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Composite fabrics in mid-crustal gneisses: observations from the Øygarden Complex, West Norway Caledonides

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Abstract—Subhorizontal Caledonian shear zones that transform migmatitic gneisses into layered gneissic tectonites in the western part of the Øygarden Complex show a number of composite fabrics. The associated structures consist of two sets of related planar surfaces showing a consistent top-to-the-west sense of shear. The development of these structures depends mainly on the nature and variation of finite strain, rheology, strain heterogeneities and extent of metamorphic mineral growth and recrystallization in the shear zones. The structures have one set of surfaces represented by slip surfaces or narrow high strain zones. Oblique to this is a complementary set of surfaces representing either a plane of mineral flattening or aligned metamorphic minerals in *S–C* structures, or rotated gneissic foliation in contractional and extensional composite structures. Rotation by folding and subsequent slip along limbs or axial planar cleavage results in contractional composite structures, while rotation by downward-cutting, extensional-type slip surfaces form extensional composite structures. Contractional and extensional composite structures involve slip transfer across the mylonitic layering, commonly between terminating weak layers within strongly anisotropic, layered tectonites. Combinations of the different types of composite structures are common, but the method of shear sense identification is always the same.

INTRODUCTION

A SIGNIFICANT portion of crustal deformation appears to occur in zones of concentrated shear. The study of shear zones is thus essential to understanding the nature of crustal deformation. The recognition of composite 'planar' fabrics in shear zones (e.g. Berthé *et al.* 1979, Lister & Snoke 1984) and their application as kinematic indicators was a major contribution in this field. Simple models for the formation of certain composite structures (structures consisting of more than one set of tectonic planar fabric) have since been suggested, both from experimental and theoretical studies (e.g. Platt 1984, Goldstein 1988, Shimamoto 1989, Dennis & Secor 1990). However, we believe that there is still a considerable amount of information to be gathered from naturally deformed rocks on this topic. In this paper we describe and discuss composite fabrics formed in exceptionally well exposed, Caledonian, mid-crustal shear zones in the Øygarden Complex, West Norway (Fig. 1).

STRUCTURAL SETTING

Composite fabrics have been studied in banded gneiss-tectonites in the western part of the Øygarden Complex (Kolderup & Kolderup 1940) within the Caledonides near Bergen, Norway (Fig. 1). The complex comprises mostly Precambrian (Sturt *et al.* 1975) migmatites, gneisses and intrusive rocks, which were hetero-

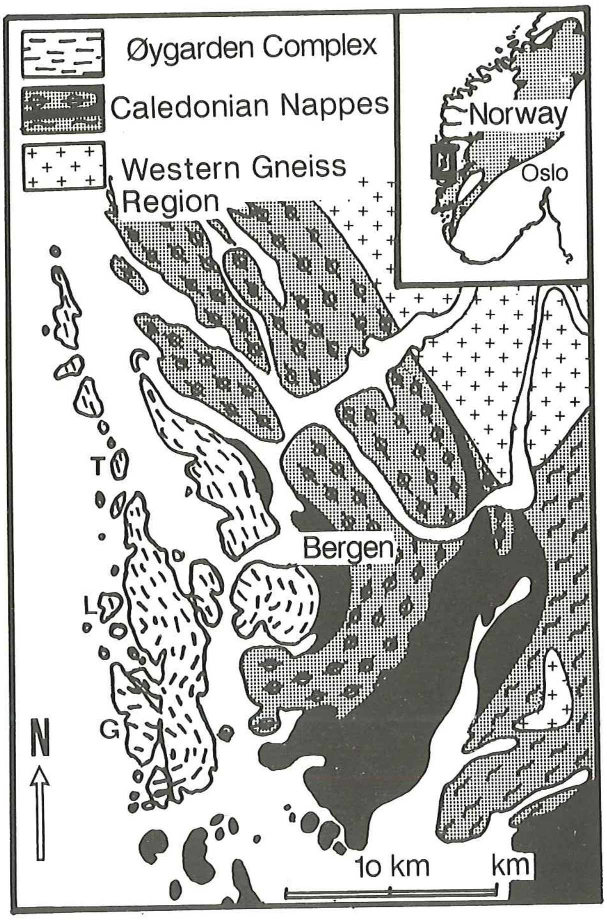

Fig. 1. Simplified geological map of the Bergen area, western Norway. T = Toftøy, L = Lokøy, G = Golta.

geneously, but generally strongly, deformed during the Caledonian orogeny (Bering 1984). The Caledonian deformation localized along gently E-dipping, anastomosing shear zones, where the Precambrian migmatites and intrusive rocks were transformed into gneisses (*L–S* tectonites). The *L*-fabric is a gently E-plunging stretching and mineral lineation which has a remarkably constant orientation throughout the Øygarden Complex (Fossen & Rykkelid 1990). Sections parallel to the lineation and normal to the foliation contain a variety of asymmetric structures indicating a top-to-the-west sense of shear in the western part of the complex. Dynamic recrystallization produced a blastomylonitic texture, and growth of amphibole and garnet indicate upper greenschist to lower amphibolite facies metamophism at the time of deformation.

Various types of composite planar fabrics are recorded from the shear zones of the Øygarden Complex. We will first discuss structures similar or identical to *S–C* structures and then concentrate on a special pair of structures related to inter-layer slip transfer, named contractional/extensional composite structures in this paper.

S–C TYPE COMPOSITE STRUCTURES

A number of composite structures in the region may be classified as, or closely resemble, *S–C* structures, using the rather wide definition given by Lister & Snoke (1984). Two groups of *S–C* structures which closely fit Lister & Snoke's Types I and II, respectively, are found in the Øygarden Complex.

Type I

Composite structures identical to the classical *S–C* structures of Berthé *et al.* (1979) and Type I *S–C* structures of Lister & Snoke (1984) are found in zones of relatively moderate strain, typically in coarse-grained, meta-igneous rocks. Sheared granitoids in the Øygarden Complex contain sub-parallel displacement zones (*C*) some millimeters or centimeters apart. Low strain domains between *C*-surfaces contain an oblique mineral foliation (*S*) inclined mostly 20–30° to *C*. This angle decreases towards *C*-surfaces, and the angular relation between *S* and *C* indicates top-to-the-west sense of shear.

A larger-scale variant of this type of structure is locally developed in heterogeneously sheared Precambrian agmatites (migmatitic breccias). Sub-parallel shear zones separate decimeter to meter thick zones of less deformed rock, where an *S*-foliation is developed parallel to the plane of flattened breccia fragments (Fig. 2). Undeformed or weakly deformed agmatites display more or less randomly oriented fragments. Where deformed, there is a clear connection between the orientation of the long axis (*X*) of the fragments and the degree of flattening. The average orientation of long axes is 20–30° to the *C*-surfaces where weakly deformed fragments define a preferred orientation. Strongly flattened objects make lower angles (θ) to *C* than weakly flattened objects. Where θ reaches about 5°, the agmatitic structures are obscured and additional deformation would have transformed the agmatite into a banded gneiss. It appears from aspect ratio/θ measurements (fig. 15 in Fossen & Rykkelid 1990) that at least in some cases the strain history was not simple shear.

In general, this type of composite structure affected the more isotropic parts of the gneisses, involved heterogeneous shear strain, and did not involve slip along the foliation (*S*) for high to moderate *S–C* angles. The orientation and intensity of the *S*-foliation seems to be related to the accumulation of finite strain (cf. Naruk 1987).

Type II

Micro-scale *S–C* structures, that may be classified as Lister & Snoke's Type II structures, occur in mica-bearing mylonites in the area. Two end-member types of such structures formed by fundamentally different processes. The first type is formed by syn-kinematic growth and recrystallization of mica oblique to the compositional layering. The compositional, mylonitic foliation formed by transposition of pre-existing structures, and is locally overprinted by an oblique, E-dipping foliation defined by aligned, millimeter long porphyroblasts of white and brown mica. Quartz may show a dimensionally preferred orientation similar to that of white mica (Fig. 3), but rapid, dynamic recrystallization has generally obscured this feature in the Øygarden Complex. Tabular micas or aggregates of mica are commonly inclined at approximately 30° to the mylonitic foliation. Other micas are less inclined, and have developed lenticular shapes due to some shear along their margins. The sheared and unsheared micas commonly occur together as asymmetric, fish-shaped aggregates, indicating top-to-the-west sense of shear. Micas in the central part of

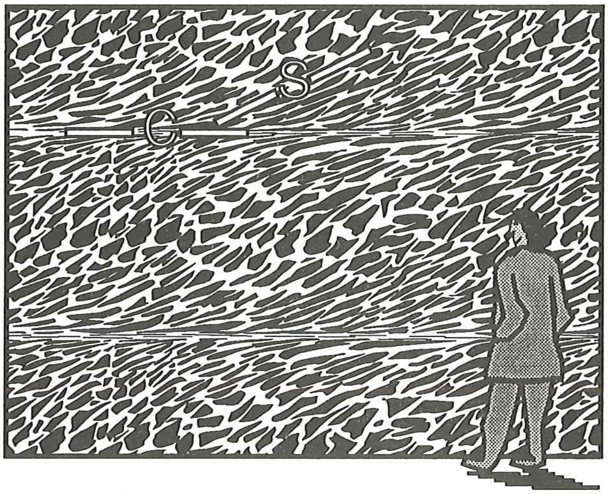

Fig. 2. Illustration of a mesoscopic composite structure similar to smaller-scale *S–C* structures. The foliation (*S*) is defined by flattened objects rotated into discrete shear zones (*C*). Idealized sketch based on observations of heterogeneously sheared agmatites, Golta.

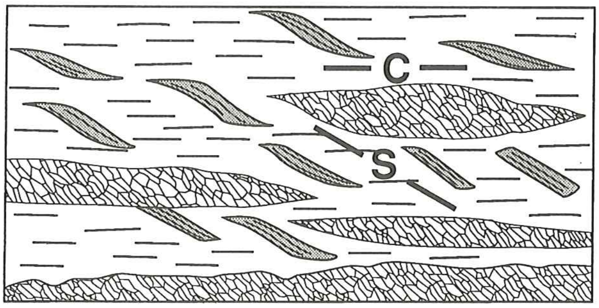

Fig. 3. Typical Type II *S–C* structure. *S* is defined by preferred orientation of micas (grey) and may also be indicated by a grain shape fabric within quartz aggregates.

the fish show the highest inclination to the mylonitic foliation (termed *C* in Lister & Snoke's terminology), while micas constituting the tails of fish are nearly parallel to *C* (Fig. 4). Late to post-kinematic, tabular micas overprint the sheared tails and the adjoining *C*-surfaces.

A second type of Type II *S–C* structure is formed by backward tilting of foliation-parallel micas during shear. This process, which is fundamentally different from the one discussed above, may be explained by a combination of slip along the mylonitic mica-foliation, extension of the foliation by oblique shear bands, and a spin component as discussed by Platt (1984) and Dennis & Secor (1987). It may be considered a micro-scale variant of the 'extensional composite structures' discussed below.

Both types of Type II *S–C* structure develop in strongly sheared and foliated micaceous gneisses. Oblique growth of mica and dynamic recrystallization of quartz is characteristic of the first type. The second type is characterized by partitioning of deformation into foliation-parallel slip rotation of micas and shear band formation, involving a net back rotation of the mica-foliation. However, a combination of the two types of structures is common (Fig. 4).

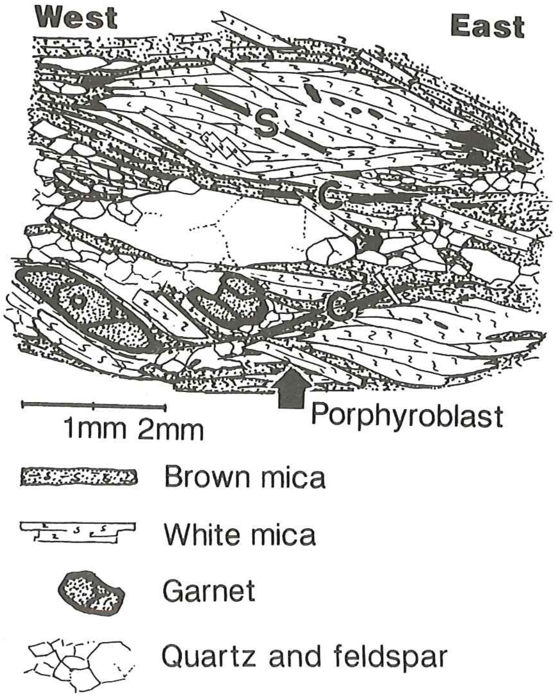

Fig. 4. Type II *S–C* structure. Note porphyroblasts of white mica (arrow) inclined to mica-fish. Both oblique growth of white mica during deformation and back rotation related to shear band formation is responsible for the *S–C* fabric. From high strain zone at Golta.

CONTRACTIONAL COMPOSITE STRUCTURES

A characteristic type of composite structure was formed in highly sheared portions of the Øygarden Complex by intrafolial folding and imbrication of the transposed, commonly mylonitic layering. It is thus characterized by local layer-parallel contraction and reverse-type slip transfer, and bears similarities with reverse-slip crenulations described by Dennis & Secor (1987). Early stages of their development are characterized by trains of open, locally symmetric but generally asymmetric folds (Fig. 5). More advanced stages consist of tighter folds, and some show an axial plane cleavage that intensifies and rotates towards the layering as the folds close (Fig. 6a). At some stage, slip occurs along the axial planar cleavage or along the short, inverted limb of the folds. The folds become sheared out, and small E-dipping reverse-slip surfaces or ramps form (Fig. 6a). Following this stage, contraction of layers precede mainly by imbrication of fold limbs. This imbrication causes backwards rotation (antithetic to bulk shear zone vorticity) of fold-limbs similar to a conventional duplex structure. Once a fold has become sheared out and rotated, the orientation of the slip plane is in a less favorable orientation for continued slip, and a neighboring fold is likely to become sheared and imbricated. The result is a train or 'duplex' of aligned, imbricated fold limbs, where the latter form a local foliation oblique to the enveloping mylonitic layering. Weak layers above and below the 'duplex' structure represent 'floor'- and 'roof'-thrusts, and approximate the enveloping surface of the folds (Fig. 8).

The evolution from folding to imbrication is somewhat complicated by rheologic variations. Banded gneisses with moderate internal competence contrast, or where incompetent layers are thin relative to competent bands, appear to imbricate readily and are, thus, dominated by duplexes (Fig. 8). On the other hand, strong

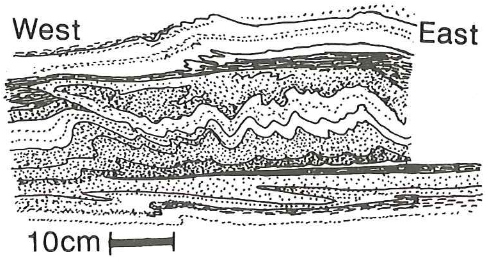

Fig. 5. Contractional composite structure where folds have developed above a terminating mica-rich layer (dark). Note orientation of axial surfaces sub-perpendicular to layering in central part of the figure. Fold axes are at high angles to the exposure. *X–Z* section, Toftøy.

competence contrasts together with thick, weak layers favor fold development. Quartz–felspathic bands in a relatively thick, biotite-rich matrix, for example, may suffer considerable shortening by folding before imbrication takes over. The geometries of these folds are described by Fossen & Rykkelid (1990).

Contractional composite structures are basically developed in two structural settings. One is where small-scale shear zones or detachments curve downwards in the direction of transport. The curving may be achieved kinematically by anastomosing high strain zones around tectonic lenses (Fig. 6b), or may be associated with asymmetric boudinage (cf. Fossen & Rykkelid 1990).

The second setting in which contractional composite structures occur is in association with the frequent terminations of dark, mica-rich layers in the shear zones (Fig. 8). Increasing strain stretches many mafic objects into long, thin discontinuous and mechanically weak biotite-rich layers along which slip is concentrated. The position of their termination with respect to the neighboring weak layers determines the resulting type of structure. Where a weak layer terminates *beneath* its nearest neighbor, reverse-slip-related structures typically develop. Alternatively, if the weak layer terminates *above*, extensional composite structures (see below) will form. The contractional composite structures may contain a series of ramps that branch out from the terminating layer, truncate and imbricate layers above, and merge into the upper layer (Fig. 8). The lower and upper weak layers contain the floor and roof thrusts of the duplex. A direct relationship exists with strike-slip fault systems. Structures such as strike-slip duplexes form in the constraining bend similar to the formation of fold trains and small-scale imbrications of fold limbs in contractional composite structures (e.g. Woodcock & Fisher 1986).

Most contractional composite structures are slightly convex, due to the relatively larger vertical thickening in the central part. The upper and lower weak layers may be pushed apart by the growing interior of the structure, and the dips of the surrounding weak layers increase in the direction of transport close to their terminations (Fig. 9). Thus, the rotation of the weak layers is opposite to that of the limbs of the folded layers, resulting in high-angle composite planar fabrics. The highest angles occur in trains of only a few folds, and in short duplexes.

EXTENSIONAL COMPOSITE STRUCTURES

Extensional composite structures consist of minor shear zones or shear bands which cut *downward* in the direction of transport, truncate the foliation beneath, and displace this in a normal sense. The truncated foliation is rotated antithetic to the main shear direction (Fig. 10, upper part). Some normal slip-related structures contain numerous extensional shear zones (Fig. 7) whilst others consist of one or two only (Figs. 10 and 11). Various extensional composite structures resemble asymmetric boudins (Platt & Vissers 1980, Gaudemer & Tapponier 1987) or type 1 and type 2 asymmetric pull-aparts (Hanmer 1986), in which the small, downward cutting shear zones may be termed shear bands (White 1979, Weijermars & Rondeel 1984, White *et al.* 1986), normal fault type shear bands (Marcoux *et al.* 1987), extensional crenulation cleavages (eccs) (Platt & Vissers 1980), or normal slip crenulations (NSC) (Dennis & Secor 1987). Extensional composite structures are also observed on a microscale as shear bands extending the mylonitic foliation. At this scale, the shear band development may cause a rotation of mica porphyroblasts as discussed above (*S–C* structures).

Extension of layers is observed where they curve upward on the upstream side of a tectonic lens (cf. fig. 12 of Fossen & Rykkelid 1990). In this situation the layers tend to stretch and thin homogeneously to form a laminated tectonite without any composite structures, even if contractional composite structures have formed on the lee side of the lens. Extensional composite structures are more frequently associated with slip transfer associated with terminations of mica layers as discussed above (Fig. 10). The development of such an extensional transfer structure is similar to extensional deformation (extensional duplexes) in the restraining bend region of a non-planar strike-slip fault (Woodcock & Fisher 1986).

DISCUSSION OF EXTENSIONAL AND CONTRACTIONAL COMPOSITE STRUCTURES

During the Caledonian deformation, pre-existing structures including foliations compositional banding, dikes, breccia fragments, and boudins were stretched and transposed into layered tectonites. The layers gradually rotated towards the flow surface, and at some stage, slip was concentrated along the weaker layers which started acting as local detachments. However, the discontinuous nature of the layers implies slip transfer from one layer to another. When slip was transferred upwards to a higher level, a region between these levels must have shortened in order to balance the structure (Fig. 12). When slip was transferred downward in the direction of transport, local shear zone parallel extension occurred (Fig. 13).

Whereas abundant asymmetric structures with consistent vergence clearly indicate the general non-coaxial deformation of the tectonites, deviations occur in areas of slip transfer. Consider an idealized case where a weak layer terminates and slip along this layer is transferred to a higher-level weak layer (Fig. 12). The strain may then be separated into a general or *distributed*, homogeneous shear strain affecting all portions of the tectonite equally, and a *localized* shear strain constrained to the weak, terminating layers. Only the localized shear will be transferred between the two layers, whereas the distributed strain remains constant. The total displacement across the sheared rocks should be equal at each side of the structure so that the internal deformation does not absorb, but only transfers, slip. The region

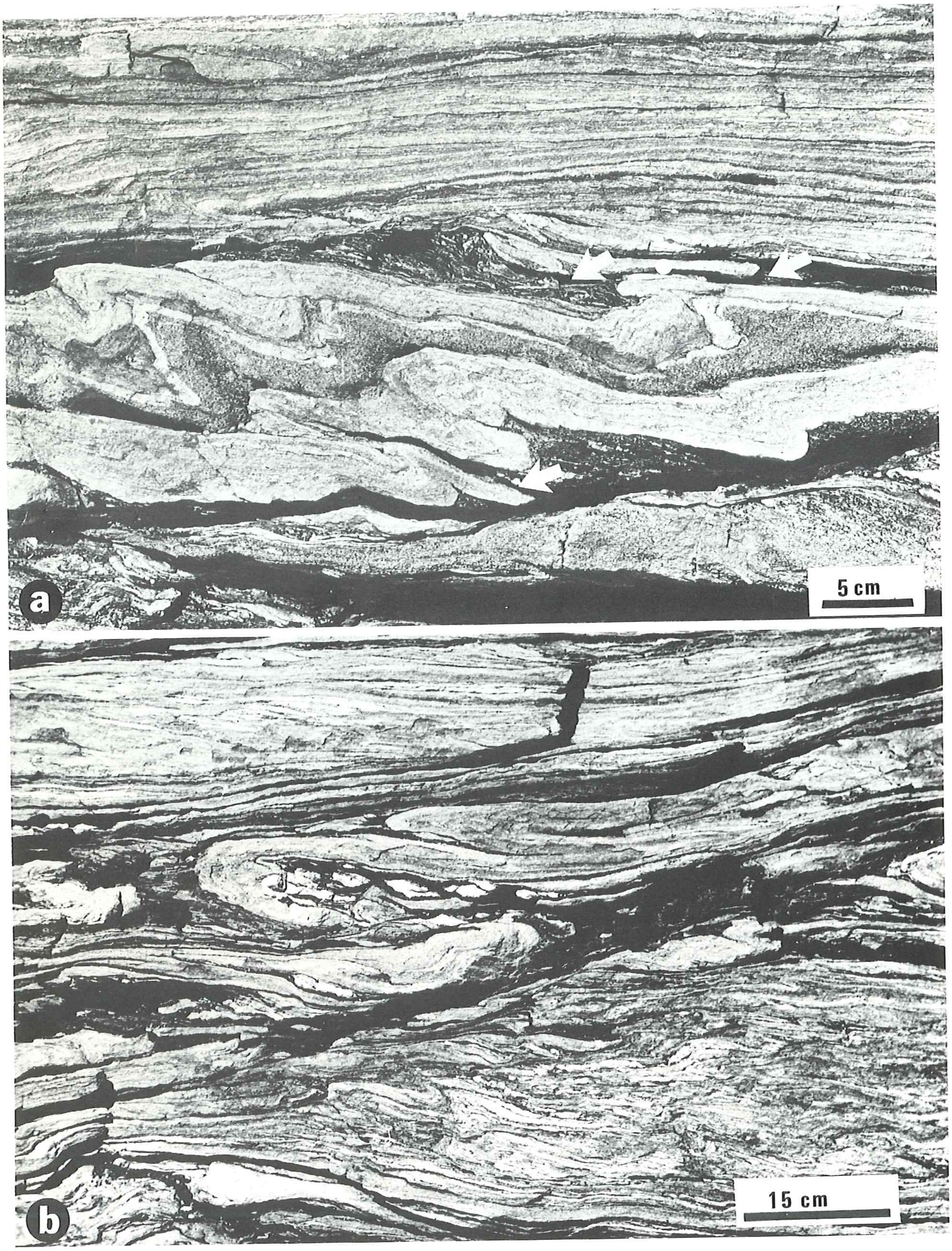

Fig. 6. Contractional composite structures in the Øygarden Complex, developed between two dark, mica-rich horizons along which slip is concentrated. Internal oblique surfaces are defined by parallel axial surfaces and limbs or sheared out limbs of isoclinal folds. Arrows in (a) indicate slip surfaces that truncate the isoclinal folds along their axial planar cleavage. The compressional composite structure in (b) is formed at the lee side of the tectonic lense in the lower part of the figure (cf. Fig. 12). *X–Z* section, Toftøy, looking north.

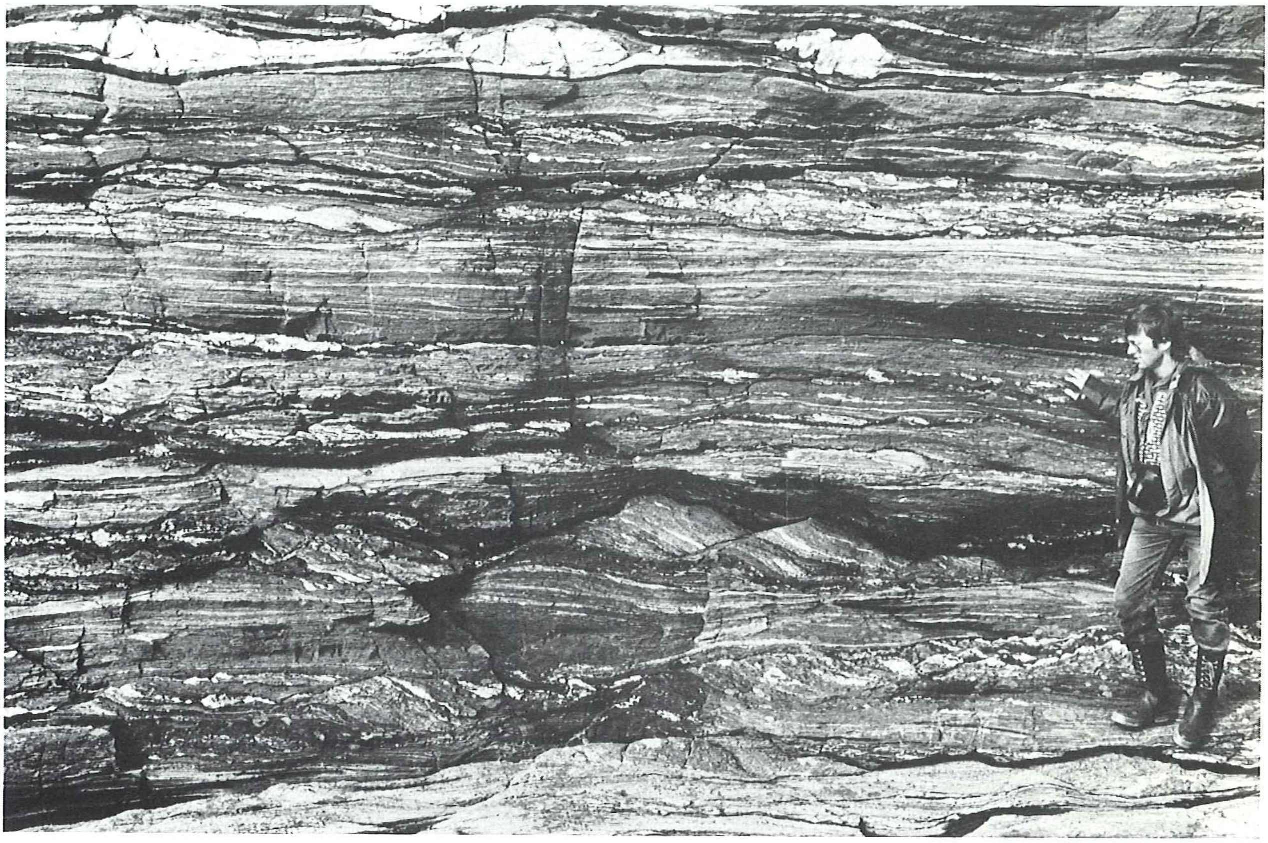

Fig. 7. Extensional duplexes (extensional composite structures) boarded by micaceous, weak layers and planar laminated gneisses. *X–Z* section, Lokøy, looking north.

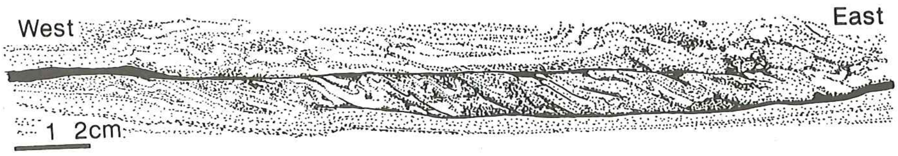

Fig. 8. 'Duplex'-structure (contractional composite structure) developed between two terminating weak, mica rich layers. *X–Z* section, Toftøy.

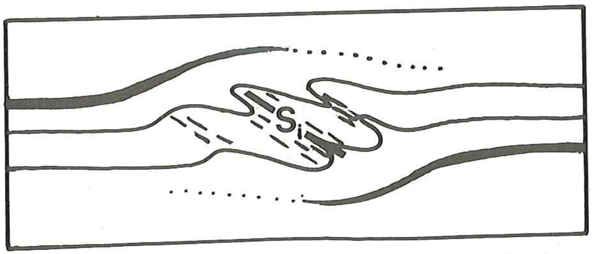

Fig. 9. Schematic diagram of a short fold train (contractional composite structure). The structure has a convex geometry with slip surfaces (black, weak layers) dipping in the direction of transport. Note the locally high angle between the internal foliation (*S*i) and the weak layers. *X–Z* section, Toftøy.

Fig. 10. Shear band (open arrows) linking two terminating micaceous layers in the upper part of the figure (extensional composite structure). The lower part displays contractional composite structures linking horizons marked with black arrows. Arrows indicate slip directions. *X–Z* section, Toftøy.

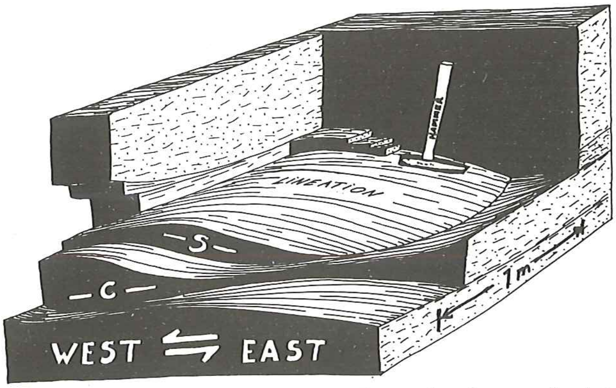

Fig. 11. Three-dimensional geometry of extensional composite structure, where shear bands (*C*) transect the mylonitic foliation (*S*). South of Golta.

between the terminating weak layers (the transfer region) will undergo a pure shear deformation with the maximum compression parallel to the weak layers (Fig. 12). The amount of shortening (Δl) parallel to the transport direction simply equals the displacement across either of the weak layers, independent of any volume change within the structure (Fig. 12). The local pure shear component is in some cases reflected by relatively symmetric, upright folds in the transfer region (Fig. 5), but the distributed non-coaxial deformation will subsequently rotate these folds to become asymmetric and W-verging (Figs. 6a and 12).

The above discussion was based on the effect of upward transfer of slip. Downward transfer of slip would have a similar, but opposite, effect; a pure shear region with extension parallel to the weak layers would develop. Conjugate sets of shear bands could develop in the transfer region, but the distributed non-coaxial deformation would favor the set synthetic with the sense of shear (Fig. 13).

It is a general feature that non-coaxial deformation is concentrated along narrow, weak layers that exchange slip. Intervening layers show lower strains, and locally shorten or stretch according to the type of slip transfer. Termination of weak layers seems to be a common reason why slip is transferred from one horizon to another. However, slip may also be transferred where the layering is perturbed by irregularities, e.g. in the vicinity of tectonic lenses. Where the layering is rotated synthetic to the shear direction, it enters the compressional field of the incremental strain ellipse, and the resultant development of folds and reverse-slip surfaces provide transfer of slip upward to stratigraphically higher layers (Figs. 6b and 14). In these cases the net slip may be more or less shear zone parallel, and the evolution of contractional composite structures enables flow oblique to the layering, but sub-parallel to the main shear zone. Similarly, where the rotation is antithetic to the shear direction, the layers enter the extensional field, and extensional composite structures may provide flow oblique to the layering and sub-parallel to the main shear zone.

The relation between an anisotropy that is inclined to the main slip direction and the local development of slip transfer structures, is discussed by Platt (1984) and Dennis & Secor (1987). Platt describes *S–C* mylonites having an inclined mica foliation (the *S*-surface) acting as a slip surface. The slip along the *S*-surfaces causes thickening of the shear zone which in turn is compensated by the development of an extensional crenulation cleavage. However, where slip occurs along foliations dipping in the direction of transport, reverse-slip crenu-

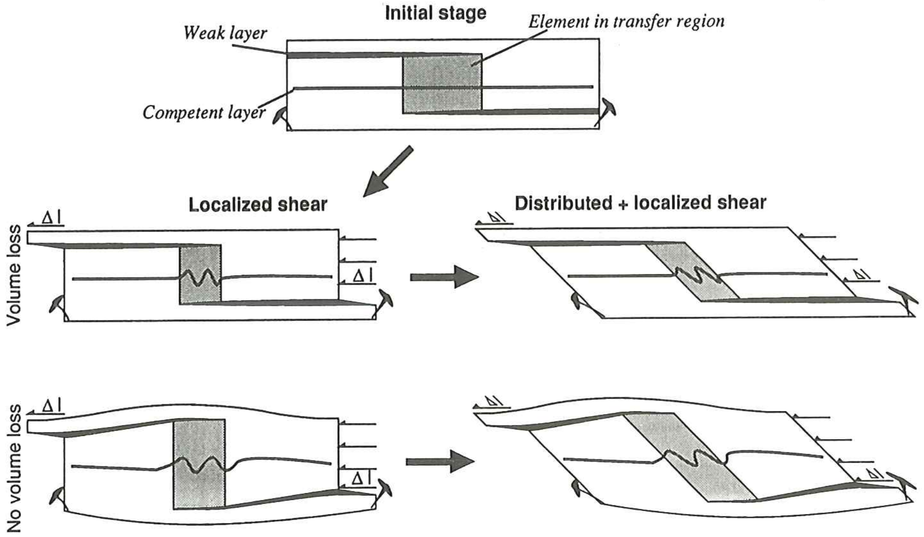

Fig. 12. Illustration of plane strain, upward transfer of slip between terminating weak layers (black). An element of the rock has been shaded and a somewhat more competent layer added to indicate the deformation in the transfer region. The local effect of the slip transfer is shown to the left, while the disturbed shear component is added to the right. Compare the lower right geometry to Fig. 9.

lations (RSCs) may form (Dennis & Secor 1987). These models for the formation of eccs and RSCs thus bear similarities with our models of extensional and contractional composite structures. Dennis & Secor's model would be directly applicable to the situation where the mylonitic foliation is perturbed through the flow plane at the lee side of tectonic lenses. However, our model with slip transfer between terminating layers and development of contractional and extensional composite structures in the transfer zone is different since slip transfer is here provided by mechanical heterogeneities and not by any particularly favorable orientation of the foliation to the shear plane. The term reverse-slip *crenulation* is normally used for micro- or cm-scale folds, whereas the contractional structures described in this paper may occur at meter scale, and include discrete slip surfaces as well as folds. Finally, the designations *reverse* and *normal* slip crenulations preclude a general use of these terms, e.g. for composite fabrics in vertical shear zones.

CONCLUSIONS

A variety of well-exposed structures of composite planar fabrics occur in the Caledonian gneisses of the Øygarden Complex. The different types have their own geometric characteristics, and differ in terms of strain and formation mechanisms. Initial heterogeneous shear strain produced a foliation (*S*) defined by flattening of minerals at a microscopic scale, and flattening of pre-existing objects or structures at outcrop scale. This foliation is oblique to sets of shear zones and the banding within the shear zones (*C*), and together they form an *S–C* structure (Type I). This type of composite planar fabric formed during the process of making a well banded or foliated gneiss from an igneous or a migmatitic protolith. The formation of other types of composite fabrics requires a strong, anisotropic foliation to be established and is therefore generally restricted to highly sheared portions of the gneisses. On a microscale,

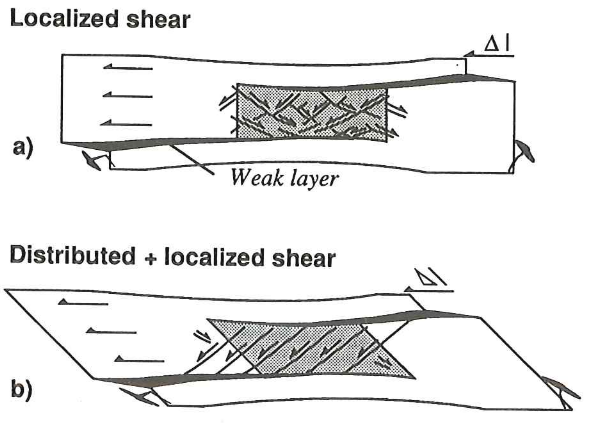

Fig. 13. Illustration of downward transfer of slip between terminating weak layers (black). Similar to Fig. 12, but for no volume loss only. Note that conjugate shear zones or shear bands are expected for localized shear only (a), and preferred development of shear zones syntetic with the general shear sense are expected in the case of additional distributed shear (b).

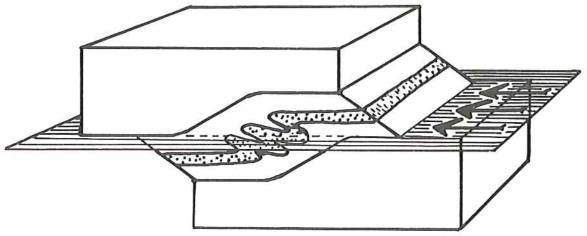

Fig. 14. Illustration of slip transfer across locally dipping layers, e.g. behind a tectonic lense. The evolving folds and possibly reverse-slip surfaces may in this case be termed reverse-slip crenulations, using Dennis & Secor's (1987) terminology.

syn-kinematic growth of metamorphic minerals oblique to the mylonitic banding produces a high-strain *S–C* structure. Mesoscopic contractional and extensional composite structures are favoured in anastomosing shear zones where the foliation becomes rotated oblique to the shear plane, or in tectonites with discontinuous, weak layers between which slip is being transferred. Contractional composite structures involve shortening whereas extensional composite structures involve extension of the mylonitic foliation. All the different structures contain one set of surfaces which represent active high-strain zones, and an oblique, internal foliation along which a relatively smaller amount of slip occurred. A second set of surfaces dips more steeply to the east in the study area, indicating a top-to-the-west sense of shear. Qualitative, angular relationship between the two foliations is directly comparable to that of the classical *S–C* mylonites of Berthé *et al.* (1979), and a detailed knowledge about their development and formation mechanism is not required for their application as kinematic indicators. This is fortunate, since different types of composite structures may form contemporaneously, and may interfere to form complex, composite structures during a single deformational event.

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