The Nordfjord-Sogn Detachment, W. Norway

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In western Norway thick continental sediments of Devonian age are found in four basins each bounded to the east by major fault zones. Shallowly dipping fault segments previously identified as thrusts have recently been reinterpreted (Hossack 1984) as parts of a single large extensional fault. Detailed fieldwork along this structure shows it to be a classic detachment (here redefined and renamed as the Nordfjord-Sogn Detachment) similar to those described from the Basin and Range province of the western USA (e.g. Davis 1983). Most of the features attributed to a late Devonian 'Svalbardian' 'Solundian' orogeny are explained as related to irregularities in the detachment surface. Other possible Devonian extensional structures in southern Norway are evaluated.

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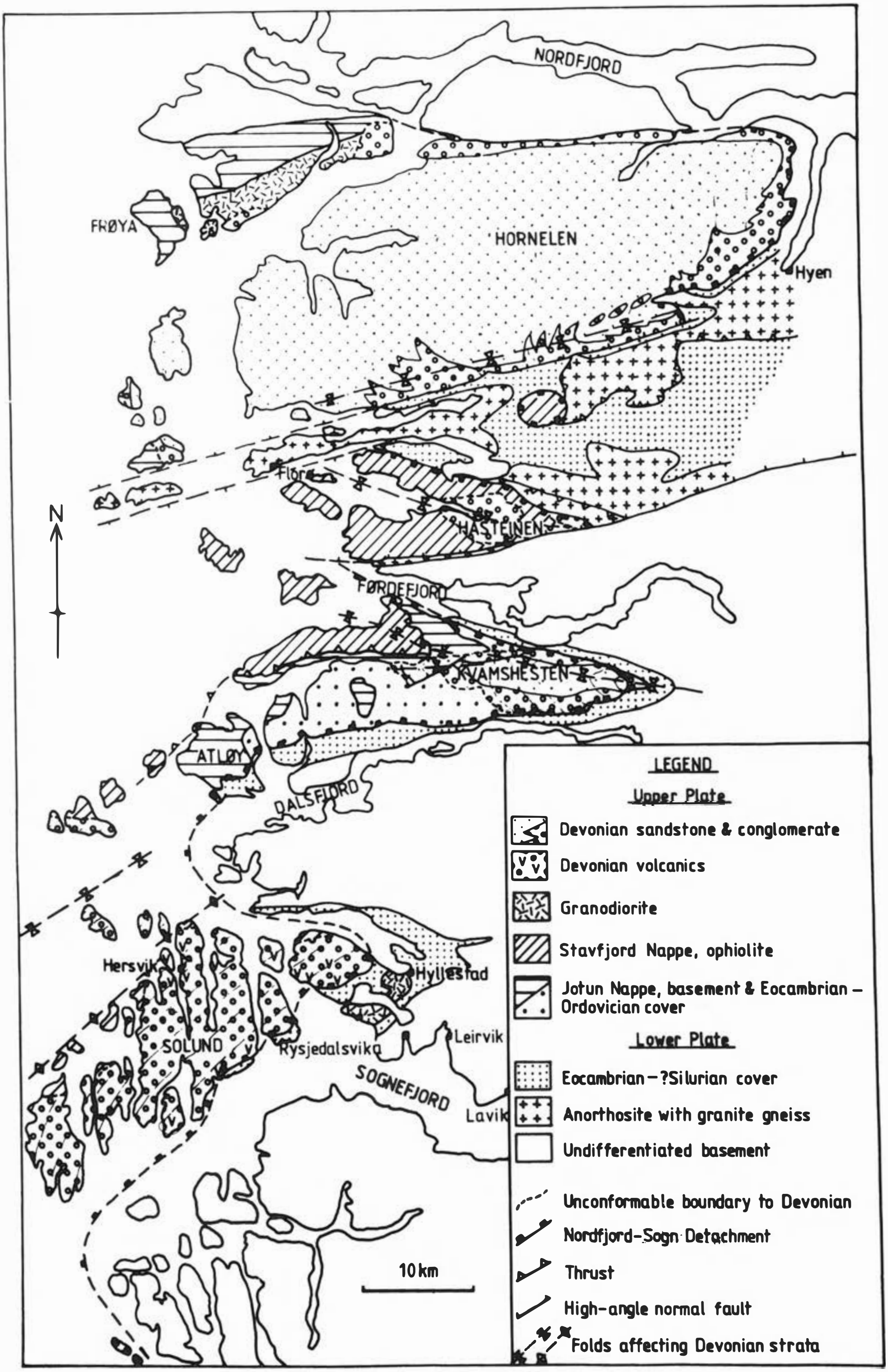
Rocks of Devonian age in western Norway are found in four major areas interpreted as separate basins (Fig. 1), from north to south: Hornelen, Håsteinen, Kvamshesten and Solund. These basins have been interpreted as forming in a dominantly strike-slip regime (Steel et al. 1977; Roberts 1983; Steel et al. 1985). Syn- to post-depositional folding has been observed in all the basins and they all have an unconformable western margin and all except Håsteinen a tectonic eastern margin. This eastern contact in each case brings the Devonian sediments against a considerable thickness (>100 m) of mylonites and the low-angle segments have been interpreted as thrusts (Høisæter 1971; Nilsen 1968; Bryhni 1978; Roberts 1983; Sturt 1983; Torsvik et al. 1986); a similar thick mylonite zone is present just to the northeast of the Håsteinen outcrop. Hossack (1984) has reinterpreted all the tectonic contacts as representing a single irregular extensional fault, which he calls the Måløy Fault. He identified this structure as an extensional fault from a consideration of the apparent omission of structural section across it as indicated on published geological maps of the area.

All existing models for the development of the basins are here reviewed taking account of both sedimentological and tectonic constraints. The field characteristics of the extensional structure, here redefined and renamed the Nordfjord-Sogn Detachment, are described and compared with similar structures developed in the Basin and Range region of the USA. Other possible detachments within the southern Norwegian Caledonides are then evaluated.

Basin development models

Before considering the main models for basin development, details of published sedimentary and tectonic observations are reviewed which provide constraints on these models.

Sedimentation in the preserved Devonian has been related to the development of long-lived alluvial fan systems along parts of their present margins. In Hornelen small debris-flow fans and fan deltas formed along the northern margin while larger stream-flow fans formed on the eastern and southeastern margins (Steel et al. 1977; Steel & Gloppen 1980). Apart from consisting mainly of conglomerate, probably of alluvial fan origin, nothing has been published on the sedimentology of Håsteinen. Kvamshesten has alluvial fan deposits along its northern (breccia dominated) and southern (conglomerate dominated) margins (Bryhni & Skjerlie 1975). Solund consists almost entirely of alluvial fan deposits (Nilsen 1968) with at least one major intercalated sedimentary slide unit (Michelsen et al. 1987). In Hornelen and in the centre of Kvamshesten the marginal fan deposits pass laterally into alluvial plain/flood-basin deposits forming an axial system. Sediment dispersal directions are from south to southwest


NORDFJORD
FRØYA
HORNELEN
Hyen
Florø
HASTEINEN
N
FØRDEFJORD
KVAMSHESTEN
ATLØY
DALSFJORD
Hersvik
Hyllestad
SOLUND
Rysjedalsvika
Leirvik
SOGNEFJORD
Lavik
10 km
LEGEND
Upper Plate
Devonian sandstone & conglomerate
Devonian volcanics
Granodiorite
Stavfjord Nappe, ophiolite
Jotun Nappe, basement & Eocambrian – Ordovician cover
Lower Plate
Eocambrian – ?Silurian cover
Anorthosite with granite gneiss
Undifferentiated basement
Unconformable boundary to Devonian
Nordfjord-Sogn Detachment
Thrust
High-angle normal fault
Folds affecting Devonian strata

along 'northern' margins, north to northwest along 'southern' margins and west to southwest in the axial systems (Steel et al. 1985). It is clear that throughout the sedimentation recorded by the Devonian strata strong source area topography was maintained.

All of the sediments are organized into coarsening upward cyclothems, c. 150 m thick in Hornelen (Steel et al. 1977), c. 200 m thick in Solund (Steel et al. 1985) and c. 20 m thick in Kvamshesten (Bryhni & Skjerlie 1975) (note that cycles of this smaller scale are also recognized in Hornelen). In Hornelen these units are traceable from the marginal fans into the axial sandstones and they appear to also be basin-wide in the other sub-basins. This shows clear tectonic control on sedimentation with a sustained, regular, periodic rejuvenation of the source region leading to alluvial fan progradation.

There is also a clear relative eastward migration of the depocentre with respect to previously deposited cycles, with progressive overlap of succeeding units. Finally, in some parts of the sub-basins there are marked discrepancies between clast lithologies in marginal fanglomerates and adjacent basement rocks across the faulted contacts (Hornelen: Steel & Gloppen 1980; Solund: Nilsen 1968).

The tectonic constraints show the character of deformation going on during sedimentation. In most cases it is impossible to prove that faulting or folding were going on during sedimentation and some published models treat virtually all the deformation of the sediments as being a distinct later event (or series of events), e.g. Roberts 1983; Torsvik et al. 1986. Other models (Hossack 1984, Norton 1986 and this paper, also Steel & Glopen 1980 from a different standpoint) attempt to explain most of the deformation of the sediments as being a result of the same process as basin formation. The features that they must explain are: the overall eastward tilt of the strata, folding or varying style and trend, and the nature of the tectonic margins.

The only unequivocal evidence of synsedimentary deformation is from the western end of the Kvamshesten Devonian where the basal unconformity is seen to be progressively rotated during deposition of later sediments (Bryhni & Skjerlie 1975). There is also the general sedimentary evidence for faulting active during sedimentation near the position of all of the present faulted boundaries. More direct sedimentary evidence comes from the southwest of Solund in the Utvaer region (Indrevaer & Steel 1975), where NNW–SSE trending extensional faults may have been active forming fault scarps during sedimentation.

Steel et al. (1985) have recently reviewed the main models proposed for the formation of the Devonian basins and I will use their nomenclature.

Model A. Hinge Faulting. This model is essentially a propagating half-graben. It explains the eastward migration of the depocentre but fails to explain (as pointed out by Steel et al. 1985) either the migration of the western end of the basin or the eastward tilting of the strata.

Model B. Strike-slip Faulting. In this model, uplift on a restraining bend on a strike-slip fault provides a sediment source for deposition in small half-grabens formed successively at a releasing bend. Despite the observations of Steel et al. (1985), the main objection to this model is the lack of evidence of a strike-slip continuation of the steep northern margin contact into basement. In Hornelen, the best described basin, the contact appears instead to continue across the mouth of Ålfotfjorden, where it enters Nordfjord (Fig. 1) directly into the thrust contact as shown by Steel et al. (1985). Steel & Gloppen (1980) have shown a series of fault lineaments in the adjacent basement which trend subparallel to this northern margin and continue to the east of the present basin margin. However, the age, amount and direction of displacement on these zones is not known. In some cases they are coincident with major lithological boundaries; they all follow basement trends. There is no evidence that any of these fault lineaments are major strike-slip faults.

This model does attempt to explain many of the structural features affecting the basin sediments by appealing to complex transpression and transtension.

Model C. Listric Normal Faulting. I am in general agreement with this model as originally proposed

Fig. 1. Geological map of the Sogn og Fjordane area, west Norway.

by Hossack (1984), although some detailed criticisms will be made in the next section. The main objection to this model raised by Steel et al. (1985) is that it does not possess a dynamic hinterland. This problem is particularly acute in Hossack's (1984) model due to the subhorizontal fault geometry on which negligible footwall uplift is predicted, leading to a progressive degradation of fault scarps. However, in a model in which the extensional structure is relatively planar and dips steadily at c.20°–30°, continuous footwall uplift would be expected to provide the necessary source rejuvenation.

Model D. Migrating Listric Fault System. This is a variant of model C but the proposed large-scale propagation of an extensional fault into its footwall seems mechanically unlikely and is not observed in model experiments of extensional fault systems (McClay & Ellis 1987).

Model C incorporates many aspects of model B, the difference being one of emphasis in the regional tectonic between dominant strike-slip with associated extension (B) and extension along a structure with major strike-slip segments (C). Both the models fit most of the constraints and a choice between them depends critically on the interpretation of the tectonic contacts as either: thrusts which if of relatively small scale are compatible with the strike-slip model (Steel & Gloppen 1980), or a large-scale extensional fault which forms the basis of model C. The nature of the low-angle tectonic contacts is considered in the following section.

Low-angle tectonic margins

The southeastern margin of Solund, both the southern and northern margins of Kvamshesten, and the eastern margin of Hornelen have, as previously indicated, been interpreted as thrusts. The lines of reasoning which have been used to support this interpretation can be summarized as:

(1) The presence of mylonites (Høisaeter 1971; Bryhni 1964; Nilsen 1968).
(2) Discordance between structures in the hanging wall, especially folded Devonian bedding, and the mylonite zone itself (Høisaeter 1971; Bryhni & Skjerlie 1975).
(3) The metamorphic grade developed in the Devonian sediments (Roberts 1983; Torsvik et al. 1986).
(4) The formation of a cleavage in the Devonian sediments (Roberts 1983; Torsvik et al. 1986).
(5) The types and orientation of magnetic fabric developed in hanging wall sediments, mylonites and footwall rocks (Torsviket al. 1986).

Before considering these point by point, I will present a model of a large-scale extensional structure (Fig. 2) adapted from Sibson (1977) and Davis (1983). Fig. 2(a) shows an extensional fault/shear zone passing through the whole crust at the beginning of its activity. Fig. 2(b) shows the same structure at the end of the extensional phase in which a large hanging wall basin has formed, and a large amount of footwall material has been eroded. Notice that the four points A, B, C, D which were all at different crustal levels have become juxtaposed at the same level due to continued movement on the zone. Rocks at A started to be deformed under amphibolite grade conditions probably as a mylonitic gneiss and have since been uplifted into very low grade conditions. Due to heterogeneous strain this area will be variable retrogressed with some areas of medium grade assemblages and fabrics remaining almost unaffected. A high strain strand of the fault has juxtaposed A against mylonites (B) which started at upper greenschist. Across another high strand area C has experienced only slight uplift with only minimum retrogression and probably consisting of both mylonites and cataclasites. Area D, representing the first deposited sediments in the half-graben, has now been juxtaposed against the other areas and has suffered in contrast a prograde burial metamorphism almost into lower greenschist facies. At this stage the part of D against the fault zone is being deformed into cataclasites and possibly mylonites. Note that sediments at D are being deformed and metamorphosed simultaneously with the deposition of the last sediment in the half-graben E. In terms of the whole basin this deformation is synsedimentary.

Point (1). Keeping the above model in mind, the presence of mylonites says nothing about the type of fault, merely the condition under which faulting occurred, examples of mylonite developed along extensional faults are now becoming widely documented in the Basin and Range (e.g. Davis 1983) and the Aegean (Lister et al. 1983).

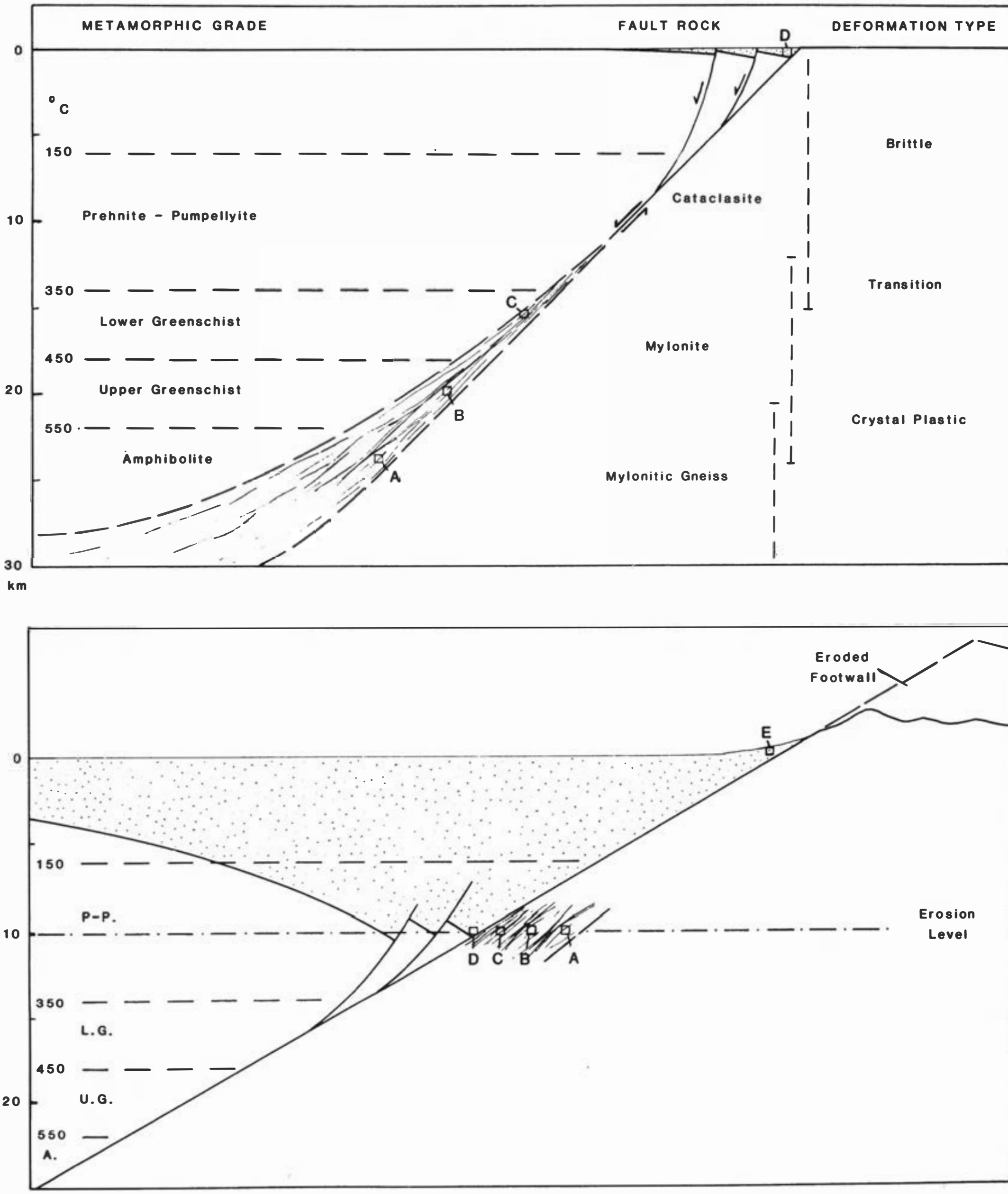


Fig. 2. Section across a hypothetical extensional fault and associated hanging wall basin at: (a) start of fault activity, (b) near end of fault activity.

Point (2). By the very nature of fault zones strain is discontinuous between hanging wall and footwall, so folds may develop in the hanging wall and not the footwall and vice versa. Folded hanging wall above unfolded footwall is a relationship better known in thrust systems but is increasingly becoming recognized in extensional systems (McClay & Ellis 1987).

Point (3). Half-graben basin thicknesses of greater than 8 km can now be regarded as relatively common, e.g. the North Celtic Sea Basin and the North Lewis Basin (Cheadle et al. 1987). Assuming a standard geotherm of 25°/km, early sediments in such a basin will undergo a burial metamorphism well into Prehnite-Pumpellyite facies and at rather higher geotherm (35°/km) approach lower greenschist.

Point (4). During such a metamorphism cleavage formation is only to be expected and is likely to be of two types: compaction cleavage which should be shallowly dipping and probably close to bedding, and a deformation cleavage related to hanging wall deformation whose orientation would be related to the geometry of the structures developed.

Point (5). The palaeomagnetic results of Torsvik et al. 1986 can be summarized as follows: (1) A magnetic fabric in the sediments subparallel to bedding apparently overprinted at the tectonic margin by a fabric subparallel to the mylonite foliation. (2) A pole indicating a middle Devonian to lower Carboniferous age for the mylonitization. (3) Evidence from a fold test of some folding after the main magnetization in the western part of the Kvamshesten Devonian.

The presence of hanging wall deformation and mylonitization along the contact is not in dispute, only the sense of the fault movement. The pole position which probably marks either uplift through a blocking temperature or the cessation of significant deformation is quite consistent with an extensional structure active from lower to middle Devonian. The local presence of some folding subsequent to the extension could be related to a post-Devonian inversion event which will be discussed in a later section.

The main argument against a thrust origin for the intensely mylonitized contact between Devonian sediments and mylonitic pre-Devonian basement is that a 'special case' model must be developed to allow the observed geometry of younger rock faulted against older (see also Hossack 1984).

A second argument concerns the change in metamorphic grade across the zone. In thrusting one would expect higher grade hanging wall rocks undergoing retrogression to be thrust over lower grade footwall rocks undergoing prograde metamorphism. In extension the reverse situation will apply and this relationship is well seen in the area studied, as will be shown in the next section.

The author knows of no unequivocal evidence to support a thrusting hypothesis for the formation of this contact.

Extensional fault geometry

Hossack (1984) presented a model for a continuous extensional fault with a highly irregular geometry which he calls the Måløy Fault. Several segments of this fault are high-angle trending WSW–ENE including the Bremangerland Fault, the Standale Fault and the pair of faults which pass north and south of Florø (Fig. 1). If these faults represent part of the extensional structure there is a major problem in fitting their orientation with the very constant lineation direction seen on most other parts of the extensional fault of 260°–310° (see Fig. 3). Taking this lineation as showing the movement direction on the fault these particular irregularities lie at a moderate angle (up to 55°) to the movement direction, which would cause severe mechanical problems in more than minor extension.

At least two of the high-angle faults clearly continue along strike into basement where the Måløy Fault changes direction, the Standale Fault and that forming the southern boundary to the Hornelen Devonian. All of these faults are here

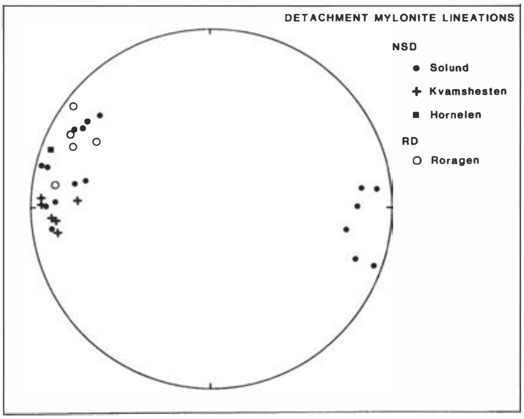


Fig. 3. Mineral elongation lineation data from mylonites in the Nordfjord-Sogn Detachment. The Solund data come from the Hyllestad area, the southeast plunging data are from the hinge zones of mesoscopic folds. The Kvamshesten data points are representative orientations from southeastern Atløy, two localities on the northern side of Dalsfjord, the region of the synclinal axis, and on the south side of Førdefjord. The orientation from Hornelen is representative of the data from near Hyen. Data from the mylonites at Røragen are included for comparison.

interpreted as being high-angle extensional faults of late- or post-Devonian age which post-date and cut the main low-angle extensional structure. They may have a similar relationship to the proposed detachment as the later high-angle extensional faults have to the low-angle detachments in the Basin and Range (Proffett 1977).

Approximately 40% of Hossacks's Måløy Fault is therefore interpreted as being non-continuous with, and a different age to, the structure which is here proposed. In addition, the scale of structure being described is quite different between; the Måløy Fault locally reactivating a thrust plane and only a few metres in thickness, the structure described in this paper as kilometric scale extensional shear zone.

In this account I have, therefore, chosen the name Nordfjord-Sogn Detachment (NSD) for the extensional structure, as this precisely describes its geographical extent, emphasizes the differences in geometry from Hossack's Måløy Fault and indicates its similarity to Basin and Range style detachments (e.g. Davis 1983). In the following section the Nordfjord-Sogn Detachment is described in detail from the Solund and Kvamshesten areas (Fig. 1).

The Nordfjord-Sogn Detachment

This is defined as a zone of high strain which puts upper plate rocks into contact with lower plate rocks. Upper plate rocks consist of three distinct units: (a) continental margin basement of Precambrian age with late Precambrian to Ordovician sedimentary cover – this unit is considered to be equivalent to the main allochthon, the Jotun Nappe; (b) ophiolitic rocks of the Stavfjord Nappe thrust onto (a); (c) Devonian coarse clastic sediments unconformable on both (a) and (b). Lower plate rocks are Precambrian basement gneisses of the Western Gneiss Region. The mylonites forming the detachment are of metasedimentary type near the contact with the upper plate and of basement type near the lower plate. The line marked on Fig. 1 represents only the top of the proposed detachment whose precise position is easily mappable; the base of the detachment zone is gradational and difficult to map precisely.

Solund area

In the Solund area (Fig. 1) assumed synextensional conglomerates with interbedded volcanics (Sigmond et al. 1984) of Devonian age form the upper plate. Even several kilometres from the detachment the conglomerate is visibly deformed with the development of a weak cleavage subparallel to bedding; bedding here dips c. 20° towards the southeast. Within a few hundred metres perpendicular distance from the detachment the cleavage becomes more intense; bedding dips more shallowly (5°–10°) to the southeast. Actually at the contact a few metres of mylonitized conglomerates are commonly observed; the cleavage is seen to rotate into the high strain zone so as to indicate an extensional sense of movement (Fig. 4).

Within the mylonite the conglomerate clasts become highly strained.Throughout the whole area the conglomerate shows a very strong pebble fabric with an a-axis preferred orientation NW–SE and a SE dipping imbrication (Nilsen 1968). Nilsen considered this fabric to be sedimentary in origin and this fits well with the humid alluvial fan environment postulated for these conglomerates. Near the detachment, however, this is obviously overprinted by the tectonic fabric which is of similar orientation. The more basic volcanics interbedded in the sediments show that the metamorphic grade of the conglomerates reached at least Prehnite-Pumpellyite. This is the highest grade known to be developed within the Devonian basins and may result from either a slightly enhanced geotherm related to contemporaneous vulcanism or a very thick basin fill

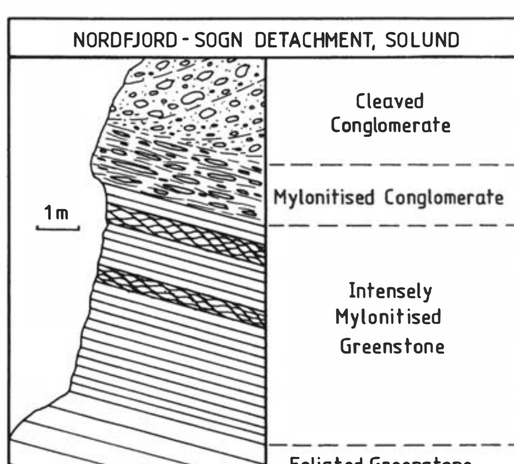


Fig. 4. Schematic section across the Nodfjord-Sogn Detachment on Solund.

(c. 10 km) combined with the present erosion level which exposes the very bottom of the basin.

The description of the detachment mylonites which follows is based on a reconnaissance traverse from Lifjell to Lavik on the north side of the Sognefjord (Fig. 1). Detailed mapping being carried out by members of the Geological Institute, University of Bergen, is expected to lead to some revision of this part of the section, but not to the general conclusions reached (Michelsen & Tillung, in prep.).

For seven metres immediately below the contact with upper plate conglomerates greenstones (assumed metavolcanics) are intensely mylonitized with a mylonitic foliation parallel to that in the conglomerate dipping between 16° and 25° to the northwest. Within the greenstone mylonites a strong mineral elongation lineation is developed plunging 18° to 302°, and the foliation is everywhere affected by a secondary shear band cleavage (White et al. 1980; Platt & Vissers 1981) indicating an oblique extensional sense of movement.

Beneath this intense shear zone which forms the top of the detachment there is c. 100 m of less deformed, though still highly strained, rather homogeneous greenstone with a foliation parallel to the upper contact of the detachment. There follows several hundred metres of a mixed sequence of irregularly alternating greenstone, pelite, psammite and semi-pelite horizons. Strain within this sequence is still moderately high with the rocks being true mylonites, although the zone is characterized by both occasional higher strain zones and low strain augen. Foliation rotation at the boundaries of these augen consistently indicates extensional sense movement, and shear band cleavage developed in favourable lithologies gives the same sense of movement. Foliation is more variable than before but overall it dips moderately (c. 30°) to the northwest with a lineation plunging shallowly (5°–15°) to 270°–300° (Fig. 3). On the northern side of the peninsula in this part of the section a large lens of psammite with deformed basic sheets is developed. The metamorphic grade of this part of the section is not known in detail but it appears to be all in greenschist facies.

Continuing eastward along the traverse a major granodiorite body (c. 500 m thick) of present sheet-like form is encountered. Although in some low strain areas the granodiorite is seen to cut an early foliation in the metasediment it is generally strongly mylonitized and the mylonite foliation itself is tightly folded. Below the granodiorite there follows a further series of metasediments and ?metavolcanics. This sequence contains psammite, pelite, marble and amphibolite units. The strains are not obviously high in the psammites and pelites, but the amphibolites and marbles show intense multiphase folding and the foliation remains subparallel to the rest of the sequence so far described. The metamorphic grade increases down the section through epidote-amphibolite to true amphibolite with a typical medium grade assemblage being found in the pelite (staurolite–almandine–kyanite), although this is partly retrogressed to greenschist. Without detailed mapping it is not clear whether the changes in metamorphic grade described are abrupt or gradual.

Continuing down the section the highly deformed cover sequence gives way to an equally highly deformed basement sequence consisting of mylonitized granite, gabbro, amphibolite and quartzofeldspathic gneisses with eclogite pods (partly retrogressed). It is instructive to describe this part of the section moving from east to west. At Lavik the basement rocks are strongly deformed, with a regular southeasterly dipping mylonitic foliation forming part of the zone of completely caledonized basement gneisses of Dietler et al. (1985) containing a lineation c. 120°. Foliation and lineation are both affected by northwest verging asymmetric folds, open to close in style with fairly constant subhorizontal axes c. 045°. Between Lavik and Leirvik the main foliation is affected by a major antiformal structure. At Leirvik the now northwest dipping mylonites are affected by similar northwest verging folds to those at Lavik but they are now close to tight in style, their axes are variable 040°–080° and clearly non-cylindrical. At Rysjedalsvika, just below the boundary with the mylonitized metasediment the same folds are tight to isoclinal in style with the axes now consistently subparallel to the lineation c. 290°. Both the progressive reorientation of the mylonite foliation and the fold axes, and the tightening up of the folds are consistent with a model of increasing simple shear of extensional sense towards the northwest.

The eclogite pods found in the lower margin and footwall of the NSD form part of the suite of eclogites found throughout the northwestern part of the Western Gneiss Region. The results of a series of studies of P/T conditions and radiometric age determinations have recently been reviewed by Griffin et al. (1985). Ages cluster around 425 Ma and for the eclogites in the footwall of the NSD P/T estimates give P = 14kb, T = 600°C. K/Ar ages from the Statlandet area (Lux 1985) suggest that the Western Gneiss Region underwent continuous uplift from soon after eclogite formation to at least the end of the middle Devonian. The close juxtaposition of basement containing these Silurian eclogites uplifted from a depth of c. 50 km against Devonian sediments which have undergone simultaneous subsidence and burial metamorphism represents very strong indirect evidence for the presence of the proposed extensional structure.

Kvamshesten area

In the Kvamshesten area three units are found in upper plate position immediately above the NSD; from west to east these are late Precambrian sediments, Precambrian mangerite-syenites and assumed synextensional Devonian conglomerates and sandstones. Preliminary data from Torsvik et al. (1986) derived from illite crystallinity in the Devonian suggest anchizone conditions (c. 200°–300° C) were developed; they also describe cleavage developed in certain fine-grained lithologies. As in the Solund area the top of the detachment is marked by a zone of intense mylonitization, the uppermost metre of which is clearly derived from the adjacent upper plate rocks. Where mangerite-syenite forms the upper plate it is also affected by cataclasite zones and associated pseudotachylyte veins immediately above the detachment. A reconnaissance study of the detachment mylonites has shown that they have an overall similarity to the section described above in the Solund area with a few thousand metres of metasedimentary mylonites passing down into mylonites of basement origin. Greenstones, however, form a far less important component of the upper part of the section and no granitic intrusions have been described. All of the mylonites are characterized by a strong mineral elongation lineation plunging shallowly (10°–25°) to (265°–275°) (Fig. 3). The detachment here has a synformal character with the northern margin dipping moderately south (30°–40°) and the southern margin dipping moderately north (20°–30°). The overall westward dip of the detachment implied is in the range 10°–15°. In the lower parts of the section tight to isoclinal northwest verging folds are observed with axes close to the lineation. Throughout the section a secondary shear-band cleavage is developed giving a consistent extensional sense of movement. The base of the extensional shear zone has not been studied in this area and no metamorphic data are available from lower plate rocks.

The proposed detachment structure may then be summarized as: a little deformed, weakly metamorphosed upper plate with synextensional sediments, the detachment with at its top a c. 10 m thick intense shear zone passing down into a thick sequence of mylonites derived from cover in the upper part and basement in the lower part of the section, varying in metamorphic grade from lower greenschist facies to mid amphibolite facies (with part retrogressed eclogites) from top to bottom. The generalized section is shown in Fig. 5; this should be compared with the hypothetical section shown in Fig. 2(b). Hossack (1984) suggested that the extensional structure formed by the reactivation of the Caledonian thrust structures. The above description, however, strongly implies that the whole of the NSD structure represents a major extensional shear zone cutting across the pre-existing tectonostratigraphy. The simplest interpretation of the mylonites is that they represent a highly attenuated section through the whole Caledonian thrust pile and part of the autochthonous basement, as indicated in Fig. 5.

Detachment geometry

Although removal of the several WSW–ENE segments from Hossack's (1984) fault does simplify its geometry, it still remains quite irregular. Many of the corrugations in the NSD can be matched with folds in the upper plate such as the overall synformal structures of the Devonian outcrops of Hornelen, Håsteinen and Kvamshesten. This has led to the proposal of a late or post-Devonian fold phase (Sturt 1983; Roberts 1983) correlated with the Svalbardian event on Spitzbergen and known as the 'Solundian' (Torsvik et al. 1986). However, one of the major synformal corrugations in the detachment (in the Solund area) is not matched with a syncline in the upper plate, which in contrast is folded in an anticlinal structure (Fig. 1) about a different axis. In this case the synformal corrugation must be an original feature of the detachment and the anticline is best explained as an upper plate accommodation structure caused by a detachment geometry as indicated in Fig. 6 (as originally outlined by Hos-

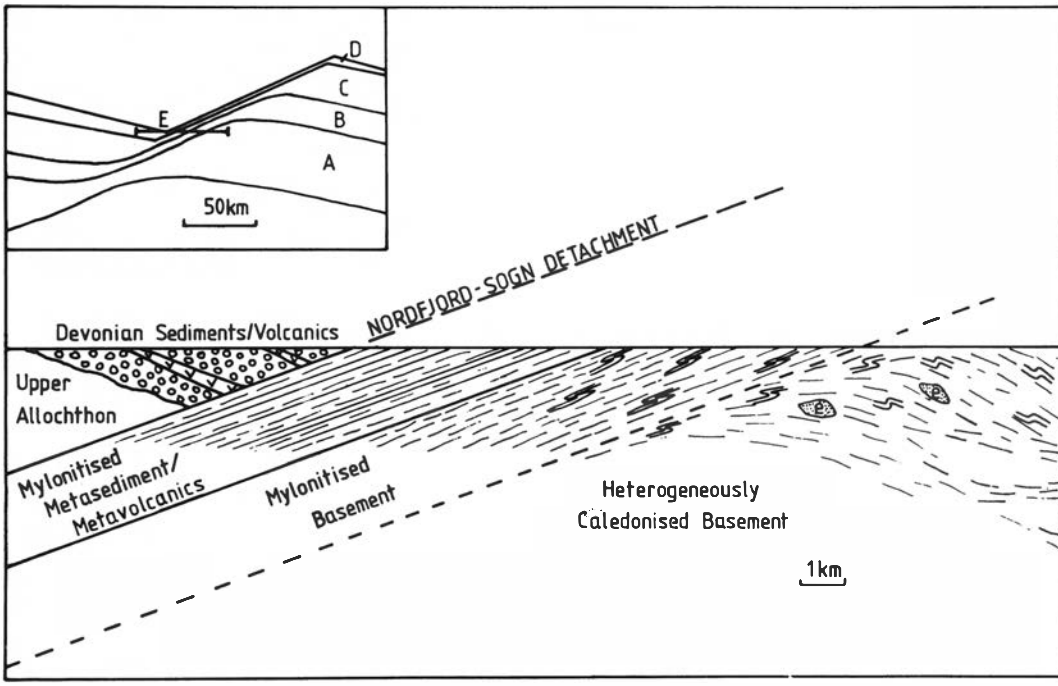


Fig. 5. Generalized section across the Nordfjord-Sogn Detachment in the Solund and Kvamshesten areas.

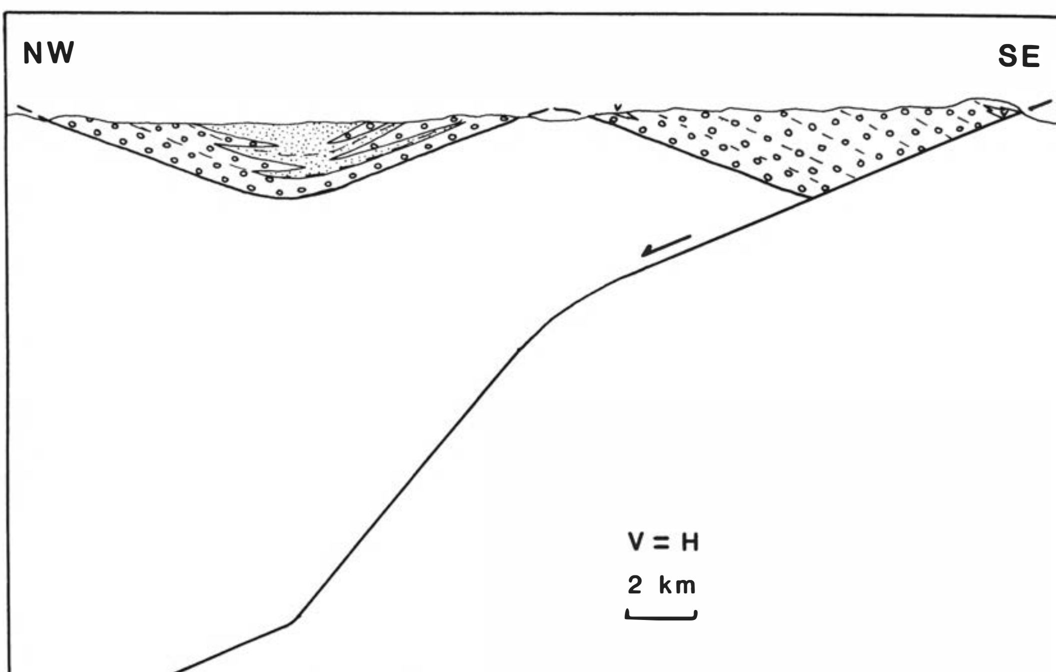


Fig. 6. Formation of anticlinal structure on Solund in upper plate due to changes in detachment dip. Line of section passes through Hersvik (Fig. 1). Note that most of the sediment at the northwestern end of the section is derived from the northeast.

sack 1984). Such corrugations are a normal feature of detachment geometry in the Basin and Range province (e.g. Frost 1981).

It is also possible to relate folding to fault geometry along the northern margin of Hornelen. Sediments in this basin have an overall shallow (20°–25°) easterly dip but as they approach the northern margin they become steeply (70°–80°) southerly dipping, forming an overall monoclinal structure. The eastern part of the northern margin has a strike of 080° which is slightly oblique to the apparent movement direction on other parts of the detachment (260°–310°). This obliquity would have been sufficient to cause transpression along this margin during extension, and the observed monocline is consistent with this.

If some of the 'Solundian' folds can be explained as upper plate responses to detachment geometry it seems likely that other major folds in the region have a similar origin (see also Hossack (1984). The syncline at Kvamshesten which appears to fold upper plate rocks, the detachment and lower plate rocks together is the most difficult to explain in this way. However, if the original geometry of the extensional shear zone in the Kvamshesten area was that of a synformal corrugation, gentle near the surface, tightening up at deeper levels, the upper plate rocks would become progressively folded as the extension continued. This proposed mechanism is in keeping with the observations of progressive overlap in the Kvamshesten Devonian which led Bryhni & Skjerlie (1975) to suggest that at least some of the folding was contemporaneous with sedimentation.

Other folds appear to be related to the cross-cutting WSW–ENE trending faults, e.g. the Grøndalen syncline whose axis exactly parallels the basin margin fault to the south. This may indicate a phase of structural inversion along these faults; such phases are recognized in the adjacent offshore regions (Pegrum 1984).

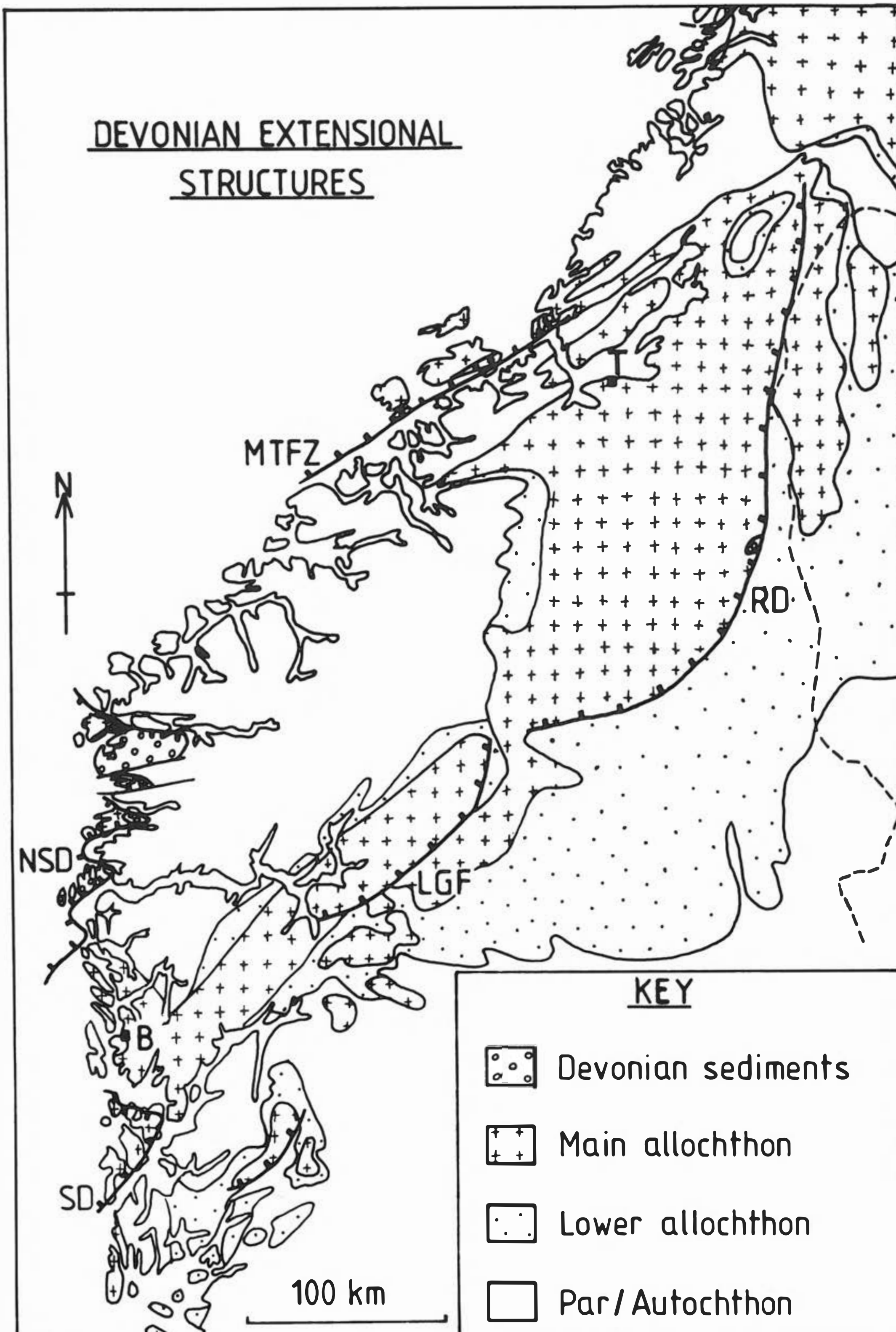
Other extensional structures in south Norwegian Caledonides

Apart from the NSD the only major extensional structure of Devonian age previously described from southern Norway is the Laerdal–Gjende Fault (Fig. 7) (Milnes & Koestler 1985). Smaller structures of similar style have, however, been reported from the Hardanger–Ryfylke nappe complex (Naterstad et al. 1973). The following evaluation of two further possible extensional structures of regional significance is based on reconnaissance fieldwork.

In the Sunnhordaland region an irregular shear zone cuts through the Sunnhordaland Batholith (late Silurian in age–Brekke et al. 1984) and its envelope. The shear zone is c. 50 m thick and the associated mylonites have a shallow westerly plunging lineation. The mylonite foliation is affected by asymmetric folds and shear band cleavage showing a consistent extensional sense. The amount of movement on this structure (for which I propose the name Sunnhordaland Detachment, Fig. 7) is difficult to estimate, but from the thickness of mylonites developed it seems unlikely to be greater than a few kilometres.

The second structure considered forms the southeastern boundary to the Trondheim Nappe. Although interpreted as a thrust it clearly cuts across the Caledonian nappe units with omission of the tectonostratigraphy (Sigmond et al. 1984) and has an extensional geometry on published sections (Wolff et al. 1980). At the Swedish border near Meråker (Fig. 7) the Caledonian east verging thrust related fabrics are clearly seen to be reworked by west verging minor structures through a zone at least 50 m thick next to an unexposed zone of a further 50 m thickness marking the contact itself. Devonian sediments are found in close association with this structure further to the south at Røragen (Fig. 7) (Roberts 1974; Steel et al. 1985). The mylonites here contain unequivocal indicators of extensional movement throughout their thickness as shown by minor fold asymmetry, shear band asymmetry, quartz c-axis asymmetry and quartz grain shape fabrics. Locally intense deformation in the finer-grained Devonian sediments may be related to irregular footwall geometry as proposed along the NSD. In order to bring the interpreted synextensional sediments into contact with mylonites in the footwall, movement of several kilometres is indicated on this structure (for which I propose the name Røragen Detachment). For more details see Norton et al. (in prep.).

The other structure shown in Fig. 7 is the WNW–ENE trending Møre–Trøndelag Fault Zone (Gabrielsen et al. 1984). The present outcrop pattern of the Devonian sediments and rocks of similar character to the upper plate of the NSD of the outer Trondheimsfjord are controlled by this fault system. These faults juxtapose the unmetamorphosed Devonian sediments with



DEVONIAN EXTENSIONAL STRUCTURES
N
MTFZ
RD
NSD
LGF
B
SD
100 km
KEY
Devonian sediments
Main allochthon
Lower allochthon
Par/Autochthon

underlying low grade metamorphic and igneous rocks against rocks of medium to high grade. The implied extensional movements on these faults are probably of Mesozoic age as indicated by their control on the development of the Møre Basin.

Devonian tectonics in the southern Scandinavian Caledonides are here interpreted as being dominated by extension. This extension has been achieved partly by the reactivation of the Caledonide thrusts (Milnes & Koestler 1985; Naterstad et al. 1973) but mainly by the development of a series of cross-cutting, NW-dipping extensional structures with displacements ranging from several hundred metres to c. 100 km (Norton 1986). All of these structures have rather irregular geometries, which has led in many cases to locally intense deformation within their hanging walls.

Conclusions

(1) Small-scale structures within mylonites along the Nordfjord-Sogn Detachment confirm its extensional nature.
(2) The Detachment cross-cuts the Caledonian nappe structures.
(3) The Detachment is similar to those seen in the Basin and Range but is on an unusually large scale.
(4) Many of the folds affecting upper plate rocks are best explained as accommodation structures resulting from irregular detachment geometry as originally suggested by Hossack (1984). Some, however, may be related to a phase of inversion along the WNW–ESE trending faults.
(5) Two other extensional structures of regional significance are proposed, the Sunnhordaland and Røragen Detachments.

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Fig. 7. Geological map of the southern Scandinavian Caledonides showing major Devonian structures. MTFZ Møre Trøndelag Fault Zone; NSD Nordfjord-Sogn Detachment, RD Røragen Detachment; LGF Laerdal-Gjende Fault; Sunnhordaland Detachment. B Bergen; T Trondheim.

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