Pergamon

Journal of Structural Geology, Vol. 16, No. 10, pp. 1385 to 1401, 1994

0191–8141/94 $7.00+0.00

0191–8141(94)E0022–Q

Caledonian compressional and late-orogenic extensional deformation in the Staveneset area, Sunnfjord, Western Norway

PER TERJE OSMUNDSEN and TORGEIR B. ANDERSEN

Department of Geology, University of Oslo, P.O. Box 1047, 0316 Blindern, Oslo 3, Norway

(*Received* 5 *November* 1992; *accepted in revised form* 5 *January* 1994)

Abstract—The studied area in Western Norway constitutes part of the hangingwall of the extensional Kvamshesten Detachment Zone (KDZ). The KDZ separates eclogite-bearing lower crust from a hangingwall consisting of a Precambrian basement-cover pair, Silurian continental margin sediments, a Silurian obduction mélange, a Late-Ordovician ophiolite and the Devonian Kvamshesten Basin, deposited unconformably on the Pre-Devonian rocks. Contractional deformation related to ophiolite obduction and to the Caledonian Scandian Orogeny produced a suite of SE-verging structures developed under greenschist facies conditions. As orogenic collapse commenced, extensional shear zones were formed in the upper and middle crust, re-activating contractional shear zones and fabrics. The direction of transport on the inherited fabrics was reversed from top-to-southeast to top-to-northwest, and structures related to the regional extension were superimposed on the contractional structures. Back-folding of the main contractional foliation by asymmetric W-vergent folds, together with NW and W-directed shearing along weak lithologies and semi-ductile faulting in the mélange, are the main structural expressions of early stages of the orogenic collapse in the Staveneset area. There is apparently no metamorphic break between the contractional fabrics and the earliest extensional structures. The extensional structures developed, however, under progressively more brittle conditions. The Devonian sediments were deposited upon a sequence of rocks in the upper plate of the Kvamshesten Detachment that had already undergone significant extensional deformation and tectonic exhumation in the Late-Silurian–Early Devonian. The extensional deformation in the upper plate of the Western Norwegian extensional detachments has up to recently been largely ignored in the discussion of the structural control of the formation of the Devonian basins.

INTRODUCTION AND REGIONAL SETTING

THE Sunnfjord region in Western Norway (Fig. 1) is a key area in the understanding of the stratigraphical and deformation history of the SW Norwegian Caledonides and the subsequent post-orogenic extensional collapse of the mountain belt. Several recent studies have focused on aspects of the geology of the area including stratigraphy, tectono-stratigraphy, geochemistry and structure (Brekke & Solberg 1987, Andersen *et al.* 1990, Furnes *et al.* 1990, Skjerlie & Furnes 1990, and several unpublished theses from the Universities of Bergen and Oslo). The tectono-stratigraphic succession comprises a lower- and an upper plate separated by large-scale extensional detachment zones; in the Sunnfjord area the detachment is known as the Kvamshesten Detachment Zone (KDZ). The KDZ developed during the post-orogenic extensional collapse of the Caledonides in the Lower–Middle Devonian (Norton 1987, Séranne & Séguret 1987, Chauvet & Séranne 1989, Andersen & Jamtveit 1990, Swensson & Andersen 1991). The KDZ was reactivated in the Upper Paleozoic and in the Mesozoic (Torsvik *et al.* 1992).

The lithologies in the lower plate are dominated by Proterozoic gneisses of the Western Gneiss Region (WGR), which are characterized by the numerous occurrences of eclogitized crustal lithologies (Bryhni 1966, Mørk 1985) with Caledonian high-*P* metamorphic assemblages (Griffin & Brueckner 1980, 1985). The lower plate also contains inclusions of mantle lithologies (Cordellier *et al.* 1981, Jamtveit *et al.* 1991) and rocks that are believed to form part of the Caledonian cover and nappes (Hernes 1954, 1956a, b, Bryhni 1989, Swensson & Andersen 1991). The rapid uplift and eduction of the lower plate, partly from mantle depths (Smith 1988, Smith & Lappin 1989), triggered the extensional collapse of the orogen (Andersen *et al.* 1991). The uplift was accompanied by the progressive retrograde reworking of the early high-*P*, non-rotational, constrictional fabrics (Andersen *et al.* 1991, Dewey *et al.* 1993). As the originally deep rocks reached middle and upper crustal levels, they were affected by the enhanced deformation in the extensional detachments (Andersen & Jamtveit 1990), characterized by rotational deformation at amphibolite to greenschist facies conditions. Studies in the upper plate have been chiefly concerned with the contractional deformation during formation of the mountain belt. In most areas that originally constituted the middle and upper crust of the Scandinavian Caledonides, contractional structures are dominant. Most of the recent publications dealing with the extensional collapse of the Scandinavian Caledonides have concentrated on the detachments and their structural control on the sedimentation in the Devonian basins of Western Norway. The sedimentology and extraordinary stratigraphic thicknesses of the Devonian basins of West Norway were described in detail by Steel and co-workers in a number of papers and unpublished theses (Steel 1976, Steel & Gloppen 1980 and others). The basins are now classic examples of sedimentation related to migrating depo-centres believed to have been controlled by faults along their margins. The importance of the exten-

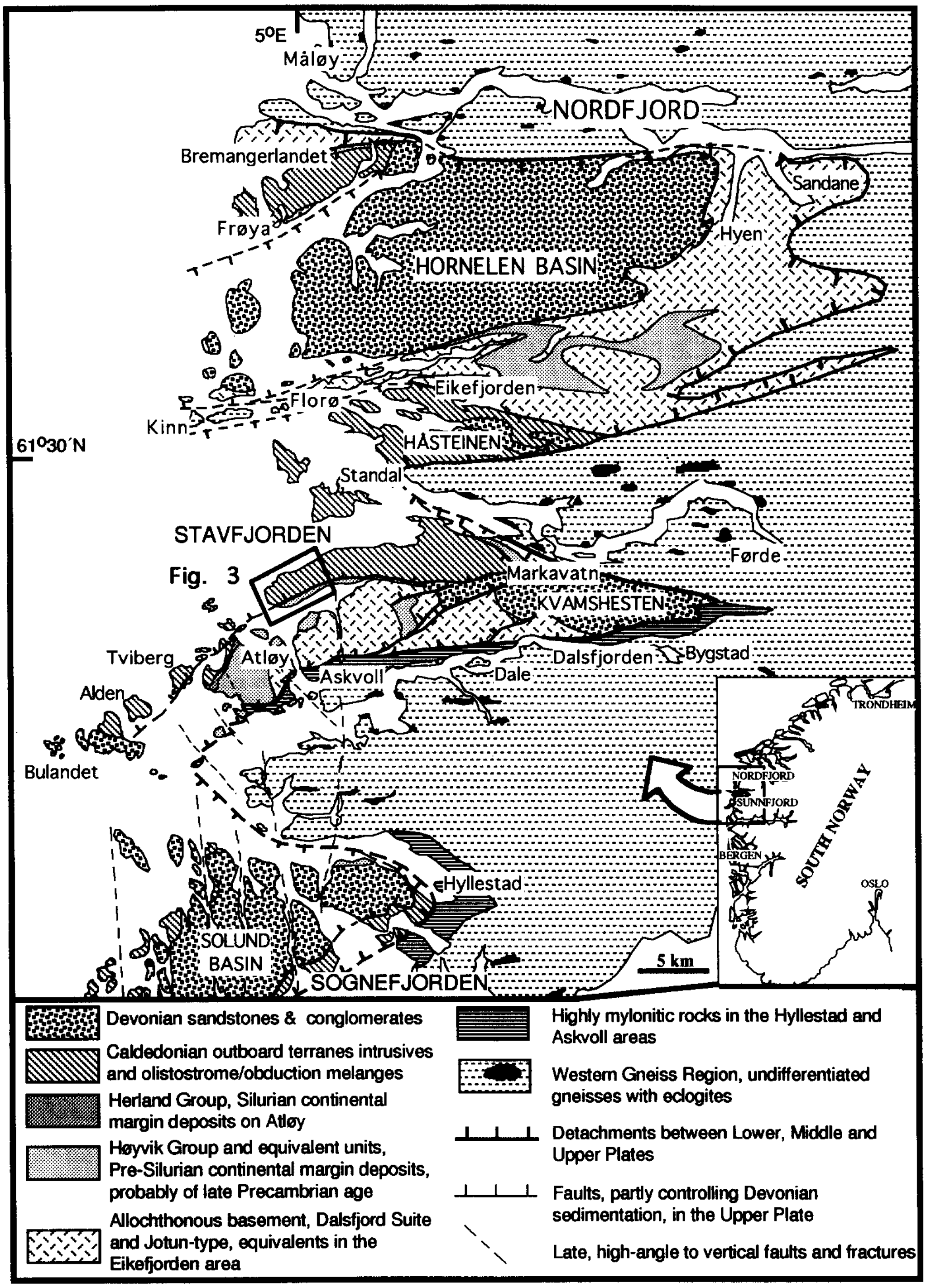

Fig. 1. Simplified geological map of Sogn–Sunnfjord region in West Norway. The area studied in detail is on the western part of the Staveneset peninsula.

sional deformation has now been recognized along the Scandinavian Caledonides from Rogaland in the south to Troms in the north (Hossack 1984, Norton 1986, 1987, Sjøstrøm & Bergmann 1989, Cashman 1990, Rykkelid & Andresen 1993). Very little attention has, however, been paid to the extensional deformation that was superimposed on the contractional structures in the hangingwall of the extensional detachments. This paper describes the geological setting and both contractional and extensional structures in the Caledonian nappe-sequence in the Staveneset area that forms parts of the substrate to the Kvamshesten Devonian basin in Sunnfjord (Fig. 1). We focus on the extensional deformation that can be attributed to the upper-crustal deformational response to the large-scale ductile extensional deformation that took place along the underlying KDZ.

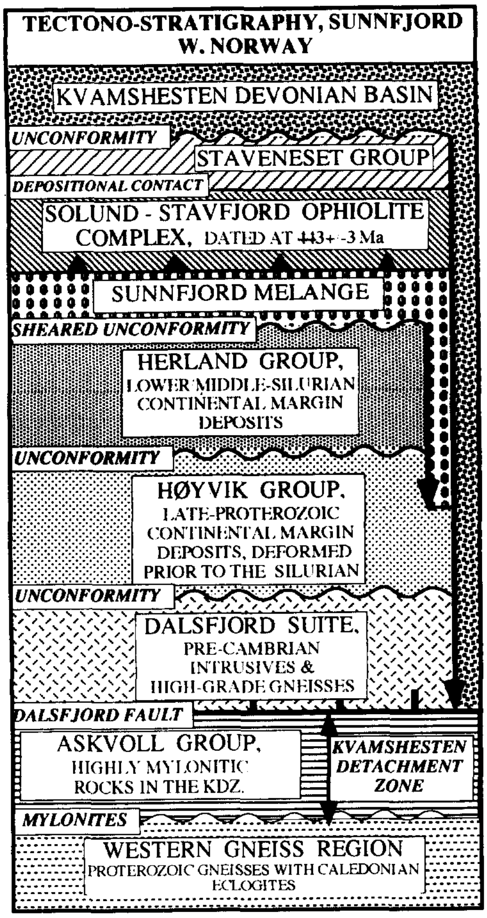

Fig. 2. Tectono-stratigraphy of the Sunnfjord region, modified after Andersen *et al.* (1990). See text for explanation.

STRATIGRAPHY AND TECTONO-STRATIGRAPHY

A summary of the tectono-stratigraphy of the hangingwall of the KDZ in Sunnfjord is shown in Fig. 2 (modified from Andersen *et al.* 1990). The area studied in detail on Staveneset (Fig. 3) forms part of the basement to the unconformably overlying Middle-Devonian sandstones and conglomerates of the Kvamshesten Basin. The lithologies discussed here belong to four stratigraphic units: the Høyvik Group (Skjerlie 1969, 1974, Brekke & Solberg 1987), the Sunnfjord Mélange (Andersen *et al.* 1990), the Solund–Stavfjord Ophiolite Complex (S–SOC) and the Staveneset Group (Furnes *et al.* 1990).

The Høyvik Group is the lowest tectonic unit exposed on Staveneset. It comprises a sequence of alternating quartz-schists, mica-schists, impure marbles and sub-arkoses that can be traced along the south coast of Staveneset, across the fjord to Atløy and farther east to the Markavatn area (Fig. 1). The Høyvik Group rests unconformably upon the Dalsfjord Suite (Andersen & Dæhlin 1986). In the type area on Atløy, Brekke & Solberg (1987) divided the Høyvik Group into four formations, out of which the upper two, the Atløy and Laukeland formations, contain pre-metamorphic mafic dikes and volcanics. Marble- and greenschist-bearing meta-sediments occurring along the south coast of Staveneset were correlated with the Laukeland Formation by Osmundsen (1990). On Atløy, the Høyvik Group is overlain unconformably by the fossiliferous continental margin sediments of the Silurian Herland Group (Brekke & Solberg 1987). This contact provides the only age-constraint available regarding the Høyvik Group. The Høyvik Group underwent polyphase deformation at upper greenschist facies metamorphism prior to the deposition of the Herland Group (Brekke & Solberg 1987). On Staveneset, however, the Herland Group is missing, and the Høyvik Group is in direct contact with the Sunnfjord Mélange. Lithostratigraphic correlation suggests that the Høyvik Group is of Late-Precambrian age, and equivalent to similar thick psammitic sequences with mafic dike-swarms in the Scandinavian Caledonides. These occur in the Middle- and possibly in the lower parts of the Upper Allochton in Norway and Sweden, and are believed to represent the most distal parts of the continental margin of Baltica (Brekke & Solberg 1987, Stephens & Gee 1989).

The Sunnfjord Mélange has been divided informally into a lower (Stubseid) and an upper (Illevika) unit (Osmundsen 1990); in most areas they are separated by the late extensional Staveneset Fault (see Fig. 3 and below). Locally on Atløy, the lower unit of the mélange has an unconformable, depositional contact with the Herland Group. In the studied area, however, the mélange has tectonized contact with the Høyvik Group. The matrix of the lower unit is dominated by greenish quartz–mica schists containing variable amounts of chlorite and plagioclase. Chlorite-rich impure marbles and greenstones occur within the lowermost levels of the Stubseid unit, as do scattered vein-quartz and epidosite clasts. Characteristic, jasper-bearing, matrix-supported, polymict conglomerates can be traced from Atløy (Berg 1988) across the studied area towards the Markavatnet area in the east (Fig. 1). The clasts in the conglomerate reflect a bimodal source of both continental and oceanic affinity (Skjerlie 1974, Andersen *et al.* 1990). In the studied area, clasts of continental affinity comprise rocks derived from the Dalsfjord Suite and Høyvik Group, deformed and metamorphosed prior to deposition, and previously undeformed sandstone clasts, probably derived from the Herland Group. Clasts of oceanic affinity are greenstones, epidosite and red jasper. In western parts of Staveneset, a greenstone marks the tectono-stratigraphically lowermost level of the mélange. The greenstone is believed to represent a fragmented dike/intrusive complex, probably an olistolith derived from the S–SOC. In the westernmost parts of the study area, a ductile shear zone marks the base of the upper unit. The shear zone is characterized by green phyllonites and phyllonitic conglomerates, carrying serpentinite, talc-schist and greenstone blocks. A large block of pillow lava with MORB composition (Carlsen 1989) occurs in tectonic contact with conglomerates of the Stubseid unit in the Illevika area (Fig. 3). The phyllonitic, ultramafic-bearing level of the mélange also occurs at Tviberg, Atløy and Markavatn (Skjerlie *et al.* 1989, Andersen *et al.* 1990, Alsaker 1991). The dominant lithology of the

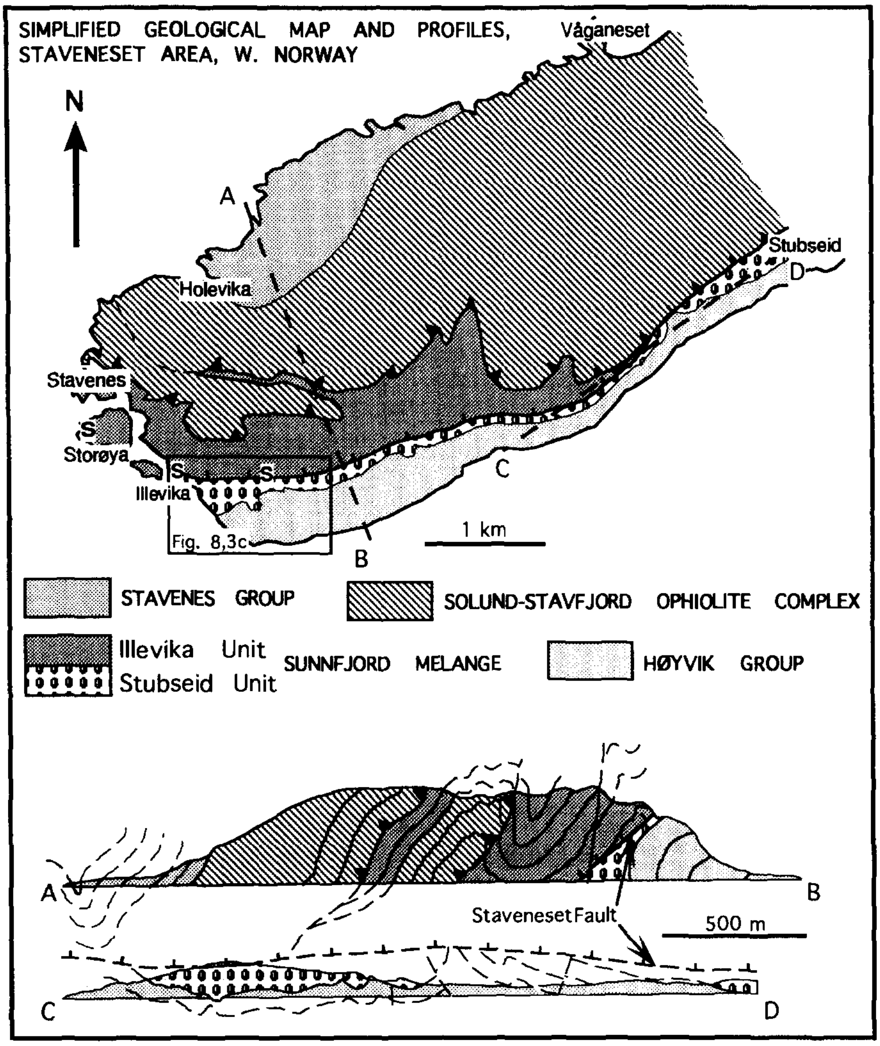

Fig. 3. Simplified geological map and cross-sections of studied area on Staveneset. In cross-section A–B, SE-verging, late contractional folds (F_{2-3}) have been distinguished in the S–SOC and Sunnfjord Mélange. Cross-section C–D shows W-vergent F_3 back-folds in the Høyvik Group and in the lower part of the Sunnfjord Mélange. The F_3-folds are truncated by the Staveneset Fault, which defines the structural contact between the lower and upper units of the Mélange.

upper unit is a chlorite-bearing, calcareous meta-greywacke. Shear zones carrying talc-schist lenses, conglomerate and impure limestone occur, however, at low and middle levels of the Illevika unit. At tectonostratigraphically higher levels of the upper unit, pods, lenses and tabular bodies of greenstone occur in the metagreywackes. Thus, the uppermost part of the mélange resembles part of the Staveneset Group that forms the primary cover to the S–SOC.

On Staveneset, various parts of the Solund-Stavfjord Ophiolite Complex (S–SOC, Furnes *et al.* 1990) rest with tectonic contact on the Sunnfjord Mélange (Fig. 3). The S–SOC constitutes an ophiolite fragment, where only upper and middle parts of the pseudo-stratigraphy have been preserved. The older parts of the ophiolite, dated (U–Pb on diorite zircons) at 443 ± 3 Ma by Dunning & Pedersen (1988), were probably deformed in a transform environment prior to a second phase of magmatic activity. The latter was related to a propagating rift segment intruding older, already deformed crust (Skjerlie 1988, Carlsen 1989, Skjerlie *et al.* 1989).

The Staveneset Group (Furnes *et al.* 1990) constitutes the uppermost preserved tectono-stratigraphic unit in the Caledonides in Sunnfjord (Fig. 2). The sequence is dominated in its lower parts by meta-greywackes with abundant meta-gabbroic sills, dikes and layers of pillow lava all with MORB composition (Carlsen 1989). In the tectonically dismembered upper parts of the Staveneset Group, rocks of calc-alkaline and alkaline affinity have been identified (Furnes *et al.* 1990). The group rests with a primary, depositional contact on the S–SOC and primary sedimentary structures in the meta-greywackes, together with well preserved pillow lavas, show younging towards the northwest away from the contact with the S–SOC (Osmundsen 1990).

STRUCTURAL GEOMETRIES AND HISTORY

In the Staveneset area, structures related to Silurian regional contraction and to subsequent extensional reactivation are strongly developed. Accordingly, structures and fabrics related to the Pre-Silurian event affecting the Høyvik/Dalfjord cover-basement pair are completely transposed or re-activated. They cannot with confidence be distinguished from the structures pro-

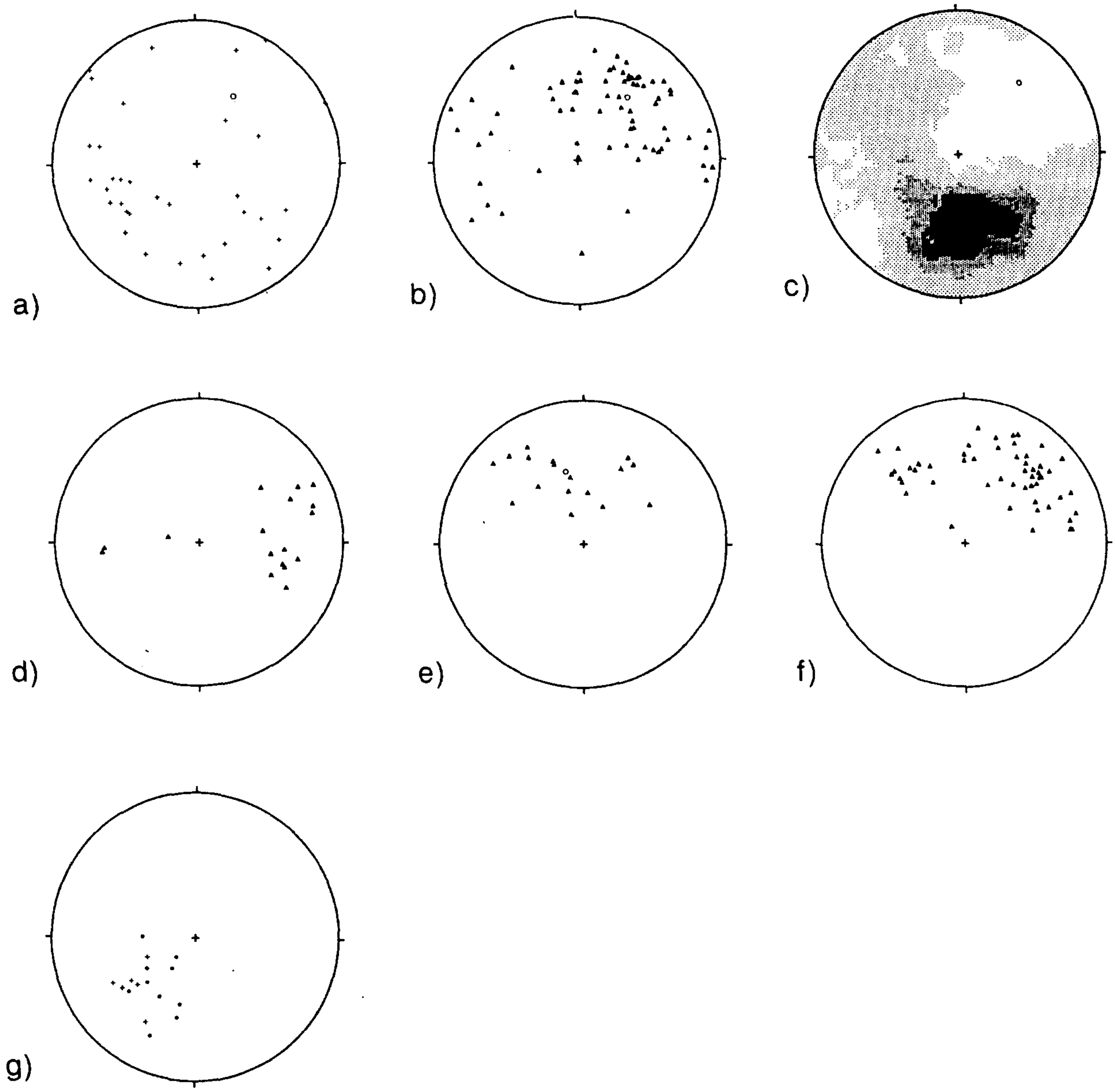

Fig. 4. Stereographic representations (equal area) of main structural elements in the Staveneset area. (a) Poles to S_1. N = 35. (b) F_{2-1} fold axes. N = 75. (c) S_{2-1} (main foliation). Pole to best-fit great circle 040/34. N = 894. Contour pattern intervals (from least dense) 00–2.0%, 2.0–4.0%, 4.0–6.0%, 6.0–7.9%. (d) F_{2-3} fold axes. Axes plotting in third and fourth quadrants are refolded by large-scale F_3 folds. N = 18. (e) Lineations. Mean lineation vector 347.47. N = 17. (f) F_3 fold axes. Mean lineation vector 029/38. Notice good correlation with pole to best-fit great circle for S_{2-1} data set. The deviation is probably related to the late contractional folds (F_{2-3})) that make the calculated fold axis a hybrid one. (g) S_3 (crosses) and F_3-related reverse faults (dots). $N = 18$.

duced during the Late-Silurian Scandian orogeny, except for clasts in the sediments that contain obvious pre-depositional fabrics.

Geometry of contractional structures

The structural elements formed during the Scandian orogeny in the Staveneset area were produced by deformation associated with the obduction and emplacement of the S-SOC and its cover and the continental collision between Baltica and Laurentia. The progressive formation of structural elements during the contractional deformation enables characterization of two deformational events (D_1 and D_2); the latter can be further subdivided into D_{2-2} and D_{2-3} phases. The oldest tectonic fabric recognized is a relict pressure solution cleavage, S_1 (Fig. 4a) that is generally parallel to bedding and can be distinguished as a separate foliation only in the hinges of F_2 folds. This fabric in the Høyvik Group (Fig. 5) must be a reactivated Pre-Silurian fabric, because S_1 pre-dates the deposition of the Herland Group on Atløy (Brekke & Solberg 1987). Over large areas, bedding and S_1 are transposed into the regional foliation (S_2).

Structures related to obduction and emplacement of the ophiolite. The S_1 foliation and bedding are folded by tight to isoclinal F_2 folds, dominantly with a northeasterly plunge (Figs. 3 and 4). F_2 folds are symmetrical to asymmetrical, commonly with sheared lower limbs. The vergence of asymmetric F_2 folds is consistently towards the southeast. Numerous F_2 folds with a well-developed crenulation cleavage (S_2) occur in the upper unit of the Sunnfjord Mélange. Fold geometries, cleavage orientations and pseudo-stratigraphy/way-up in the ophiolite together suggest the presence of a large-scale F_2 anticlinal hinge in the southern parts of the studied area (Fig. 3, profile A–B). The anticline was sheared out along its southeastern inverted limb, as frequently displayed by the smaller-scale F_2 folds. A similar style of deformation related to the emplacement of the ophiolite has been described from the Herland Group on Atløy (Andersen *et al.* 1990). The more penetrative deformation observed in the Staveneset area, however, resulted in a larger degree of parallelism between the main foliation (S_2) and the shear planes. The main foliation, S_2, is penetrative throughout the Staveneset area. The foliation is a pressure-solution cleavage in the meta-sediments, ranging from a spaced-planar cleavage in quartz-rich lithologies to stylolitic cleavage in meta-carbonates and is continuous in rocks rich in phyllosilicates (Powell 1979). In most of the fine-grained mafic rocks of the S–SOC, the S_2 is developed as a continuous cleavage defined mainly by elongate chlorite aggregates. In F_2 hinges, S_2 forms a zonal- to discrete crenulation-cleavage on the S_1 cleavage (Gray 1979). In large parts of the area, S_1 and S_2 are indistinguishable because of strong transposition of both bedding and S_1.

The mylonitic and phyllonitic fabrics of most shear zones in the area are defined by strong parallelism of the shear planes and the S_2 foliation, indicating that movement on the shear zones commenced as the planes of flattening, the initial axial planar cleavage, rotated towards the shear plane during progressive non-coaxial deformation. The S_2 foliation has a NW–SW strike and NW dip in most of the area (Fig. 4c). Later refolding related to both regional compression and extension gives a considerable scatter in the plotted orientations of early D_2 structures (Fig. 4c).

Late compressional structures. The S_2 foliation is folded by two sets of asymmetrical folds, F_{2-2} and F_{2-3} (Fig. 4d). F_{2-2} folds are tight, strongly asymmetrical and occur as intrafolial folds along the sheared contact between the ophiolite and the mélange. The fold axes plunge towards the northeast, and the vergence of the small-scale folds is consistently towards the southeast. A NW-dipping, zonal to discrete crenulation-cleavage (S_{2-2}) is developed in the cores of the F_{2-2} folds. A set of large-scale, asymmetrical folds (F_{2-3}) is the youngest feature related to regional compression identified in the studied area. The F_{2-3} folds deflect the main foliation (S_2) and are prominent features both in the field and in cross-section (Fig. 3). The F_{2-3} axes generally plunge towards the E (Fig. 4d). Fold axes plotting in the left half of the stereogram represent F_{2-3} axes refolded by large-scale, NW-plunging F_3 folds related to the phase of regional extension. A zonal crenulation-cleavage (S_{2-3}), dipping towards the NNW, is developed with variable intensity in the cores of F_{2-3} folds. S_{2-3} crenulates the mylonitic S_2 fabric along the contact between the S–SOC and the mélange. Cross-cutting relationships between S_{2-3} and the more local S_{2-2} have not been observed and, although the geometry of these sets of structures are distinguishable in the field, it cannot be ruled out that they formed contemporaneously.

Composite planar fabrics related to the regional compression. Several large-scale shear zones of regional importance have been recognized in the area: (1) the contact between the Høyvik Group and the Sunnfjord Mélange; (2) the shear zone between the lower and upper unit of the Sunnfjord Mélange; and (3) the shear zone separating the Sunnfjord Mélange from the S–SOC (Fig. 3). These shear zones can be traced (Fig. 1) from Tviberg and Atløy, along Staveneset to the Markavatn area in the east (Skjerlie *et al.* 1989, Andersen *et al.* 1990, Furnes *et al.* 1990, Skjerlie & Furnes 1990, Osmundsen 1990, Alsaker 1991). Late movements related to regional extension have re-activated most contractional shear zones as normal faults. A common feature of all these incompetent rocks is that the compressional fabrics have been modified or obliterated during the regional extension (see below). Kinematic indicators related to the regional compression are best preserved in relatively competent rocks of the Høyvik Group and the Sunnfjord Mélange. The most common shear sense indicators related to the rotational deformation are: (1) *S–C* structures (Berthé *et al.* 1979, Lister & Snoke 1984), shear-bands and extensional crenulation-cleavage/normal slip crenulations (NSC), (Platt & Visser 1980, White *et al.* 1980, Simpson & Schmid 1983, Dennis & Secor 1987, 1990); (2) progressive folding, rotation and extension of quartz-filled extensional veins; (3) the vergence and asymmetrical shearing of F_2 folds; (see above); and (4) outcrop-scale foliation-duplexes and stacked units.

Kinematic indicators in the Høyvik Group. The sub-arkoses of the Høyvik Group display *S–C* fabrics involving an early transposed foliation (S_1), a crenulation-cleavage and *C*-planes sub-parallel to the regional foliation (Fig. 5). The crenulation-cleavage constitutes the *S*-element of the composite fabric, and was formed by folding of the already existing S_1 fabric. The crenulation foliation was enhanced by pressure-solution along the limbs of the small-scale folds transposing the pre-existing S_1 foliation planes; the progressive formation of the *S–C* fabric is illustrated in Fig. 5. The *S*-surfaces strike between 030° and 060° and dip towards the northwest. Small-scale duplex/imbricate structures in the sub-arkoses indicate the same top-to-southeast movement as the *S–C* fabric. The composite *S–C* fabric was re-activated and folded during the subsequent regional extension (discussed below). In the eastern parts of the studied area, NSC-type structures (Dennis & Secor 1987, 1990) are developed in a sequence of interbedded quartz-schists and pebbly sub-arkoses of the Høyvik Group. The geometry of the NSC surfaces is consistent with thrusting towards the SE, in accordance with the *S–C* fabric. Microscopic *S–C* fabrics occur abundantly in

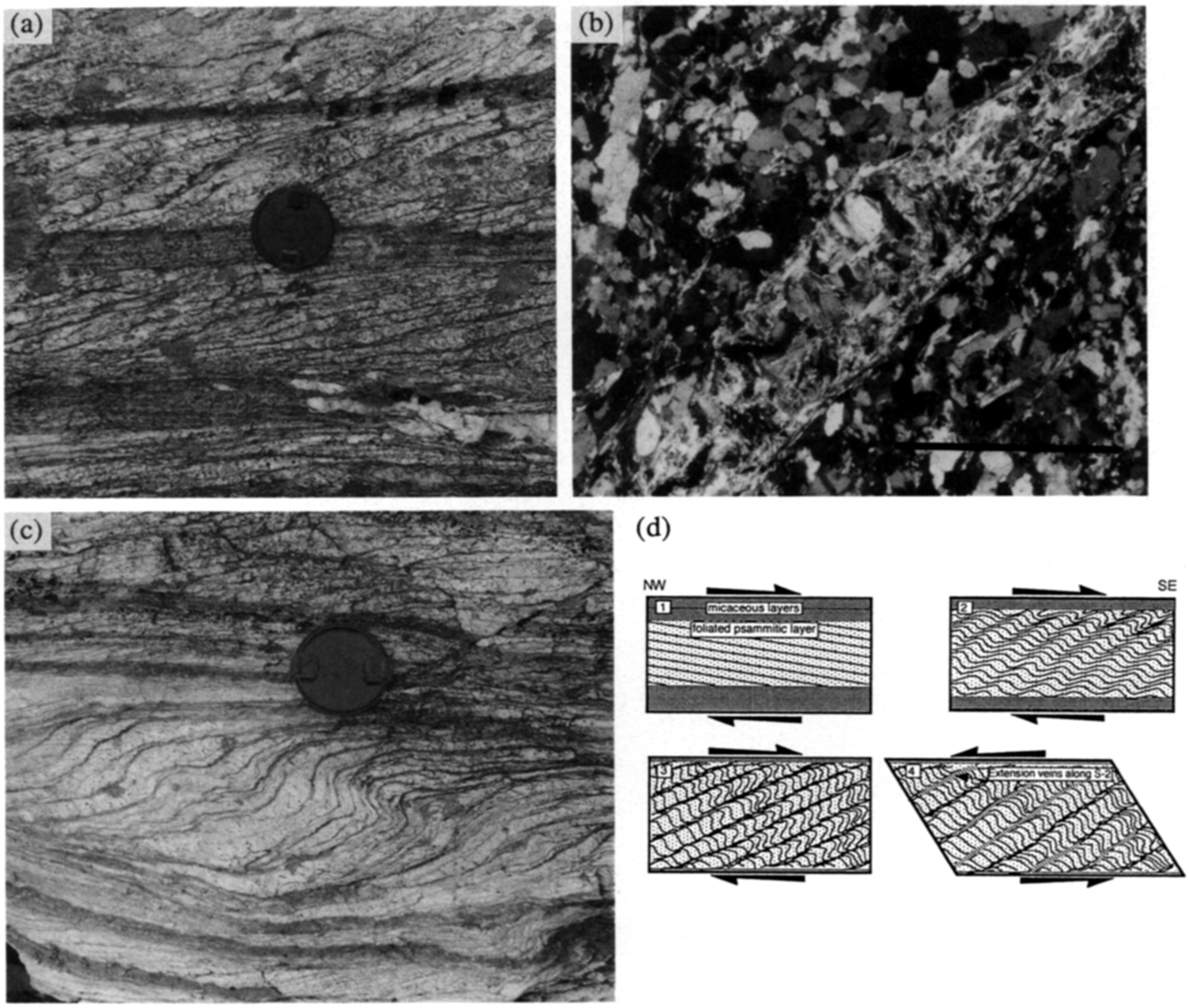

Fig. 5. Relations between contractional and extensional fabrics in metapsammites of the Høyvik Group, southwest Staveneset. (a) Commonly developed composite *S–C* fabric in a section oriented NW–SE. The macroscopic structures are related to regional contraction. The *S*-element is a crenulation cleavage, deflecting pre-Silurian S_1 foliation that is well preserved in the microlithons. Note also top-to-southeast shear zone in the lower part of the photograph. (b) Photomicrograph of *S*-surface in (a). This shows that the previous planes of flattening have been re-activated as extensional veins. White micas that previously defined the cleavage planes have been fragmented and occur as fragments that float in matrix of newly formed chlorites partly crystallized normal to the vein walls. (c) W-vergent F_3 back-folds of the *S*-surfaces of composite S–C fabric shown in (a). See the text for further discussion. (d) A model for the formation of the structures/textures shown in (a) & (b). The Pre-Silurian S_1 fabric (1) was deformed by SE-ward directed simple shear. This produced a NW-dipping, oblique S_2 crenulation cleavage (2) seen in (a). Reversal of polarity on the *C*-planes (3) during the extensional collapse resulted in opening of tension veins (4) along the S_2 crenulation cleavage (b), and in local back-folding as the S_2 cleavage had an orientation close to the direction of maximum compressive stress during initiation of the extensional deformation.

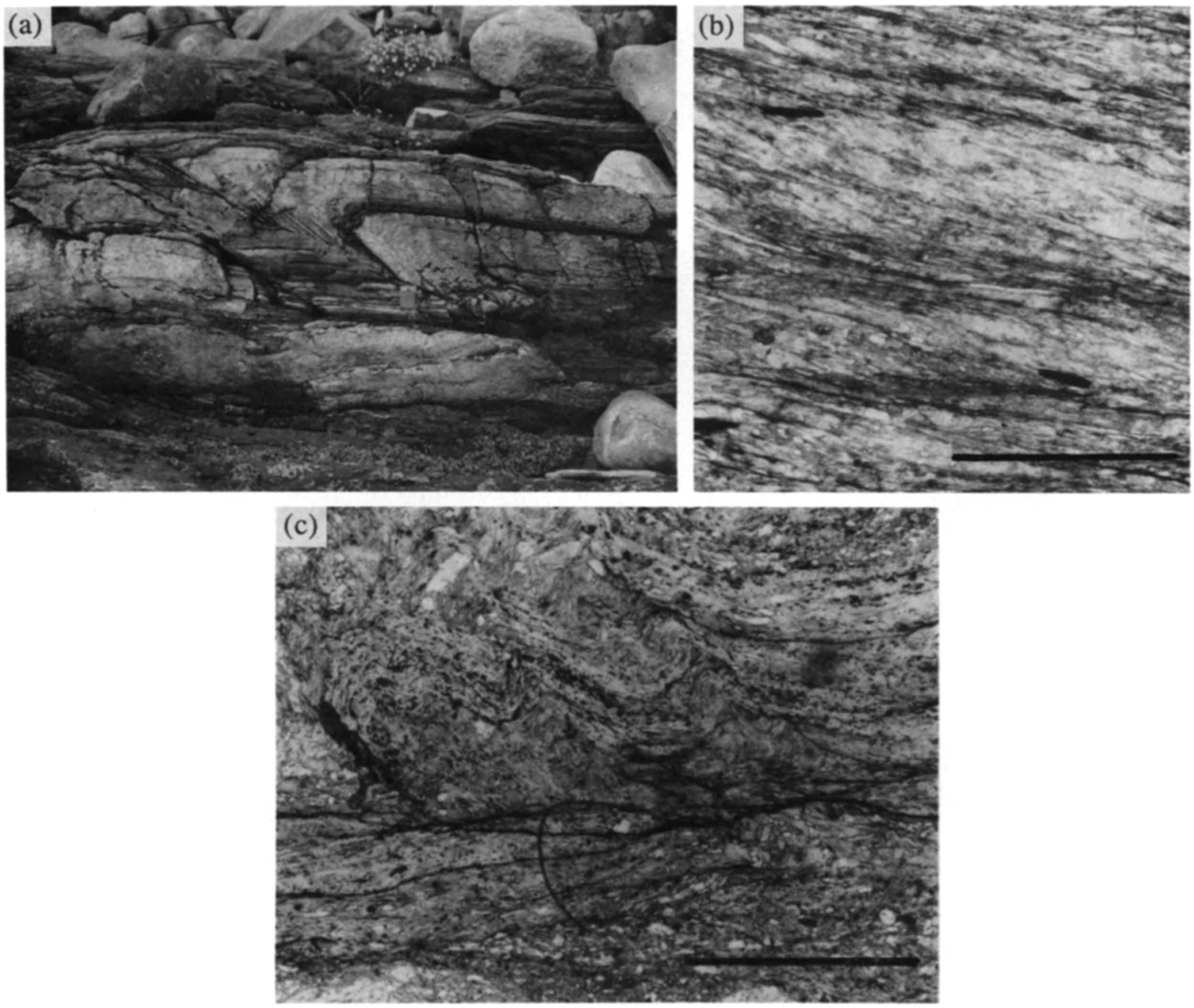

Fig. 6. (a) Typical outcrop-scale, F_3 back-fold in metapsammites of the Høyvik Group. Notice the shear fracture subparallel to its axial surface. The fracture is a small-scale reverse fault, which flattens out in the less competent horizon beneath the fold core, thus giving the fold a fault propagation fold-type geometry. Notice also that the axial surface bends sigmoidally into another shear zone above the fold hinge indicating a top-to-the-NW sense of shear. A spaced crenulation S_3 cleavage is developed in the fold core. (b) Photomicrograph of *S–C* fabric in graphite-bearing, micaceous unit structurally below the F_3 fold in (a). The *S–C* fabric deflects the main foliation (S_{2-1}), and displays a polarity consistent with vergence of the F_3-folds. The less competent lithologies acted as décollement horizons during F_3-folding. Scale bar is 1 mm. (c) Photomicrograph of an F_3-microfolds in a chlorite phyllonite in the Sunnfjord Mélange. The microfolds are developed above a limonite-rich shear band subparallel to the main foliation. The microfolds have a vergence towards the west, consistent with both outcrop- and map-scale F_3 folds in the studied area. Scale bar is 1 mm.

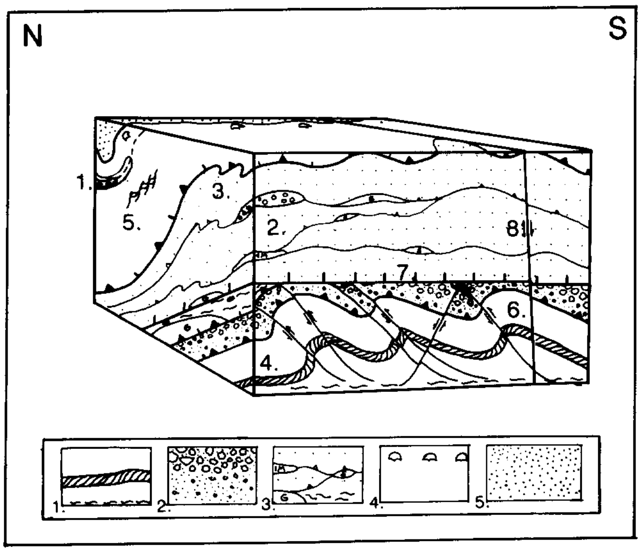

Fig. 7. Block diagram summarizing the geometry of the contractional and extensional structures at Staveneset. The numbered structures on the diagram are: (1) F_{2-1} folds and the main S_{2-1} foliation; (2) Shear zones that generally parallel the main foliation anastomose between tectonic lenses and blocks in the Sunnfjord Mélange; (3) Late contractional F_{2-3} folds in the S–SOC and Sunnfjord Mélange; (4) Composite planar fabrics preserved in metapsammites of the Høyvik Group; (5) Kinematic indicators with northwest polarity in incompetent lithologies; (6) W-vergent F_3-folds and associated structures; (7) The Staveneset Fault, post-dating the F_3-folds and associated structures; and (8) Steep NNW–SSE striking faults and joints, post-dating all other structures in the area. Legend: (1.) Høyvik Group, (2.) Sunnfjord Mélange (lower unit), (3.) Sunnfjord Mélange (upper unit), (4.) Solund–Stavfjord Ophiolite Complex, (5.) Staveneset Group.

relatively competent rocks at several tectonostratigraphic levels of the Høyvik Group. Along the contact to the Sunnfjord Mélange, contractional NSC-type structures consistent with top-to-southeast movement are developed in a strongly sheared quartzites in contact with the greenschists of the mélange.

Kinematic indicators in the Sunnfjord Mélange. The greenish quartz–chlorite schists of the Stubseid unit have microscopic mica-fish (Lister & Snoke 1984) and NSC-structures close to the contact with the Høyvik Group; both features show top-to-southeast shear sense. Consistent kinematic indicators related to regional compression have not been identified in the green phyllonites in the upper part of the melange. In the meta-greywackes, however, NSC-type structures occur in sandy horizons close to the lowermost, ultramafic-bearing level of the unit. Subordinate NSC occurs between the main S_2 shear planes, deflecting S_1, indicating that slip occurred along the main foliation during the compressional phase. The sense of shear shown by the NSC accords with a transport direction with top-to-southeast.

Outcrop-scale imbricate structures occur close to the contact between the mélange and the S–SOC in meta-greywackes of the upper unit of the mélange. The individual horses are separated by talc-schist shear zones, some of which are several meters thick. A duplex on the island of Storøya (Fig. 3) displays shear zones dipping towards the SE. The dip direction is, however, probably a result of later folding, for F_2 folds verge towards the northwest in a restricted area around Storøya.

Structures related to regional extension

Radiometric dating of eclogites in the Western Gneiss Region (WGR) gives Lower Devonian to Upper Silurian (*ca* 410–420 Ma) ages for peak metamorphism (Griffin & Brueckner 1980, 1985, Gebauer *et al.* 1985, Jamtveit *et al.* 1991). Widespread amphibolite facies conditions persisted in the WGR to approximately 390 Ma (Brueckner 1972, Lux 1985, Kullerud *et al.* 1986, Tucker *et al.* 1987). Mineral associations in the rocks of the studied area show that obduction-related contractional fabrics in the Staveneset area developed at greenschist facies; only on islands 10–15 km NW of the studied area are rocks of the S–SOC and the Staveneset Group at upper greenschist/lower amphibolite facies conditions (Skjerlie 1974, Osmundsen 1990). The studied rocks are unconformably overlain by Devonian sediments (Bryhni & Skjerlie 1975). Jarvik (1949) assigned fish fossils to the lower Middle-Devonian, and it is generally assumed that all the Devonian basins in Western Norway are of this age. This corresponds to an age of approximately 383 Ma (McKerrow *et al.* 1985). During a time-span of approximately 30 Ma, contemporaneous with the eduction and rapid uplift of the high-*P* rocks in the WGR (Andersen *et al.* 1991), the rocks of the area were exhumed and unconformably overlain by the conglomerates and sandstones of the Kvamshesten Devonian Basin (Bryhni & Skjerlie 1975). Structural development and models for the rapid uplift of the WGR were described by Andersen & Jamtveit (1990) and Andersen *et al.* (1991) and Dewey *et al.* (1993). We demonstrate, below, that the SE-directed contractional fabrics in the hangingwall of the KDZ were partly reactivated, and partly obliterated by the superimposed, generally top-to-the-west directed deformation during the extensional collapse of the orogen.

Geometry of extensional structures

Structures and textures related to extensional deformation in the studied area comprise: (1) composite planar fabrics and rotated porphyroclasts; (2) stretching lineation; (3) F_3 back-folds and associated faults; (4) the Staveneset Fault; and (5) high-angle late brittle faults and joints (Fig. 7). The structures related to the post-orogenic, regional extension were formed under progressively more brittle conditions. As noted above, kinematic indicators related to the southeastward transport during crustal shortening are preserved mainly in the competent rocks of the Høyvik Group and the Sunnfjord Mélange. Less competent rocks commonly display structural and textural evidence for transport towards the west and northwest.

The Høyvik Group. A graphite-bearing mica-schist is the tectono-stratigraphically lowest exposed rock in the area studied in detail. The mica-schist displays *S–C* structures showing transport towards the northwest Fig. 6c). The collision-related *S–C* fabrics in the sub-arkoses of the Høyvik Group show superimposed extensional deformation. Locally, tension gashes have opened along the previous planes of flattening (*S*-surfaces) originally characterized by pressure-solution (Fig. 5b). Muscovite aggregates in the pressure-solution lamellae were fragmented and rotated as the extensional fractures opened. Chlorite aggregates with long axes normal to fracture walls crystallized between muscovite aggregates (Fig. 5b). In places, the earlier pressure-solution cleavage was back-folded by asymmetrical west-vergent F_3 folds (Fig. 5c). Both the opening of extensional fractures parallel to earlier flattening planes and the asymmetrical back-folding of NW-dipping foliation planes strongly indicate a change from shortening to extension. This corresponds to a switch in shear-sense polarity from southeast to northwest (Fig. 5).

The Sunnfjord Mélange and the S–SOC. The thrust between the ophiolite and the mélange was reactivated by down-to-northwest movements. At outcrop scale, this is seen most readily by a discordance in the foliation across the contact in the westernmost parts of the studied area. In the mélange and the ophiolite, zones of intense deformation occur along chlorite-rich lithologies. In the mélange, these are generally confined to the Illevika Unit. Kinematic indicators are mainly normal slip crenulations (NSC) (Dennis & Secor 1987). The NSC show down-to-northwest transport, and are associated with a NW-plunging stretching lineation (Fig. 4e) that subsequently was folded by large-scale F_3 folds. In the northeastern parts of the studied area, the lineation is defined by the long axis of deformed pillow lavas in the ophiolite. Outcrop-scale shear bands occur in highly phyllonitic shear zones cutting the volcanic sequence. The NSC are often associated with the occurrence of limonite along the shear planes (Fig. 6c). Commonly, slip occurred as décollement-like displacement along segments of the earlier foliation planes and is associated with microscopic F_3 folds with Class 1B & 1C geometries (Ramsay 1967) (Fig. 6). The shear bands locally cut down through the S_2-planes in the direction of transport, producing offsets on microscopic marker horizons and displaying a true NSC geometry. The angle between the NSC and the main foliation varies but is rarely $>25°$. These structures formed by slip along the pre-existing main foliation, according to the model proposed by Dennis & Secor (1987). NSC showing down-to-northwest sense of shear are common both at outcrop scale and in thin sections (Figs. 6 and 7).

Other types of kinematic indicators, such as rotated and asymmetrical porphyroclasts, especially of epidote, accompany the NSC, and our observations show that re-activation of the contractional structures was localized along the weaker chlorite-rich lithologies. Re-activation was accompanied by minor recrystallization, local grain-coarsening as well as migration of fluids in the zones of enhanced extensional shear strain (Osmundsen 1990). Contractional fabrics in the competent lithologies of the Høyvik Group and the mélange were less modified during extension. It is likely that the phyllosilicate-rich rocks were also subjected to localized shear deformation during crustal shortening. The development of weak phyllosilicate-rich and stronger quartz-dominated lithologies by pressure-solution during crustal shortening probably resulted in more inhomogeneous shear strains with time, further amplified by preferential shearing along low-shear-strength horizons during the extensional event. No metamorphic gap has been identified between the contractional structures and the earliest, ductile extensional structures. Thus, the greenschist facies regional metamorphism (Osmundsen 1990) was apparently the same during formation of the late contractional and earliest extensional fabrics. Uplift and cooling, however, were clearly associated with the subsequent F_3-folding.

F_3-*folds and associated structures.* In the Sunnfjord region, back-folding of the main foliation generated asymmetric folds verging northwest, west and southwest (Skjerlie 1969, 1974, Andersen *et al.* 1990). Back-folding is a widespread phenomenon in the Western Norwegian Caledonides (Goldschmidt 1912, Kvale 1960, Naterstad *et al.* 1973, Andresen 1974, Roberts 1977, Banham *et al.* 1979, Torske & Andresen 1979, Fossen 1986, 1993 Norton 1987). F_3-type folding is particularly common close to major tectonic features like the 'Fahltungsgraben' (Goldschmidt 1912, Torske & Andresen 1979) and the extensional detachments of West Norway (Norton 1987, Chauvet & Séranne 1989). In the Staveneset area, the F_3 back-folds are open to tight, asymmetrical folds. In relatively competent lithologies, such as the foliated sub-arkoses of the Høyvik Group, F_3-folds typically are of chevron- and kink type. In less competent rocks, F_3-type folds also include more ductile Class 1C and 2 folds (Ramsay 1967) in addition to kink- and chevron-type geometries (Osmundsen 1990). F_3-folds are mostly asymmetrical with vergence towards the west (from southwest to northwest), axial-surfaces dipping east (northeast to southeast) and with axes plunging towards the north (northwest to northeast) (Fig. 4f). F_3-folds occur from the map-scale (Skjerlie 1974, Andersen *et al.* 1990) to microscopic, westward verging crenulations of the main S_2 foliation (Fig. 6c).

In the footwall of the Staveneset Fault along the southern part of Staveneset (Fig. 3), F_3-folds control the outcrop pattern of the Høyvik Group and the lower parts of the mélange (Fig. 3, profile C–D). Both the Høyvik Group and the Stubseid unit commonly have outcrop-scale F_3-folds; and locally, a spaced S_3 crenulation-cleavage is developed in the cores of mesoscopic F_3-folds. At higher structural levels in the mélange (Illevika unit) and in the ophiolite, large-scale, open folds deflect the main foliation. The asymmetrical, mesoscopic F_3-folds are less common in these units. In the western parts of the studied area, the F_3-folds refold F_{2-3}-folds to produce a complex pattern of interference.

Faults and fractures subparallel to the axial surface are typically associated with the formation and tightening of the F_3-folds (Fig. 6). Reverse faults dominate, but joints and normal faults subparallel with the axial-surface have also been observed. The Høyvik Group displays outcrop-scale variations in relative competence where quartz-schists, mica-schists and impure marbles alternate on metre-scale across the main transposed layering. F_3-related faults bend into and are frequently rooted in semi-ductile shear zones parallel with the main foliation and transposed layering. Shear zones are confined to the low-shear-strength lithologies, have composite *S–C* fabric in thin section and functioned as décollements during F_3-folding (see above and Fig. 6). In the footwall, adjacent to the fault-plane of the Staveneset Fault, asymmetric chevron-type F_3-folds occur in the lower unit of the melange. The axes plunge towards 080°, the folds verging in a northerly (NNW) direction. In the hangingwall, more symmetrical kink-bands and chevron folds occur close the fault; however, where direction of transport can be determined, it is towards the northwest.

The S_3-foliation is variably developed within the area. In the cores of mesoscopic F_3-folds, S_3 is a zonal to discrete crenulation-cleavage, with the foliation planes defined by phyllosilicates and opaques. S_3 also occurs as micro- and mesoscopic crenulations of the main foliation, related to larger scale folds, or above limonite-bearing shear bands (Fig. 7c). Pressure-solution during its formation is evident by the depletion and enrichment of quartz and feldspar in cleavage-domains and microlithons, respectively. S_3 dips consistently in a north-easterly direction within the studied area (Fig. 4g).

A model for F_3*-folding*. The F_3-folds and their associated structures apparently developed along horizons of relatively low shear-strength. These horizons acted as décollements during the F_3 folding, as their kinematic indicators suggest westerly to northwesterly directed shear. Axial surfaces and F_3-related faults were bent progressively into the re-activated S_2 foliation in accordance with the late top-to-northwest shear (Fig. 7). F_3 folds are consequently similar to reverse slip crenulations (RSC). In their model, Dennis & Secor (1987) suggested that RSC-associated folding and reverse faulting require an already existing planar fabric inclined to the shear zone, and that the acute angle between the pre-existing fabric and the transport direction of the shear zone must point in the shear direction. Thus, slip on the pre-existing fabric is compensated by the creation of the RSC. It is a reasonable assumption that the main contractional fabric had a dip towards the hinterland (northwest) at the terminal stages of the collisional event. As the model for the formation of RSC is independent of scale, we suggest that both small and large scale F_3 folds formed by normal/oblique-slip re-activation of contractional shear zones and the main S_2 foliation analogous to the back-folding of the oblique crenulation-cleavage in the Høyvik Group described above (Fig. 5).

The area is situated on the southern limb of a large-scale synform (Skjerlie 1974). It could be argued that the observed F_3-related geometries were developed by flexural-slip during formation of the large fold. As the polarity of some extensional structures is in a northwesterly direction towards the axial surface of the synform, however, this model is not favoured. The F_3 axes display a considerable scatter in orientation (Fig. 4f). Axes of the large-scale open folds cannot be measured accurately in the field but plunge in a northerly direction. In addition, a set of large-scale, upright to slightly overturned late folds with axial surfaces striking approximately E–W fold both the compressional and extensional structures as well as the Devonian sediments (Fig. 1). The late folds are believed to be of Late Paleozoic age and record regional N–S shortening in Western Norway (Torsvik *et al.* 1987). At the present stage, no well-founded conclusions can be made regarding the formation of the E–W-trending folds, although similarities to extension-parallel structures deflecting metamorphic core complexes in the Basin and Range (Hamilton 1987) may be pointed out. Late folding may partly be responsible for the spread in the orientation of the F_3 axes, but the scatter is too large to be explained by late folding alone and even on a very local scale, a considerable variation in the orientation of F_3 axes is recorded (Osmundsen 1990).

Several aspects must be considered in explaining the F_3 fold geometry and orientation. These include: (1) variations in pre-F_3 orientation of the main foliation; (2) variation in shear direction on re-activated shear zones; and (3) differential rotation of F_3 axes towards the shear direction (Bell 1978, Berthé & Brun 1980, Malavieille 1987) and the Late Paleozoic regional folds. The average F_3 axis plots approximately 30° east of the mean orientation of lineation (Figs. 4e & f). The age-relationships between NW-plunging stretching lineation and the F_3 folds are, however, not unambiguous as the lineation is folded. Given the increasingly brittle conditions during which the F_3 folds were formed, it is reasonable to assume that the NW-plunging lineation was generated mainly at an early stage and pre-dates much of the F_3 folding. Both the micro- and macroscopic observations show that the F_3 folds and their associated faults were formed above extensional shear zones related to large-scale shear movements towards the west and northwest during the collapse of the orogen.

The Staveneset Fault. The Staveneset Fault has been mapped along the southern part of Staveneset (Fig. 3). On the island of Tviberg (Fig. 1), Skjerlie *et al.* (1989) described the same structure as the Storevatn Fault. The fault dips approximately 25° NW in the eastern part of the studied area, where the fault-plane and associated hangingwall breccias are exposed. Farther west, however, the fault is generally more steeply dipping (40–60° to the NW). On Staveneset, talus and vegetation in many places inhibit a detailed investigation of the rocks immediately adjacent to the fault plane. Detailed mapping of marker horizons in the footwall, however, shows that the fault cuts F_3 folds and their associated structures (Fig. 3). In the hangingwall, the contact between the S–SOC and the upper part of the mélange is cut by the fault. Although the above observations demonstrate that the Staveneset Fault cross-cuts older structures, the fault partly follows the serpentinite-bearing level of the Sunnfjord Mélange on both Tviberg and Staveneset. Kinematic indicators along the fault comprise semi-brittle, chevron-type folds with ENE-plunging axes formed close to the fault-plane both on Staveneset (Osmundsen 1990) and on Tviberg (Skjerlie *et al.* 1989); the folds verge towards the NNW. In eastern parts of the studied area, bending of the main foliation from the footwall into the fault-plane indicates a more W-directed component of shear. A regional investigation is being carried out by the present authors to further evaluate the geometry and significance of the Staveneset Fault and related structures.

NNW–SSE striking faults and joints. Sub-vertical faults and fractures that strike NNW–SSE are widespread in the studied area. The steeply dipping faults and joints dip both to the east and west. Offset, if any, is normally not more than a few metres, although individual faults and fractures can be traced for kilometers along strike (Fig. 1). Topographically, these structures are expressed as narrow steep-sided valleys. In general, they cut all previous structures. Locally, however, they have re-activated low-angle shear zones in the mélange, thus forming a listric geometry. The orientation of the faults and joints is parallel with a regional system of lineaments occurring with variable frequency along the western coast of Norway (Ramberg *et al.* 1977). South of Bergen (Fig. 1), late faults and joints with a similar orientation are associated with mafic dykes of Permian–Mesozoic age (Færseth *et al.* 1976); east of Askvoll (Fig. 1), a peralkaline dyke of late Permian age (Furnes *et al.* 1982) cuts mylonites and breccias of the KDZ (Swensson personal communication 1990). The magmatic activity has been correlated (Færseth *et al.* 1976) with the Hardegsen pulse (Ziegler 1975), a Permo-Triassic tectonic event related to the opening of the North Sea basin. Palaeomagnetic dating of breccias along the KDZ in Sunnfjord indicate Permian and Upper Jurassic/Lower Cretaceous repeated movements on the post-orogenic, low-angle extensional structures in the Sunnfjord area (Torsvik *et al.* 1992). Therefore, the late faults and fractures are considered to be of Late-Paleozoic to Mesozoic age.

SUMMARY AND DISCUSSION

The Caledonian contractional structures

The contractional deformation in the Caledonides of Sunnfjord was polyphase; the earliest phase affected only the pre-Silurian allochthonous continental rocks of the Dalsfjord Suite and the Høyvik Group. It is not known what caused this early event or what the palaeogeographic position of the rocks were at the time. It may have been related to accretion of oceanic materials at the westernmost parts of the Baltic continental margin as has been argued for the Early-Caledonian (490–510 Ma) tectono-thermal events affecting similar rocks in the central parts of the Scandinavian Caledonides (Dallmeyer & Gee 1986, Mørk *et al.* 1988, Stephens & Gee 1989, Sturt *et al.* 1991). However, as the allochthonous continental rocks in Sunnfjord are underlain by the highly mylonitic rocks in the Kvamshesten Detachment Zone, (Swensson & Andersen 1981, Furnes *et al.* 1976, Hveding 1992), the status of the Dalsfjord-Høyvik basement-cover pair with respect to Baltica must be regarded as suspect (Andersen & Andresen 1994).

In the Høyvik Group on Atløy, the S_1 foliation represents a pre-Silurian contractional fabric, and it is likely that S_1 in the Høyvik Group at Staveneset originated in the same pre-Silurian tectonic event. In tectonostratigraphically higher units, however, the origin of S_1 must be sought elsewhere as these rocks are younger than the Early-Caledonian event that affected the underlying allochthonous continental rocks. Serpentinite-bearing meta-greywackes and greenish phyllonites of the Sunnfjord Mélange, as well as parts of the S–SOC, have been interpreted as having developed in a transform environment in a Late Ordovician–Early Silurian back-arc basin (Dunning & Pedersen 1988, Andersen *et al.* 1990, Furnes *et al.* 1990, Skjerlie & Furnes 1990). Obduction of the S–SOC was probably initiated along a transform/fracture zone (Andersen *et al.* 1990, Skjerlie & Furnes 1990). Thus, the S_1 in the Staveneset Group, the S–SOC and the upper unit of the Sunnfjord Mélange may represent the earliest stages of compressional tectonics along the transform. During the obduction, S_1 was folded in tight to isoclinal F_2 folds and the main foliation, S_2, developed as the corresponding axial plane cleavage. Shear zones developed sub-parallel and parallel with the S_2 foliation as this was progressively rotated towards orientations with higher shear-stresses. These W-dipping shear zones accommodated further crustal thickening and transport of the thrust-sheets onto the continental margin. Kinematic indicators related to the SE-directed transport are preserved mainly in competent lithologies; in less competent lithologies, thrust-related kinematic indicators were partly obliterated during the subsequent regional extension. Conglomerates in the structurally lower and youngest parts of the melange are interpreted as foreland-basin deposits, receiving debris from both the advancing nappes of oceanic rocks and from faulting in the continental margin related to the formation of a peripheral bulge during the obduction (Andersen *et al.* 1990). Thus, the shear zone separating the Illevika- and Stubseid units of the mélange represents the thrust above which rocks of oceanic affinity were transported onto the continental margin.

At a late stage of the emplacement of the ophiolite, rotation of the stress-field or large-scale inhomogeneous rotational strains produced shortening of the previous shear-planes and the S_2 foliation. Structures associated with the terminal stages of collision are SE-verging F_{2-2} and F_{2-3} folds and their corresponding axial-planar cleavages. Age constraints for the obduction (Andersen *et al.* 1990), are given by: (1) The age of the ophiolite, dated at 443 ± 3 Ma. (U–Pb on zircons, Dunning & Pedersen 1988); and (2) the depositional contact between conglomerates of the Sunnfjord Mélange and the fossiliferous Middle Silurian Herland Group on Atløy. This agrees well with the best defined radiometric ages of the eclogites in the Western Gneiss Region (WGR) (Griffin & Brueckner 1980, 1985) that indicate peak metamorphic conditions of the Scandian phase in the Late Silurian–Early Devonian (410–420 M.a.).

The Scandian orogeny in SW-Norway began by Middle-Silurian closure of the remnants of the Iapetus ocean and marginal basins formed along its western margin. The composite oceanic terranes that were accreted to Baltica at this stage (Andersen & Andresen 1994) contained already deformed ophiolitic and mature island-arc complexes, which, in parts, may have included old continental basement (Andersen & Jansen 1987, Pedersen *et al.* 1992). A number of the older ophiolite/arc sequences are unconformably overlain by sequences of Middle to Upper Ordovician age (Thon 1985, Ingdahl 1989, Andersen & Andresen 1994). Also, newly formed back-arc crust were accreted to Baltica (Dunning & Pedersen 1988, Pedersen *et al.* 1991). The convergence between Laurentia and Baltica resulted in the major continental collision between the westward subducting Baltic plate and the over-riding Laurentian continent (Andersen *et al.* 1991).

The extensional structures

Extensional structures in the Sunnfjord area record tectonic denudation of the Caledonian nappe pile. The earliest extension occurred contemporaneously with the rapid decompression of the eclogite-bearing rocks of the WGR (Andersen & Jamtveit 1990). The rapid vertical thinning and uplift of the lower plate was associated with rotational strains accommodating down-to-west transport on the main detachments between the lower and upper plates, and bulk non-rotational deformation at deeper levels in the lower plate gneisses (Andersen *et al.* 1991, Dewey *et al.* 1993). As demonstrated above, the Malavieille 1987, extension also involved widespread re-activation of the pre-existing contractional structures in the middle and upper crustal rocks in the hangingwall of the detachments.

The earliest extensional structures recorded in the upper plate are abundant NSC and a NW-ward plunging lineation, indicating top-to-NW transport. The common F_3-folds and their associated E-dipping reverse faults (Figs. 7 and 8) are considered to be large-scale analogues of RSC-type structures (Dennis & Secor 1987, 1990), and were probably formed by shear accompanying the large-scale, rapid uplift of the deep crust during the orogenic collapse. During the Scandian collision, the penetrative main S_2 foliation within the individual thrust sheets developed oblique to the thrust planes. Re-activation of the thrusts by the superimposed extensional deformation produced F_3-type folds of the more steeply W-dipping main foliation by westward slip along the normally re-activated thrust planes (Fig. 8). The NSC structures were formed by extensional slip along the previous S_2 planes of flattening. F_3-type folds occur abundantly in the WGR close to the KDZ, as well as proximal to other major extensional features of the Western Norwegian Caledonides (Goldschmidt 1912, Torske & Andresen 1979, Andresen 1982, Fossen 1986, Norton 1987). We suggest that a mechanism similar to that described above (see also Figs. 7 and 8) may have been responsible for the W-vergent folding on a regional scale. This implies large-scale re-activation of the thrust-planes during the extensional collapse, a common phenomenon in many mountain-belts. Our observations in the Staveneset area suggest that re-activation of earlier contractional structures within the thrust-sheets was chiefly localized to the less competent lithologies, whereas the contractional fabrics are preserved though locally modified in the competent lithologies. The deformational mechanism, whereby some extensional strains were accommodated by slip (NSC) along previous planes of flattening, became partly 'locked' as the F_3 folds and their associated W-directed reverse faults inhibited further slip on the S_{2-1} surfaces. However, as the S_3 cleavage and the F_3-related E-dipping reverse faults developed, a new system of semi-ductile W-dipping faults analogous to NSC formed.

The age of the ductile to semi-ductile extensional structures is bracketed by the Middle Silurian (*ca* 425 Ma) obduction of the S–SOC (Andersen *et al.* 1990), and the unconformity beneath the Lower-Middle Devonian (Jarvik 1949) Kvamshesten Basin at approximately 383 Ma (McKerrow *et al.* 1985). Assuming that F_3-folding commenced during or shortly after the Scandian collision, a time span of some 30 Ma characterized by extensional deformation of the hangingwall above the main detachment, elapsed before these rocks were unconformably overlain by Devonian sediments. A Late Silurian to Early Devonian age for F_3-folding coincides with the widespread eclogite and amphibolite facies conditions in the WGR (Griffin & Brueckner 1980, 1985, Griffin *et al.* 1985, Gebauer *et al.* 1985, Lux 1985, Kullerud *et al.* 1986). F_3-folding, related to large-scale west-directed tectonic transport of the nappe pile, occurred at crustal levels corresponding to the ductile–brittle transition, approximately contemporaneous with large-scale movements on the main detachments and probably contemporaneous with non-rotational-dominated deformation at amphibolite facies conditions in lower parts of the WGR (Dewey *et al.* 1993). This is in accordance with a model for the extensional collapse where non-coaxial deformation predominates in the middle and upper crust, whereas the lower crust experiences coaxial bulk deformation (Andersen & Jamtveit 1990). As the rocks in the upper crust eventually reached very high crustal levels, re-activation and distributed movement along the re-activated slip systems described above could no longer persist and the continued extension of the hangingwall consequently had to be accommodated by more localized and highly brittle structures, which eventually controlled the sedimentation in the Devonian basins.

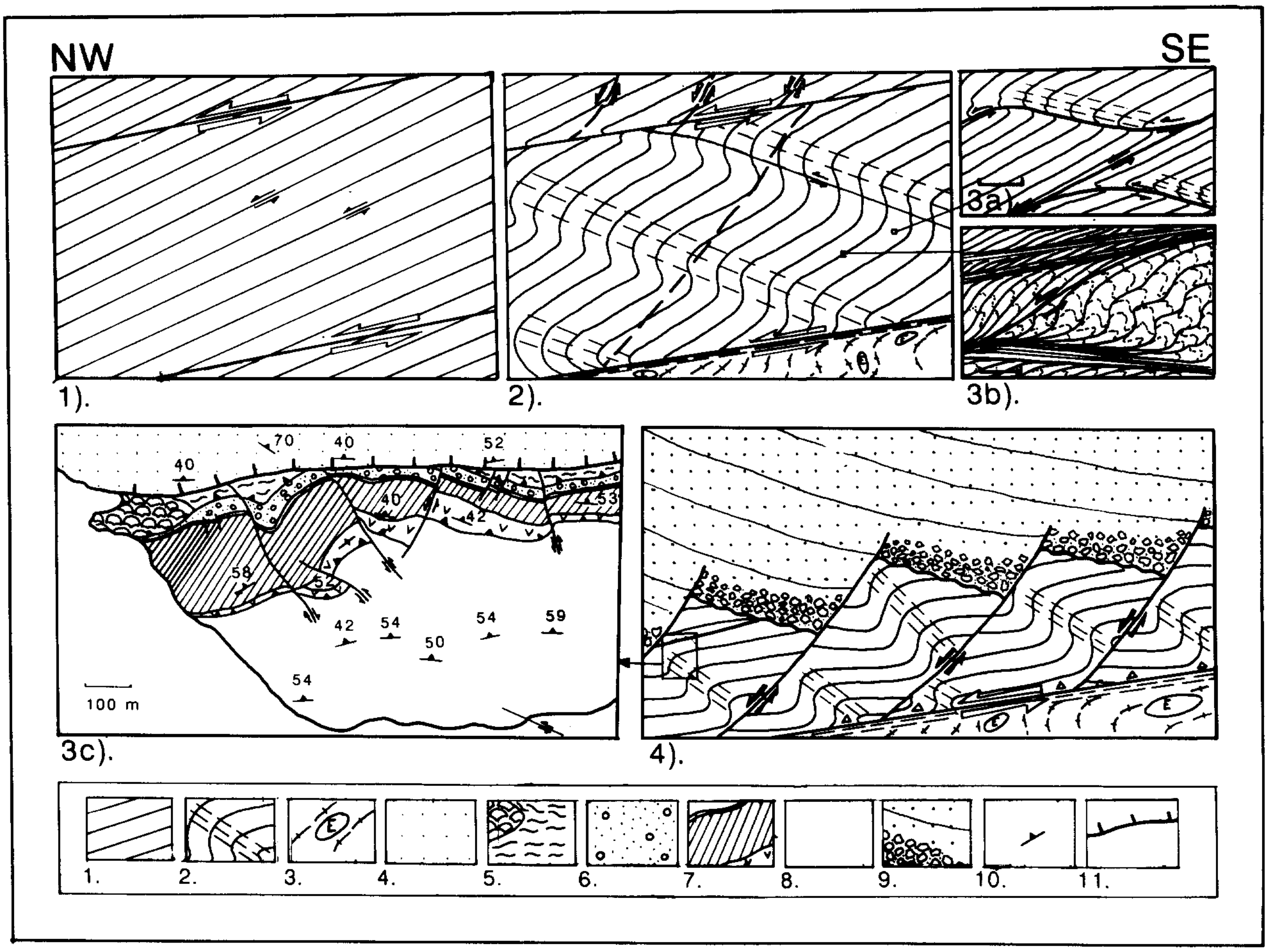

Fig. 8. Schematic model for the formation of extensional structures and the Devonian sedimentary basin in the upper plate of the Kvamshesten Detachment, Sunnfjord, West Norway. (1), (2) and (4) are principal cross-sections, each panel representing a crustal section several kilometers thick. (1) Extensional shear zones re-activate the Scandian contractional fabrics in the upper/middle crust at 420–400 Ma, as a response to rapid uplift of the thickened orogenic crust. The sheet dip of the inherited contractional foliation is towards the northwest. (2) Reversal of the polarity on shear zones leaves the main (contractional) foliation in the field of compressional stress. F_3 back-folds, reverse faults and S_3 crenulation cleavage form as a response to W- to NW-directed shear. The Staveneset Fault, dotted in (2), cuts the F_3-structures. (3a) The mesoscopic F_3-folds are related to transfer of shear strain between weak horizons parallel to main foliation (scale bar/1m). (3b) Back-folded crenulation cleavage in the metapsammites of the Høyvik Group illustrate model on a small scale (scale bar 5 cm). (3c) Map-scale cross-cutting relationships between the Staveneset Fault and F_3-fold with related structures on westernmost part of Staveneset. (4) In the lower plate, eclogite-bearing rocks experienced rapid uplift and retrograde metamorphism. Brittle faults were superimposed on the already sheared and back-folded rocks in the upper crust above the Kvamshesten Detachment Zone. Continued westward transport on the detachment led to rotation of fault blocks in the hangingwall, above which Devonian sediments were deposited. Legend: (1.) Main foliation with NW sheet dip; (2.) S_3; (3.) Eclogite-bearing lower crust; (4.) Metagreywackes in the Sunnfjord Mélange, Upper unit; (5.) Phyllonites with ultramafics and greenstone blocks, Sunnfjord Mélange, Upper Unit; (6.) Polymict conglomerate in the Sunnfjord Mélange, Lower unit; (7.) Greenish quartz-schist with scattered vein-quartz, greenstone and phyllonite; (8.) Høyvik Group; (9.) Devonian conglomerates and sandstones; (10.) Strike and dip of main foliation, and (11.) The Staveneset Fault.

The Staveneset Fault partly re-activates a suture, separating the S–SOC and the oceanic upper unit of the Sunnfjord Mélange from the foreland basin deposits of the lower parts of the obduction mélange (Andersen *et al.* 1990, Osmundsen 1990). During the extensional collapse, the Staveneset Fault was one of probably several upper-crustal faults and shear zones that accommodated W- to NW-directed transport of the Caledonian nappes. During early, semi-ductile re-activation, the serpentinite-bearing level of the mélange probably acted as a décollement for F_3-folding. Later, more brittle movements cross-cut previously formed structures and produced calcite-cemented breccias in the hangingwall. Thus, the Staveneset Fault is located along a shear zone with a long and complicated movement history that, with certainty, can be traced back to the obduction of the ophiolite during the Scandian continental collision between Baltica and Laurentia and probably originated as a transform fault at the oceanic stage during formation of the S–SOC in the Late Ordovician (Andersen *et al.* 1990, Skjerlie & Furnes 1990). Farther to the north in the Caledonian nappes of Western Norway, similar extensional re-activation of older contractional structures in the upper plate has also been demonstrated (Hartz 1992, Hartz *et al.* 1994). In this area the rocks are unconformably overlain by the sediments of the Hornelen Devonian basin.

The rocks of the studied area constitute part of the hangingwall of the KDZ. Several studies of detachment-related extensional systems show that upper plate sedimentary basins are produced by brittle extension of the hanging wall above detachments (Davis 1983, Wernicke 1985, Hamilton 1987, Buck 1988, Jolivet *et al.* 1990). The detachment was clearly active in the Late Silurian to Early Devonian (Norton 1986, Séranne & Séguret 1987, Swensson & Andersen 1991), and palaeomagnetic data from fault-rocks along the KDZ also demonstrate that it was re-activated both in the Permian and the Upper Jurassic/Lower Cretaceous (Torsvik *et al.* 1992). This gives a considerable timespan through which crustal extension has affected the southwest coast of Norway. A large number of mafic and ultra potassic dykes have intruded extensional faults and fractures along the southwest coast of Norway (Færseth *et al.* 1976, Furnes *et al.* 1982). These are parallel with the system of late faults and joints in the Sunnfjord area (strike NNW–SSE), which, consequently, are considered to be of a late Paleozoic–Mesozoic age.

The KDZ constitutes the most prominent extensional feature in Sunnfjord; this study of its hangingwall, however, demonstrates that significant extensional strains were accommodated by re-activation of the Scandian contractional structures. As re-activation commenced, the rocks in question were still at depths corresponding with the brittle–ductile transition (10–15 km, Sibson 1977). Mylonites of the major E-directed contractional shear zones constituted zones of low shear strength, along which, W-directed rotational deformation during the early, ductile extension was preferably localized. The penetrative main foliation inherited from the Scandian phase was also re-activated in less competent lithologies within the older thrust-sheets. The hangingwall of the detachments underwent considerable extensional deformation prior to brittle upper-plate collapse that finally controlled the deposition of the fault-bounded Devonian basins.

Acknowledgements—We thank Prof. J. F. Dewey for improving an early draft of this paper. P.T.O. thanks Petrine and the late Chester Saltskår for their kind hospitality during the fieldwork, Truls Carlsen for stimulating discussions during mapping in the Staveneset area. T.B.A. acknowledge the Dept. of Earth Sciences, Univ. of Oxford for providing facilities during sabbatical leave in 1992. The study was financed by the Norwegian Research Counsil for Science and Humanities (NAVF), grants ABC/LR 440.92.002 & 007 to TBA.

REFERENCES

Alsaker, E. 1991. Et geokjemisk og petrografisk studie av Sunnfjord Mélange i Markavatnområdet, Sunnfjord. Cand. scient. thesis, University of Bergen, Bergen.

Andresen, A. 1974. New fossil finds from Cambro-Silurian metasediments on Hardangervidda. *Bull. Nor. geol. Unders.* **304**, 55–60.

Andresen, A. 1982. Stratigraphy and structural history of the Lower Paleozoic metasediments on Hardangervidda, South Norway. Ph.D. dissertation, University of California, Davis, California.

Andersen, T. B. & Andresen, A. 1994. Stratigraphy, tectonostratigraphy and accretion of outboard terranes in the Caledonides of Sunnhordland, W. Norway. *Tectonophysics* **231**, 71–84.

Andersen, T. B. & Dæhlin, P. Chr. 1986. Basement-cover kontakten mellom Høyvikgruppen og Dalsfjordsuiten på Atløy, en prekaledonsk avsetningskontakt. *Geolognytt* **21**, 13.

Andersen, T. B. & Jamtveit, B. 1990. Uplift of deep crust during orogenic extensional collapse: A model based on field studies in the Sogn-Sunnfjord region of Western Norway. *Tectonics* **9**, 1097–1111.

Andersen, T. B., Jamtveit, B., Dewey, J. F. & Swensson, E. 1991. Subduction and eduction of continental crust: major mechanisms during continent–continent collision and orogenic extensional collapse, a model based on the south Norwegian Caledonides. *Terra Nova* **3**, 303–310.

Andersen, T. B. & Jansen, Ø. J. 1987. The Sunnhordland Batholith, W. Norway: regional setting and internal structure, with emphasis on the granitoid plutons. *Norsk. geol. Tidsskr.* **67**, 159–183.

Andersen, T. B., Skjerlie, K. P. & Furnes, H. 1990. The Sunnfjord Mélange, evidence of Silurian ophiolite accretion in the West Norwegian Caledonides. *J. geol. Soc. Lond.* **146**, 59–68.

Banham, P. H., Gibbs, A. D. & Hooper, F. W. M. 1979. Geological evidence in favor of a Jotunheimen Caledonian suture. *Nature* **227**, 289–291.

Bell, T. H. 1978. Progressive shearing and reorientation of fold axes in a ductile mylonite zone: the Woodroff thrust. *Tectonophysics* **44**, 285–320.

Berg, T. 1988. Sedimentology of the Herland Group on Atløy, Sunnfjord, Western Norway. Cand. scient thesis, University of Bergen, Bergen.

Berthé, D. & Brun, J. P. 1980. Evolution of folds during progressive shear in the South Amorican Shear Zone, France. *J. Struct. Geol.* **2**, 127–133.

Berthé, D., Choukroune, P. & Jegouzo, P. 1979. Orthogneiss, mylonite and non-coaxial deformation of granites: the example of the South Amorican Shear Zone. *J. Struct. Geol.* **1**, 31–42.

Brekke, H. & Solberg, P. O. 1987. The geology of Atløy, Sunnfjord Western Norway. *Bull. Nor. geol. Unders.* **410**, 73–94.

Brueckner, H. B. 1972. Interpretation of Rb–Sr ages from the Precambrian and Palaeozoic rocks of southern Norway. *Am. J. Sci.* **272**, 334–358.

Bryhni, I. 1966. Reconnaissance studies of gneisses, ultrabasites, eclogits and anorthosites in outer Nordfjord, Western Norway. *Bull. Nor. geol. Unders.* **241**, 1–68.

Bryhni, I. 1989. The status of the supracrustalrocks in the Western Gneiss Region, S. Norway. In: *The Caledonian Geology of Scandinavia* (edited by Gayer, R. A.). Graham & Trotman, 221–228.

Bryhni, I. & Skjerlie, F. 1975. Syn-depositional tectonism in the Kvamshesten district (Old Red Sandstone), Western Norway. *Geol. Mag.* **112**, 593–600.

Buck, W. R. 1988. Flexural rotation of normal faults. *Tectonics* **7**, 959–973.

Carlsen, T. 1989. Geologiske relasjoner mellom magmatiske og sedimentœre litologier på Staveneset, Solund-Stavfjord Ofiolittkompleks: Tektonomagmatiske og sedimentœre modeller. Unpublished Cand. scient thesis, University of Bergen, Bergen.

Cashman, P. H. 1990. Evidence for extensional deformation during a collisional orogeny, Rombak window, northern Norway. *Tectonics* **9**, 859–886.

Chauvet, A., Kienast, J. R., Pinarden, J. L. & Brunel, M. 1992. Petrological constraints and *PT* path of Devonian collapse tectonics within the Scandinavian mountainbelt (Western Gneiss Region, Norway). *J. geol. Soc. Lond.* **149**, 383–400.

Chauvet, A. & Séranne, M. 1989. Microtectonic evidence of Devonian extensional westward shearing in southwest Norway. In: *The Caledonian Geology of Scandinavia* (edited by Gayer, R. A.). Graham & Trotman, 245–254.

Cordellier, F., Boudier, F. & Boullier, A. M. 1981. Structural study of the Almklovdalen peridotite massif (southern Norway). *Tectonophysics* **77**, 257–281.

Dallmeyer, R. D. & Gee, D. G. 1986. ^{40}Ar/^{39}Ar mineral dates from retrogressed eclogites within the Baltoscandian miogeocline. implications for a polyphase Caledonian orogenic evolution. *Bull. geol. Soc. Am.* **97**, 26–34.

Davis, G. A. 1983. Shear-zone model for the origin of metamorphic core complexes. *Geology* **11**, 342–347.

Delong, S. E., Dewey, J. F. & Fox, P. J. 1979. Topographic and geologic evolution of fracture zones. *J. geol. Soc. Lond.* **136**, 303–310.

Dennis, A. J. & Secor, D. T. 1987. A model for the development crenulations in shear zones with applications from the Southern Appalachian Piedmont. *J. Struc. Geol.* **9**, 809–817.

Dennis, A. J. & Secor, D. T. 1990. On resolving shear direction in foliated rocks deformed by simple shear. *Bull. geol. Soc. Am.* **102**, 1257–1267.

Dewey *et al.* In press.

Dewey, J. F., Ryan, P. D. & Andersen, T. B. 1993. Orogenic uplift and collapse, crustal thickness, fabrics and metamorphic phase changes: the role of eclogites. *Spec. Publs. geol. Soc. Lond.* **76**, 325–343.

Dunning, G. & Pedersen, R. B. 1988. U/Pb ages of ophiolites and arc-related plutons of the Norwegian Caledonides: implications for the development of Iapetus. *Contrib. Mineral. Petrol.* **98**, 13–23.

Færseth, R. B., Macintyre, R. M. & Naterstad, J. 1976. Mezozoic alkaline dykes in the Sunnhordland region, western Norway: ages, geochemistry and regional significance. *Lithos* **9**, 331–345.

Fossen, H. 1986. Structural and metamorphic development of the Bergen Area, West Norway. Cand. scient. thesis, University of Bergen, Bergen.

Fossen, H. 1993. Structural evolution of the Bergsdalen Nappes. *Bull. Nor. geol. Unders.* **424**, 23–49.

Furnes, H., Mitchell, J. G., Robins, B., Ryan, P. D. & Skjerlie, F. J. 1982. Petrography and geochemistry of peralkaline, ultrapotassic syenite dykes of Middle Permian age, Sunnfjord, West Norway. *Nor. geol. Tidsskr.* **62**, 147–159.

Furnes, H., Skjerlie, K. P., Pedersen, R. B., Andersen, T. B., Stillman, C. J., Suthren, R., Tysseland, M. & Garman, L. B. 1990. The Solund-Stavfjord Ophiolite Complex and associated rocks, west Norwegian Caledonides: Geology, geochemistry and tectonic environment. *Geol. Mag.* **127**, 209–224.

Furnes, H., Skjerlie, F. J. & Tysseland, M. 1976. Plate tectonic model based on greenstone geochemistry in the late Precambrian-lower Paleozoic sequence in the Solund–Stavfjord areas, West Norway. *Nor. Geol. Tidsskr.* **56**, 161–186.

Gebauer, D., Lappin, M. A., Grünenfelder, M. & Wyttenbach, A. 1985. The age and origin of some Norwegian eclogites: a U–Pb zircon and REE study. *Chem. Geol.* **52**, 227–247.

Goldschmidt, V. M. 1912. Die kaledonische deformation der südnorwegishen urgebirgstafel. *Skr. Vidensk. Selsk., Christiania* **19**.

Gray, D. R. 1979. Microstructure of crenulation cleavages: an indicator of cleavage origin. *Am. J. Sci.* **279**, 97–128.

Griffin, W. L. Austrheim, H., Brastad, K., Bryhni, I., Krill, A. G., Krogh, E. J., Mørk, M. B. E., Qvale, H. & Tørudbakken, B. 1985. High-pressure metamorphism in the Scandinavian Caledonides. In: *The Caledonide Orogen—Scandinavia and related areas* (edited by Gee, D. G. & Sturt, B. A.). John Wiley & Sons, New York, 783–801.

Griffin, W. L. & Brueckner, H. K. 1980. Caledonian Sm–Nd ages and a crustal origin for Norwegian eclogites. *Nature* **285**, 319–321.

Griffin, W. L. & Brueckner, H. K. 1985. REE, Rb–Sr and Sm–Nd studies of Norwegian eclogites. *Chem. Geol.* **52**, 249–271.

Hamilton, W. B. 1987. Crustal extension in the Basin and Range Province, southwestern United States. In: *Continental Extensional Tectonics* (edited by Coward, M. P., Dewey, J. F. & Hancock, P. L.). *Spec. Publs. geol. Soc. Lond.* **28**, 155–176.

Hartz, E. 1992. Structural observations along a large scale extensional detachment zone at Bremangerlandet, Western Norway. Cand. scient. thesis, University of Oslo, Oslo.

Hartz, E., Andresen, A. & Andersen, T. B. 1994. Structural observations adjacent to a large-scale extensional detachment zone in the Hinterland of the Norwegian Caledonides. *Tectonophysics* **231**, 123–137.

Hernes, I. 1954. Eclogite-amphibolite on the Molde Peninsula, Southern Norway. *Nor. geol. Tidsskr.* **33**, 163–184.

Hernes, I. 1956a. Geologisk oversikt over Molde-Kristiansundsområdet. Det Kgl. Norske *Vidensk. Selsk. Skrifter*, **1955**, Nr. 5, Trondheim.

Hernes, I. 1956b. Surnadalsynklinalen. *Nor. geol. Tidsskr.* **36**, 25.

Honorez, J. & Bonatti, E. 1975. Mylonites from equatorial Atlantic fracture zones. *IUGG* **16**, General assembly, Grenoble 1975.

Hossack, J. R. 1984. The geometry of listric normal faults in the Devonian basins of Sunnfjord, W. Norway. *J. geol. Soc. Lond.* **141**, 629–637.

Hveding, B. S. 1992. En strukturgeologisk undersøkelse av mylonittsonen under Dalsfjordforkastningen i Atløy-Askvoll området Sunnfjord. Cand. scient. thesis, University of Oslo, Oslo.

Ingdahl, S. E. 1989. The Upper Ordovician–Lower Silurian rocks in the Os area, Major Bergen Arc, Western Norway. *Nor. geol. Tidsskr.* **69**, 163–175.

Jarvik, E. 1949. On the Middle Devonian Crossopterygians from the Hornelen field in western Norway. *Universitetet i Bergen Årbok, Naturvitensk, Rekke*, **8**.

Jamtveit, B., Carswell, D. A. & Mearns, E. W. 1991. Chronology of the high-pressure metamorphism of Norwegian garnet peridotites/pyroxenites. *J. Meta. Geol.* **9**, 125–139.

Jolivet, L., Dubois, R., Fournier, M., Goffé, B., Michard, A. & Jourdan, C. 1990. Ductile extension in alpine Corsica. *Geology* **18**, 1007–1010.

Kolderup, N. H. 1921. Der Mangeritsyenit und umgebende gesteine zwischen Dalsfjord und Stavfjord in Søndfjord im westlischen Norwegen. *Bergen Mus. Årbok*, **1920-21**.

Kullerud, L., Tørudbakken, B. O. & Ilebekk, S. 1986. A compilation of radiometric age determinations from Western Gneiss Region, South Norway. *Bull. Nor. geol. Unders.* **406**, 17–42.

Kvale, A. 1960. The nappe area of the Caledonides in Western Norway. *Bull. Nor. geol. Unders.* **212**.

Lister, G. S. & Snoke, A. W. 1984. *S–C*-mylonites. *J. Struct. Geol.* **6**, 617–638.

Lux, D. R. 1985. K/Ar ages from the Basal Gneiss Region, Stadtlandet area, Western Norway. *Nor. geol. Tidsskr.* **65**, 277–286.

Malavielle, J. 1987. Kinematics of compressional and extensional ductile shearing deformation in a metamorphic core complex of northeastern Basin and Range. *J. Struct. Geol.* **9**, 541–554.

McKerrow *et al.* 1985.

Mørk, M. B. E. 1985. A gabbro to eclogite transition on Flemsøy, Sunnmøre, SW-Norway. *Chem. Geol.* **50**, 283–310.

Mørk, M. B. E., Kullerud, K. V. & Stabel, A. 1988. Sm–Nd dating of Seve eclogites, Norrbotten, Sweden—evidence for early Caledonian (505 Ma) subduction. *Contr. Miner. Petrol.* **99**, 344–351.

Naterstad, J., Andresen, A. & Jorde, K, 1973. Tectonic succession of the Caledonian nappe front in the Haukelidsæter-Røldal area, Southwest Norway. *Bull. Nor. geol. Unders.* **292**.

Norton, M. G. 1986. Late Caledonian extension in western Norway: a response to extreme crustal thickening, *Tectonics* **5**, 195–204.

Norton, M. G. 1987. The Nordfjord-Sogn detachment, W. Norway. *Nor. geol. Tidsskr.* **67**, 93–106.

Osmundsen, P. T. 1990. Tektonostratigrafi og strukturell utvikling, Staveneset, Sunnfjord. Cand. scient thesis, University of Oslo, Oslo.

Pedersen, R. B., Furnes, H. & Bruton, D. L. 1992. Ordovician faunas, island arcs and ophiolites in the Scandinavian Caledonides. *Terra Nova* **4**, 217–222.

Pedersen, R. B., Furnes, H. & Dunning, G. 1991. A U/Pb age for the Sulitjelma Gabbro, North Norway: further evidence for the development of a Caledonian marginal basin in Ashgill–Llandovery time. *Geol. Mag.* **128**, 141–153.

Platt, J. P. & Visser, R. L. M. 1980. Extensional structures in anisotropic rocks. *J. Struct. Geol.* **2**, 397–410.

Powell, C. McA. 1979. A Morphological classification of rock cleavage. *Tectonophysics* **58**, 21–34.

Ramberg, I. B., Gabrielsen, R. H., Larsen, B. T. & Solli, A. 1977. An analysis of fracture patterns in southern Norway. *Geologie. Mijnb.* **56**, 295–310.

Ramsay, J. G. 1967. *The Folding and Fracturing of Rocks*. McGraw Hill Book Company, New York.

Roberts, J. L. 1977. Allochthonous origin of the Jotunheimen Massif in southern Norway: a reconnaissance study along its northwestern margin. *J. geol. Soc. Lond.* **134**, 351–362.

Rykkelid, E. & Andresen, A. 1993. Late-Caledonian extension in the Ofoten area, northern Norway. *Tectonophysics*.

Séranne, M. & Séguret, M. 1987. The Devonian basins of western Norway: tectonics and kinematics of an extending crust. In: *Continental Extensional Tectonics* (edited by Coward, M. P., Dewey, J. F. & Hancock, P. L.). *Spec. Publs. geol. Soc. Lond.* **28**, 537–548.

Sibson, R. H. 1977. Fault rocks and fault mechanisms. *J. geol. Soc. Lond.* **133**, 191–213.

Simpson, C. & Schmid, S. M. 1983. An evaluation of criteria to deduce the sense of movement in sheared rocks. *Bull. geol. Soc. Am.* **94**, 1281–1288.

Sjøstrøm, H. & Bergmann, S. 1989. Asymmetric extension and Devonian (?) normal faulting; examples from the Caledonides of eastern Trøndelag and western Jämtland. *Geologiska Føreningens i Stockholm Førhandlingar* **111**, 407–410.

Skjerlie, F. J. 1969. The Pre-Devonian rocks in the Askvoll-Gaular area and adjacent districts Western Norway. *Bull. Nor. geol. Unders.* **258**, 325–359.

Skjerlie, F. J. 1971. Sedimentasjon og tektonisk utvikling i Kvamshesten devonfelt, Vestlandet. *Bull. Nor. geol. Unders.* **270**, 77–108.

Skjerlie, F. J. 1974. The Lower Palaeozoic sequence of the Stavfjord district, Sunnfjord. *Bull. Nor. geol. Unders.* **302**, 1–32.

Skjerlie, K. P. 1988. Geologiske relasjoner mellom gabbro og gangkompleks, petrogenese og Tektonomagmatisk utvikling i området Tviberg-NW Atløy, Solund Stavfjorden Ofiolittkompleks. Cand. scient thesis, University of Bergen, Bergen.

Skjerlie, K. P. & Furnes, H. 1990. Evidence for a fossil transform fault in the Solund-Stavfjord Ophiolite Complex: West Norwegian Caledonides. *Tectonics* **9**, 1631–1648.

Skjerlie, K. P., Furnes, H. & Johansen, R. J. 1989. Magmatic development and tectono-magmatic models for the Solund–

Stavfjord Ophiolite Complex, west Norwegian Caledonides. *Lithos* **23**, 137–151.

Smith, D. C. 1988. A review of the peculiar mineralogy of the Norwegian coesite–eclogite province, with crystal–chemical, petrological, geochemical and geodynamical notes and an extensive bibliography. In: *Eclogites and Eclogite-facies Rocks* (edited by D. C. Smith). *Dev. in Petrol.* **12**, Elsevier Science Publishers, Amsterdam, 1-206.

Smith, D. C. & Lappin, M. A. 1989. Coesite in the Straumen kyanite–eclogite pod, Norway. *Terra Nova* **1**, 47–56.

Steel, R. J. 1976. Devonian basins of western Norway—sedimentary response to tectonism and to varying tectonic context. *Tectonophysics* **36**, 207–224.

Steel, R. J. & Gloppen, T. G. 1980. Late Caledonian basin formation, western Norway: signs of strike-slip tectonics during infilling. *Spec. Publ. Intern. Ass. Sed.* **4**, 79–103.

Stephens, M. B. & Gee, D. G. 1989. Terranes and polyphase accretionary history in the Scandinavian Caledonides. *Spec. Pap. geol. Soc. Am.* **230**, 17–30.

Sturt, B. A., Ramsay, D. M. & Neuman, R. B. 1991. The Otta conglomerate, the Vågåmo Ophiolite—further indications of early Ordovician orogenesis in the Scandinavian Caledonides. *Nor. geol. Tidsskr.* **71**, 107–115.

Swensson, E. & Andersen, T. B. 1991. Petrography and basement-cover relationships between the Askvoll Group and the Western Gneiss Region, Sunnfjord, W. Norway. *Nor. geol. Tidsskr.* **71**, 15–27.

Thon, A. 1985. Late Ordovician and Early Silurian cover sequences to the west Norwegian ophiolite fragments: stratigraphy and structural evolution. In: *The Caledonide Orogen: Scandinavia and Related areas*. (edited by Gee, D. G. & Sturt, B. A.). J. Wiley & Sons, 407–415.

Torske, T. & Andresen, A. 1979. Senkaledonsk deformasjon langs foldningsgrøftens østgrense i Hardanger. *Geolognytt* **13**, 72.

Torsvik, T. H., Sturt, B. A., Ramsay, D. M. & Vetti, V. V. 1987. The tectono-magnetic signature of the Old Red Sandstone and Pre-Devonian strata in the Håsteinen area, western Norway, and the implications for the later stages of the Caledonian Orogeny. *Tectonics* **6**, 305–322.

Torsvik, T. H., Sturt, B. A., Swensson, E., Andersen, T. B. & Dewey, J. F. 1992. Palaeomagnetic dating of fault rocks: evidence for Permian and Mesozoic movements and brittle deformation along the extensional Dalsfjord Fault, western Norway. *Geophys. J.* **109**, 565–580.

Tucker, R. D., Råheim, A., Krogh, T. E. & Corfu, F. 1987. Uranium–lead zircon and titanite ages from the northern portion of the Western Gneiss Region, south-central Norway. *Earth Planet. Sci. Lett.* **81**, 203–211.

Wernicke, B. 1985. Uniform-sense simple shear of the continental lithosphere. *Can. J. Earth Sci.* **22**, 108–125.

White, S. H., Burrows, S. E., Carreras, J., Shaw, N. D. & Humpreys, F. J. 1980. On mylonites in ductile shear zones. *J. Struct. Geol.* **2**, 175–187.

Ziegler, W. H. 1975. Outline of the geological history of the North Sea. In: *Petroleum and the Continental Shelf of North-West Europe 1, Geology*. (edited by Woodland, A. W.). Applied Science Publishers, London.