication of minimum finite shear strain

It is clear from the strong fabrics that the shear strain has been fairly high in the blastomylonitic zones in the Øygarden area. Although strain markers are scarce in the gneisses, an idea of the minimum strain in the blastomylonites can be obtained from inhomogeneously sheared Precambrian agmatitic breccias. The amphibolitic breccia fragments are surrounded by light grey, granitoid veins (matrix). Neither the strongly stretched amphibolite fragments nor the light veins show any sign of boudinage. The expected competence contrast between the fragments and the matrix seems therefore to have been low during the deformation, and the shape of the deformed fragments gives an indication of the local finite strain. Their original non-spherical shapes introduce another error, which is reduced somewhat by their random initial orientation. The deformation seems to deviate somewhat from the theoretical simple shear strain curve (Fig. 15). This could be due to a higher viscosity in the fragments than the matrix and/or to a pure shear component. Shear strains (γ) of 15 and more (Fig. 15) is indicated in the high-strain zones. When γ reaches a value of about 15, a banded, mylonitic gneiss is formed. Since the well-developed, mylonitic banding in the gneisses is commonly folded and refolded into sheath-like geometries as described above, $\gamma > 15$ is indicated in the mylonites.

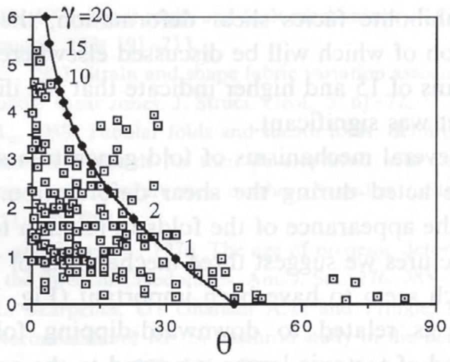

Fig. 15. Plot of strain data from deformed agmatitic breccia, Sotra. The X/Z ratios of deformed agmatitic fragments have been plotted against the angle (θ) between the X axis and a local shear zone. Theoretical curve for simple shear deformation of passive strain markers is indicated.

Conclusions

The classical model of fold development where fold axes form normal to the stretching lineation and passively rotate towards the movement direction, has not been confirmed in the shear related folds in the Øygarden Complex. The folds seem to have formed at various orientations in a rather complex manner, commonly related to the coeval development of inhomogeneous small-scale shear zones. They do, however, share a common feature in the way their short limbs systematically pass through a period of thickening until they become attenuated by increasing strain. This development is accompanied by a tightening of the folds. Small-scale extensional shear zones and locally small "thrusts" are associated with the folds, and the geometries and consistency of asymmetric structures indeed indicated a non-coaxial deformation with top-to-the-west sense of shear for the amphibolite facies shear deformation, the implication of which will be discussed elsewhere. Shear strains of 15 and higher indicate that the displacement was significant.

Several mechanisms of fold generation seem to have acted during the shear deformation. Based on the appearance of the folds in relation to other structures we suggest three mechanisms of folding which seem to have been important (Fig. 11a–c). One is related to downward-dipping foliations ahead of tectonic lenses, a second to the accretion of material in the evolving gap between the "footwall" and "hangingwall" during the synmylonitic development of small extensional shear zones of normal fault geometries. The third mechanism involves fold initiation by slip along an inclined *S* foliation which causes perturbation of the already established mylonitic layering, and fold development by amplification of these irregularities. These mechanisms have in common a rotation of the mylonitic foliation into the instantaneous shortening field leading to fold development.

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