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Tectonometamorphic development of Devonian rocks of western Solund, and regional implications

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REPORT

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Title: Tectonometamorphic development of Devonian rocks of western Solund, and regional implications

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Summary:

Many modern accounts of the Devonian rocks of western Norway, which emphasise the extensional phenomena affecting them, tend to ignore or gloss over the deformation and metamorphism which these rocks have suffered during contractional deformation. The present account describes extensive ductile folding, penetrative cleavage formation and low-grade metamorphism developed in the Devonian strata of the outer Solund region. It will also be shown that the Devonian rocks of the Scandinavian Caledonides share a common tectonothermal development. In summary, the bulk observations support a regional contractional event which, conceptually, may relate either to a Mid-Late Devonian arc-continent collision, or to a transpressional strain regime.

Keywords: Devonian	Solund	Tectonometamorphic
Folding	Cleavage	Transposition
Thrusting	Collision	

CONTENTS

1. INTRODUCTION

In recent years, many of the descriptions of the structural development of the Devonian rocks of western Norway (Fig. 1) have been dominantly concerned with extensional tectonics, which account for the origin of these basins and part of their subsequent history (Hossack 1984; Norton 1985; Hossack & Cooper 1986; Serrane & Seguret 1987; Andersen 1998). Less attention, however, has been given to effects of compressional deformation and attendant regional metamorphism within the areas of Devonian rocks. These features are not unknown and are the themes of a number of studies (e.g. Roberts 1974, 1981; Sturt 1983; Torsvik et al. 1986, 1987, 1988; Bøe et al.1987; Braathen 1999). We will here attempt to redress the balance between these modes of deformation, which are by no means incompatible considering the time frame available.

Early accounts of the Devonian geology of the Solund area (Kolderup 1926; Nilsen 1968) indicate the deformational history to have been quite complex, and these authors proposed that the Devonian rocks had suffered both thrusting and folding in a Late Devonian orogenic event, later referred to as the '*Solundian Phase*' by Sturt (1983). This proposition has been, in many ways, superseded by accounts which relate the deformation features to an extensional tectonic regime, producing a major detachment or mylonite zone, the Nordfjord-Sogn Detachment, and besides, a low-angle fault beneath the Devonian, the Solund Fault (Norton 1986; Seranne & Seguret 1987). Both the origin of the Devonian 'Basins' and their subsequent tectonothermal development is related by those authors to such a tectonic regime. Other accounts, e.g. Bøe et al. (1989) from the Hitra-Smøla area, have described tectonothermal developments in a compressional strain regime. Torsvik et al. (1986) discussed folding and low-grade metamorphism in the Kvamshesten Devonian basin, and Braathen (1999) focuses on thrusting of the steeply inverted northern limb of the Kvamshesten syncline. The overall geometric pattern, i.e. the location of the Devonian basins, is that of a series of major synclines (Fig. 1c)(e.g., Krabbendam & Dewey 1998). The form of the synclines is in fact tighter than that shown by Krabbendam & Dewey (1998), and indeed the northern limbs of the Hornelen and Kvamshesten synclines are, in part, inverted (see Braathen 1999).

Reconnaissance work by one of us (BAS) some years ago indicated that the Devonian rocks of outer Solund, in the islands of the Utvær group, had undergone significant folding with cleavage formation. This is related to considerable contractional strains, and fairly complete cleavage-related transposition of the primary features of this conglomerate-dominated sequence has occurred. In the present account we will describe the structure of these rocks and their related low-grade metamorphism.

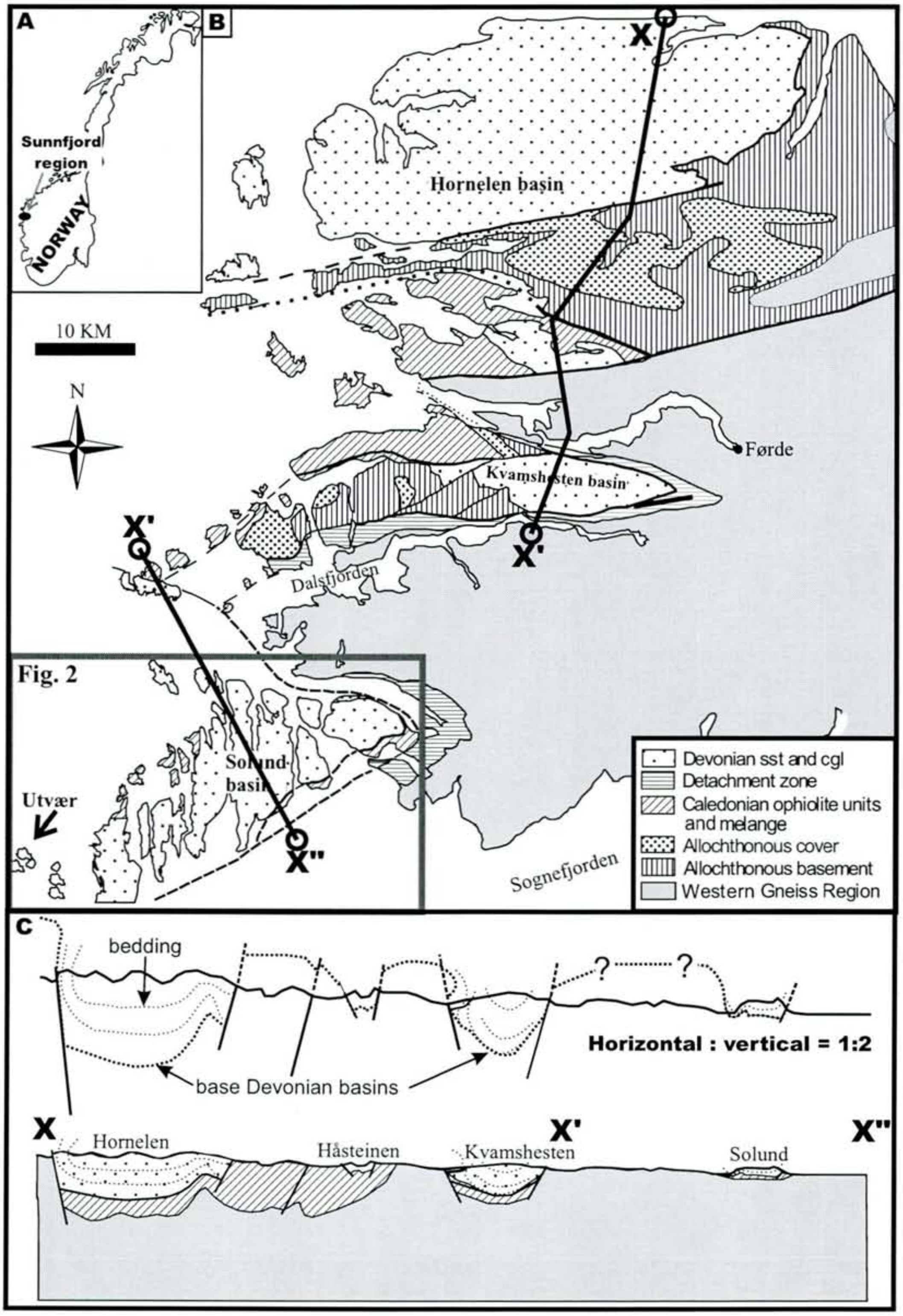


Fig. 1. (a) Outline map of Norway, locating the Sunnfjord region of western Norway. (b) Simplified bedrock map of the Sunnfjord region, modified from Kildal (1970) with additions from Osmundsen & Andersen (1994). (c) Schematic N-S cross-section, strongly modified from Krabbendam & Dewey (1998) in that the cross-section line, as located in Fig. 1b, is placed in a position that incorporates the most intensely folded part of the Devonian basins. The schematic line-drawing highlights the base of the Devonian basins, in order to delineate the intensity of folding.

2. THE GENERAL GEOLOGY OF THE DEVONIAN ROCKS OF THE SOLUND AREA

The unfossiliferous Devonian conglomerates and sandstones of the Solund area unconformably overlie previously deformed Cambro-Silurian metamorphic rocks (Figs. 1 and 2). The contacts of the Devonian with the basement rocks, according to Nilsen (1968), are of three types:-

(i) tectonic – along the southeastern boundary, i.e. the Solund Fault,

(ii) unconformable – on Leknessund, Hersvik, to the south of Lågøyfjord, and along the westernmost islands (Fig. 3),

(iii) tectono-unconformable – primary unconformity but with some movement along the contact, i.e. the northern edge of the Lifjellet Peninsula.

According to Steel et al. (1985), the basin infill has a stratigraphic thickness of at least 6 km. The oldest part of the succession, apparently restricted to the centre of the present basin contains fluviatile conglomerates and interbedded trachytic and rhyolitic lava flows (Furnes & Lippard 1983). The succession along the northern margin is more varied with evidence of small fans which built out southwards and were at times dominated by debris flows. Sandstones of flood-plain type are most widespread towards the northern margin of the basin. Indrevær (1980) indicated a progressive basement onlap by Devonian strata producing a great apparent basinal thickness, though with only a modest vertical thickness. There are a number of gabbro/greenstone slices recorded in the central part of the basin (Kolderup 1926), and these have been the subject of diverse interpretations. They have been considered as thrust slices by Kolderup (1926), igneous intrusions by Nilsen (1969), debris flows by Bryhni (1976) and as gabbroic breccias formed from giant rock slides (Michelsen et al. 1983).

Field reconnaissance by the present authors along the cliff-sections at the eastern side of Tollesundet, beneath Lifjellet, shows the presence of three formerly unrecorded, mafic rock slices within the Devonian sequence (Fig. 4a-d).They consist of pillow lavas cut by basic dykes, and are truncated by a basal ductile to semi-ductile mylonite zone approximately 2 m thick (Fig.4c, e, g). The mylonite is developed from both the hangingwall (pillow lava and dykes) and footwall (conglomerate), and reveals a strongly developed foliation which is decorated by chlorites and small grains of white mica, an assemblage indicative of low greenschist-facies conditions. The footwall conglomerate is densely foliated towards the mylonite, but the intensity of the cleavage decreases downwards. The mylonite is reworked and brecciated by low-temperature cataclastic deformation (< 50 cm zone and mm-wide bands), which is presumed to relate to movements on the Solund Fault (Fig.4c, f, h).The upper surface of the slices is an irregular primary contact, where the overlying conglomerates unconformably truncate both the dykes and an earlier foliation in the rocks of the slice. The relationships are those of a basement-cover depositional contact, indicating that the lower contacts of the slices are thrusts, since older rocks (basement) are placed onto younger rocks (Devonian cover). We have not yet re-investigated the slices of gabbro, and other rocks, in the central Solund area, but these will be re-studied as part of an ongoing project.

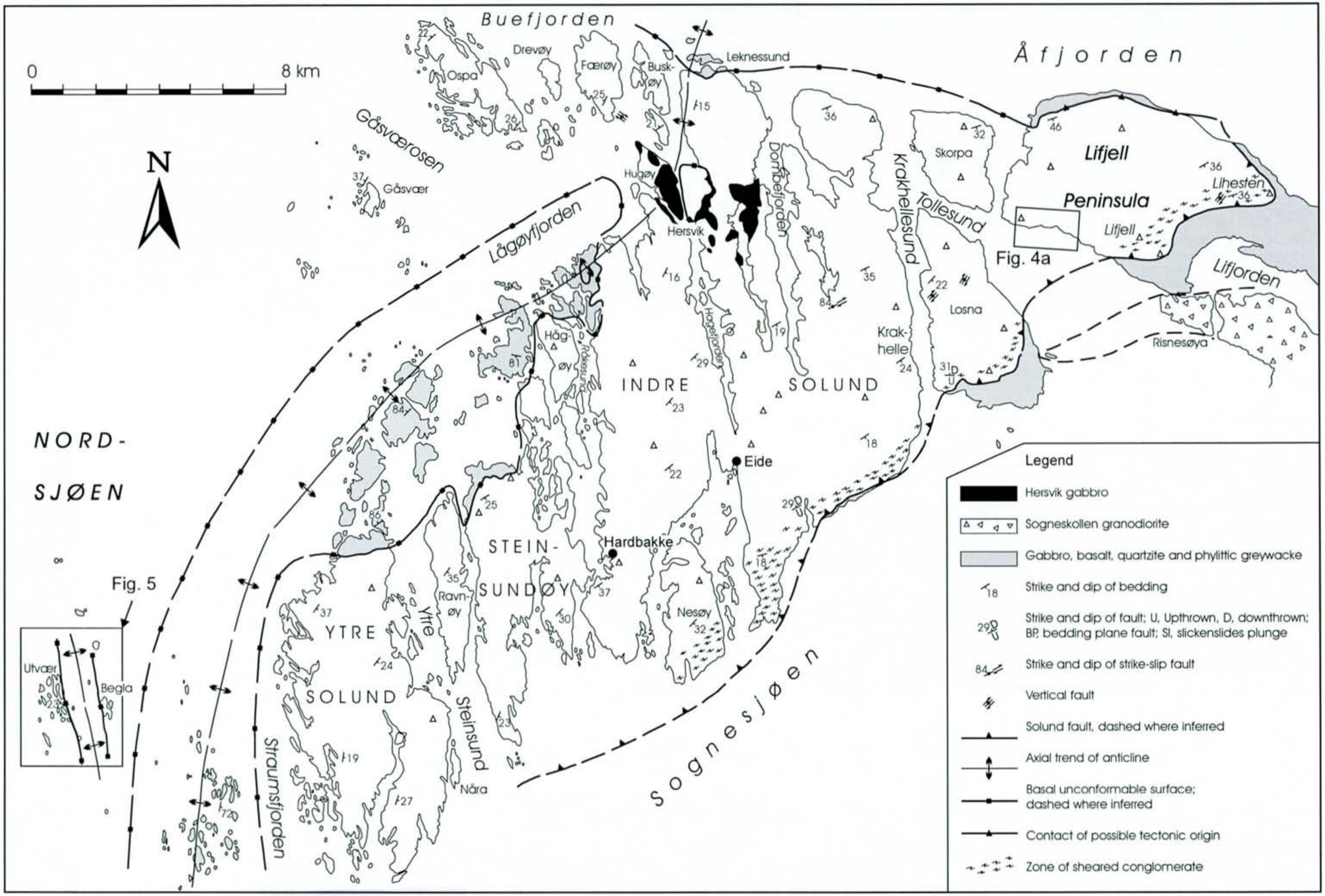


Fig. 2. Bedrock map of the Solund Devonian field, modified from Nilsen (1968).

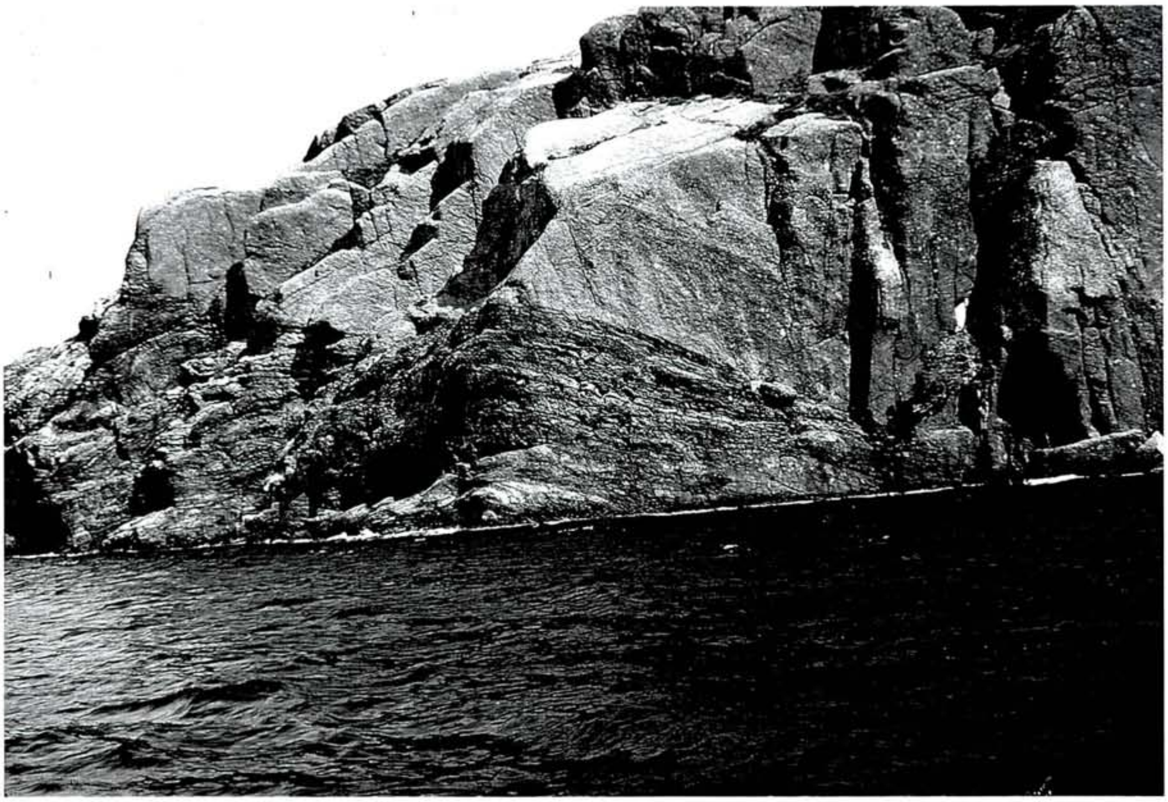
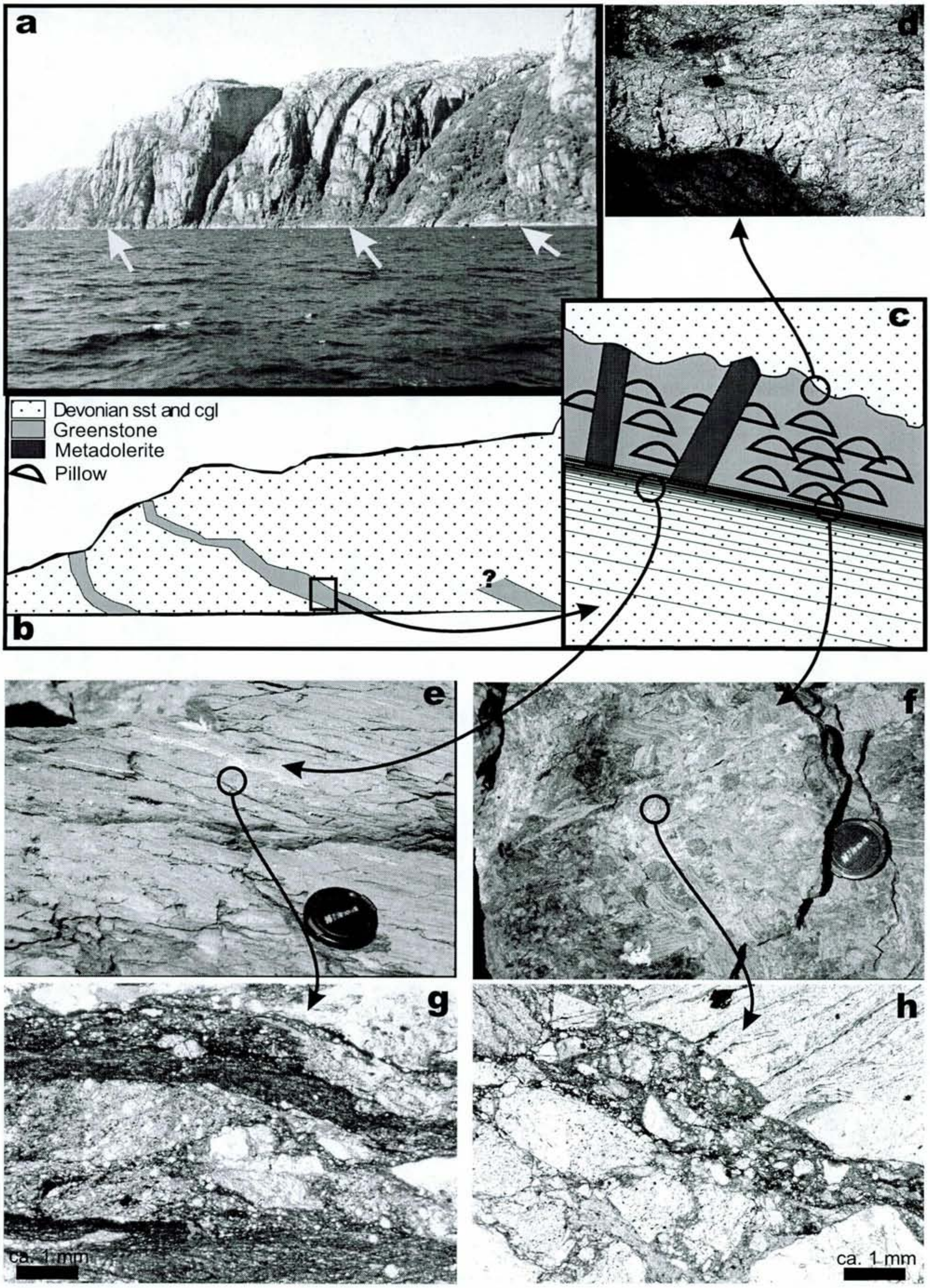


Fig. 3. Photograph of the basal unconformity of the Solund Devonian basin on NW Færøy, looking south-westward. Note the low angularity between the transposed layering in the Caledonian greenstone basement and the bedding in the overlying Devonian conglomerate.

Little details of the structure of the Solund region are, however, to be found in the literature. Nilsen (1968) conceived a sequence of structural development to include:

- an arching of the sediments into a broad anticline (Nilsen 1968, figure 3 therein, essentially Fig. 2 of the present paper),
- thrusting of the southern margin of the Devonian rocks towards the southeast, over older basement rocks,
- normal faulting along the Solund Fault, and
- a zone of deformed pebbles, some two and a half kilometres wide along the southern margin of the Devonian succession. The pebbles can be strongly elongated, in a ductile mode, in the southernmost part, a point also emphasised in Seranne & Serguet (1987).

It is now generally accepted that the Solund Fault is a substantial normal fault and is a part of the Nordfjord-Sogn Detachment (e.g., Norton 1985; Andersen 1998). We will return, however, to the general nature of structures in the Solund Devonian field in a subsequent report, and here will confine ourselves to a description of the structures in the outermost Solund area, which to our knowledge have not been previously described.



a
b
c
d
e
f
g
h
Devonian sst and cgl
Greenstone
Metadolerite
Pillow
?
ca. 1 mm
ca. 1 mm

Fig. 4. (a) Photograph of the southwestern slope of Lifjellet, eastern Solund basin, viewed from the south. Arrows locate three large greenstone slices within the Devonian conglomerates. (b) Line-drawing of the photograph in a. (c) Sketch of the structural relationships associated with the greenstone slices; note how the dykes are cut-off at their base by mylonite, and at top by the conglomerate. (d) Photograph of the angular unconformity between the greenstone and the Devonian conglomerate. (e) Photograph of part of the ca. 2 m-wide zone of mylonitised conglomerate beneath the greenstone slice in c. (f) Photograph of brecciated mylonite, which makes up an upper 50 cm-thick fault zone directly beneath the greenstone. (g) Photomicrograph of the mylonite in e, showing the ductile mylonite matrix, and partly brittle-fragmentation of larger sandstone grains/clasts. (h) Photomicrograph of cataclasite, present in f; note fragment of ductile mylonite at arrowhead.

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3. THE STRUCTURAL GEOLOGY OF THE SOLUND ISLANDS OF THE UTVÆR GROUP

Details of the geology of this island group are given in Fig. 5. The Devonian strata are very strongly deformed with a considerable development of megascopic asymmetrical folds of modified Class 1C (Ramsay 1967), and the bedding in the conglomerates and sandstones is variably to completely transposed into a dominating cleavage. This strong cleavage was figured and discussed by Indrevær & Steel (1975, figs. 2 and 3 therein), but they appear to have been unaware of the associated folding.

The unconformity between the Devonian sedimentary rocks and the ophiolitic substrate is well developed on the islands of Utvær, Frostholmen and a small island to the south of Frostholmen (Figs. 5 and 6a, b), as was also realised by Nilsen (1968) and Indrevær & Steel (1975). On the eastern side of Utvær the unconformity is perfectly exposed; it is tightly folded and, in places, can be seen in a steep to moderately inclined, overturned position. The Devonian rocks have developed a strongly penetrative cleavage, which is expressed as a crenulation cleavage in the substrate (Fig.6a, b). The latter is particularly well marked in the hinges of folds (Fig. 6a). Indrevær & Steel (1975) considered that the strong deformation of both cover and basement observed on Frosthomen and Indrevær was related to the zone of strong shearing recorded by Nilsen (Fig. 2), which they believed to represent the deformational expression of a thrust at depth.

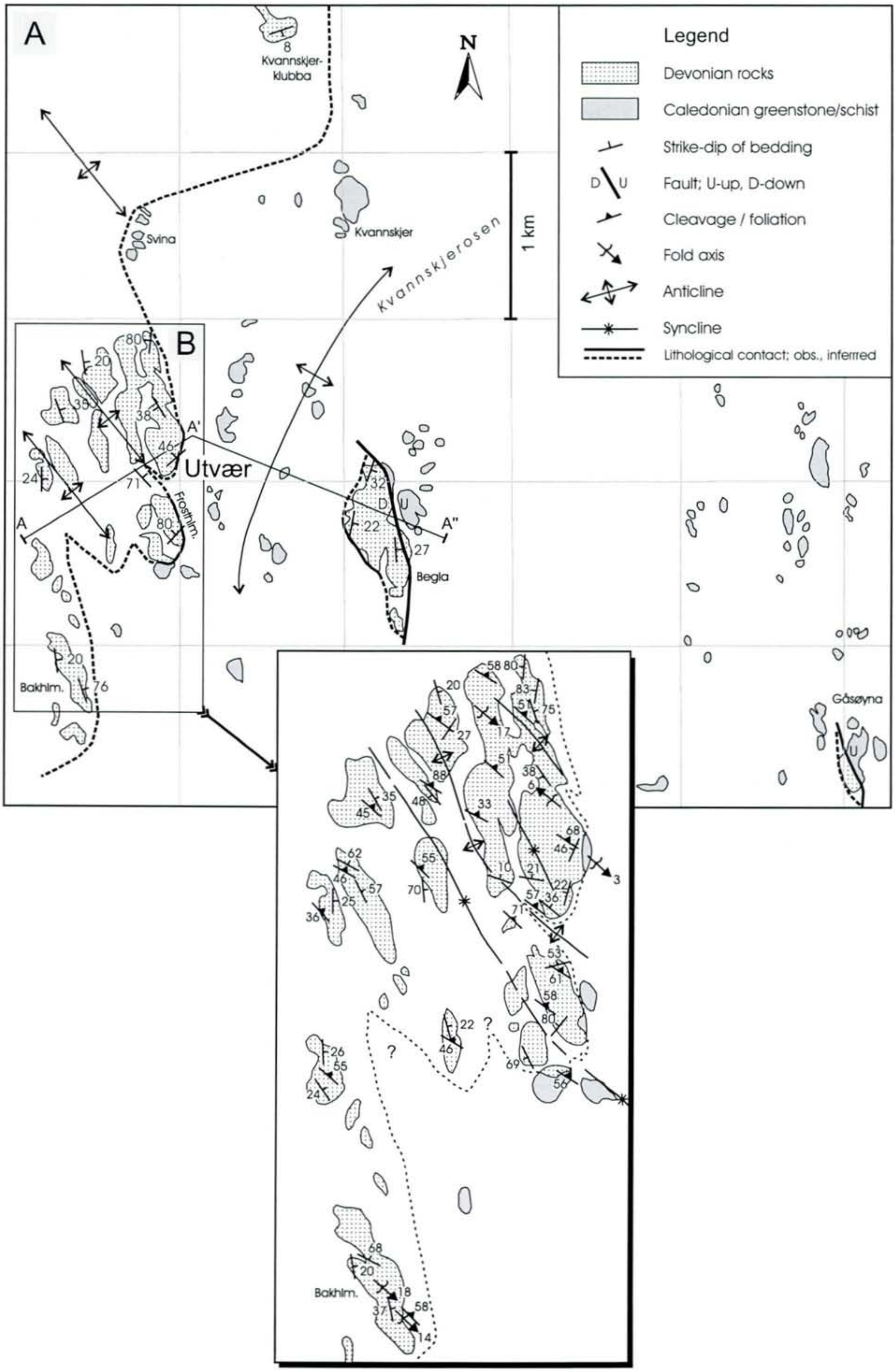


Fig. 5. Bedrock map of the Utvær islands. Outside of Utvær islands and Begla, the map is essentially from Indrevær & Steel (1975), with additions from Nilsen (1968). See Fig. 2 for location.

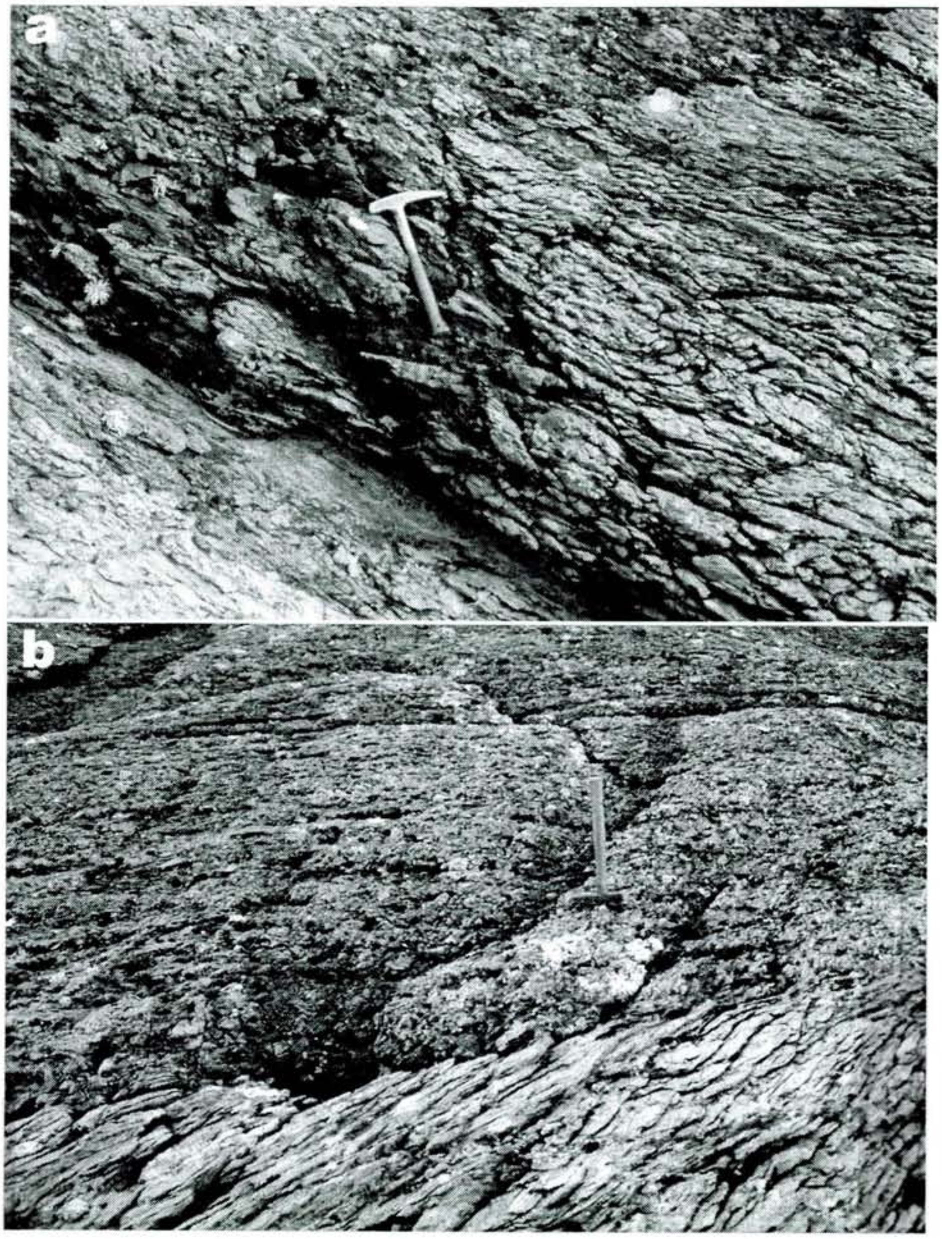


Fig. 6. (a) Photograph of the locally inverted basement-Devonian contact on Utvær. Note the well-developed cleavage in both the conglomerate and the basement (lower right to upper left), and that the clasts of the conglomerate are transposed into the cleavage (left).
(b) Photograph of the basement-Devonian contact on Utvær. The cleavage in the conglomerate makes a fairly low angle with the contact.

3.1 Nature of the structures

The overall structure of the Indrevær island group is a series of asymmetric folds (Fig. 7), with moderately northeasterly dipping axial planes, and the folds of the contact have generally moderate to steep northwesterly plunging axes. An axial plane cleavage (schistosity) is strongly developed in the Devonian conglomerates and sandstones, but is revealed only as a more sporadically developed crenulation cleavage in the foliated rocks of the underlying ophiolitic substrate. In thin-section, this cleavage is seen to be decorated by phengite and chlorite, and elongate pebbles are rotated into the cleavage (Fig. 8). The cleavage is very pronounced and is a moderately coarse-grained feature, and could equally well be referred to as a *schistosity.* A considerable amount of pressure solution also appears to have taken place in association with the cleavage formation. The deformation occurred under greenschist-facies metamorphism, as will be discussed in a later section.

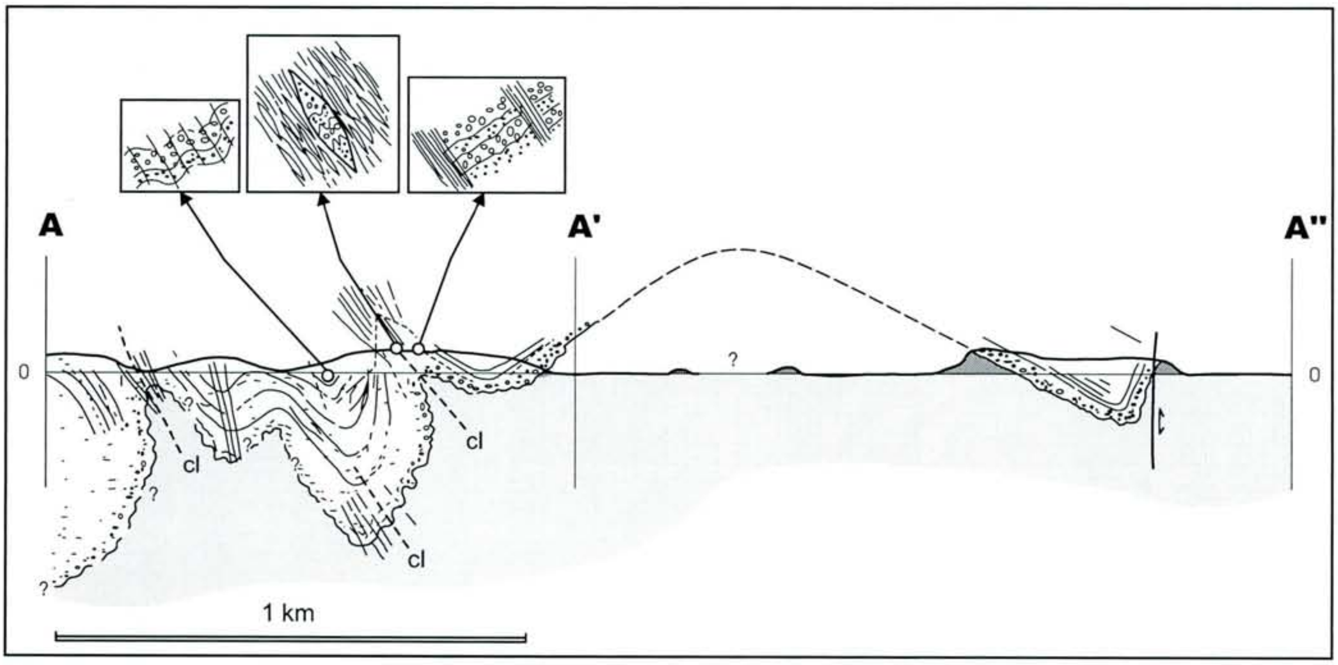


Fig. 7. Geological cross-section of the Utvær group of islands. The cross-section line is located in Fig. 5.

The folds of the contact are moderately tight structures and show a considerable variation in plunge from moderate to steep in a northwesterly direction. The mesoscopic folds in the Devonian rocks, on the other hand, are markedly asymmetric in form and appear to be modified Class 1c structures of Ramsay (1967). The long limbs of the folds are essentially shallow or only moderately dipping structures. Fold axes, although generally gently plunging, are fairly variable and spread towards a great circle distribution (Fig. 9b), indicating that they have an incongruous relationship (Ramsay & Sturt 1977) with the larger folds of the contact. That the folds are markedly non-cylindrical is shown by the variability in the orientation of the intersection lineation between bedding and cleavage (Fig. 9b). This intersection lineation makes a conspicuous great circle distribution, coinciding with the mean dip of cleavage (Fig. 9b), although there are pronounced maxima showing shallow northwesterly or southeasterly plunges. These megascopic folds are usually more appressed than those of the contact, and may show considerable style variations towards a subisoclinal form (Fig. 10a). The long limbs of the folds are strongly extended and the cleavage may, in some cases, become almost parallel to the bedding (Fig. 10b). In more extreme examples the middle limbs are also strongly attenuated. In order to shed further light on this problem we have plotted separately the poles to bedding where the cleavage/bedding intersection angle (i) is < 30° (Fig. 9d) and (ii) where it is > 30° (Fig.9c). These plots produce two distinctly different patterns. In case (i) the bedding poles describe an approximate NE-SW great circle with a shallow northwesterly plunge, i.e. statistically in the cleavage (Fig. 9d). In case (ii), on the other hand, the bedding poles describe an approximate great circle trending NW-SE with a near-horizontal NE-SW axis. This latter set of bedding measurements represents the orientation of the middle limbs and the hinge zones of the folds. The cleavage, however, is quite consistent and corresponds to a general great circle dipping at some 60° towards the southwest (Fig.9b). Another consistent measurement is that of pebble lineation which plunges towards the SW (Fig.9a), though it should be mentioned that this involves very few measurements (N=6). The deformed conglomerates on the Utvær islands are, however, not strongly lineated rocks.

Fig. 8. Photograph of steep primary layering (diffuse) in the Devonian conglomerates, which are very well cleaved (subparallel to hammer). Note how elongate boulders have been rotated into the cleavage. Outcrop on Utvær.

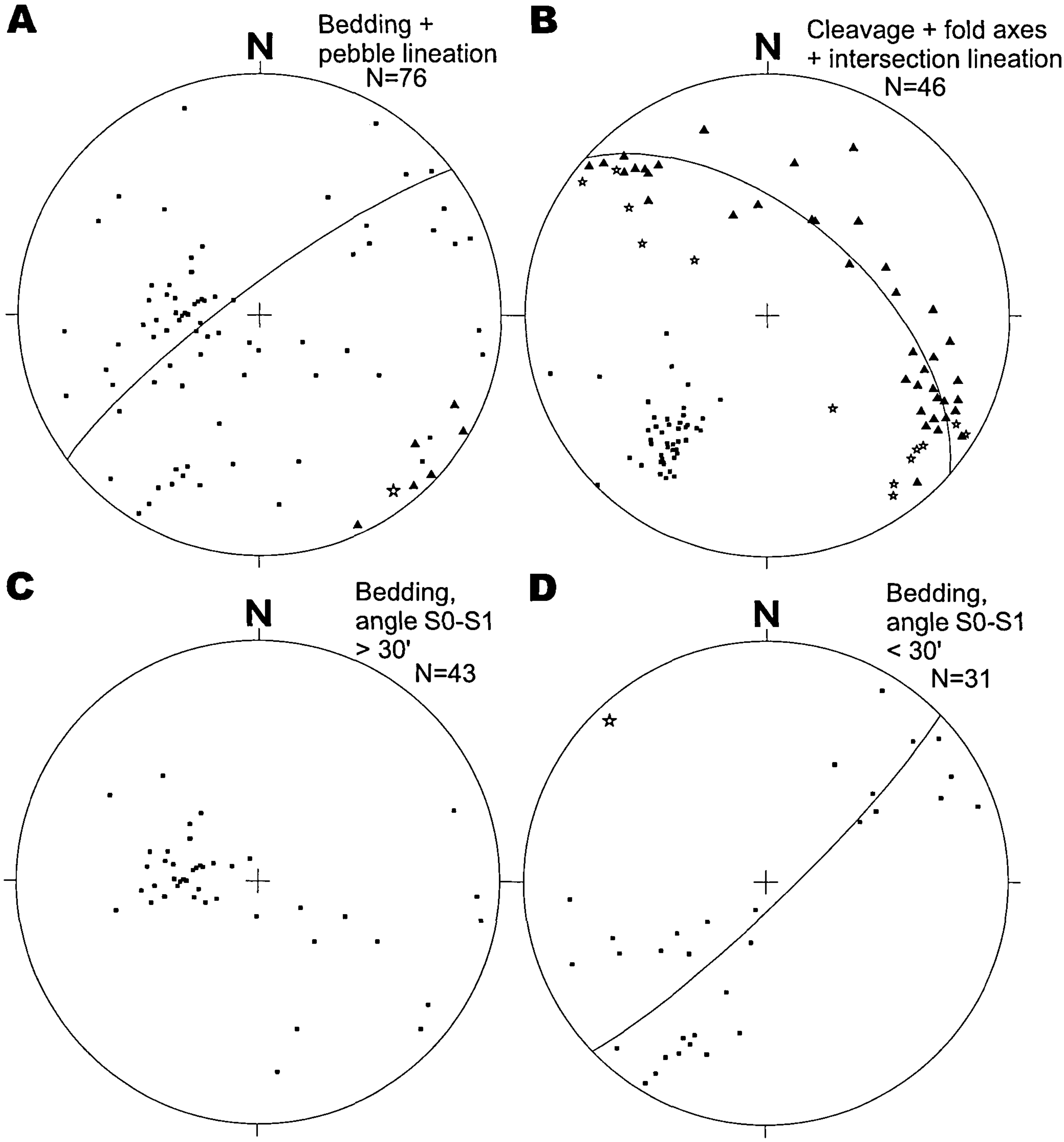


Fig. 9. Structural data from the Utvær islands, plotted on equal area, lower hemisphere stereonets. (a) Poles to bedding (squares) that plot along a crude great circle, indicating a SE-plunging fold axis (star). The pebble lineation is plotted as triangles. (b) Poles to cleavage (squares) define an average great circle. The intersection lineation (S_0-cleavage) is plotted as triangles, whereas recorded fold axes are shown as stars. (c) Poles to bedding with an angle to the cleavage greater than 30°. (d) Poles to bedding with an angle to cleavage smaller than 30°. The poles plot along a great circle that defines a NW-plunging fold axis.

Fig. 10. (a) Photograph of well-cleaved Devonian conglomerate, showing strong transposition, and with a high angle between bedding and cleavage. Note the sigmoidal shape of the clasts, whose long axes are parallel to the cleavage. (b) Photograph of Devonian conglomerate-sandstone, showing bedding and near-parallel cleavage.

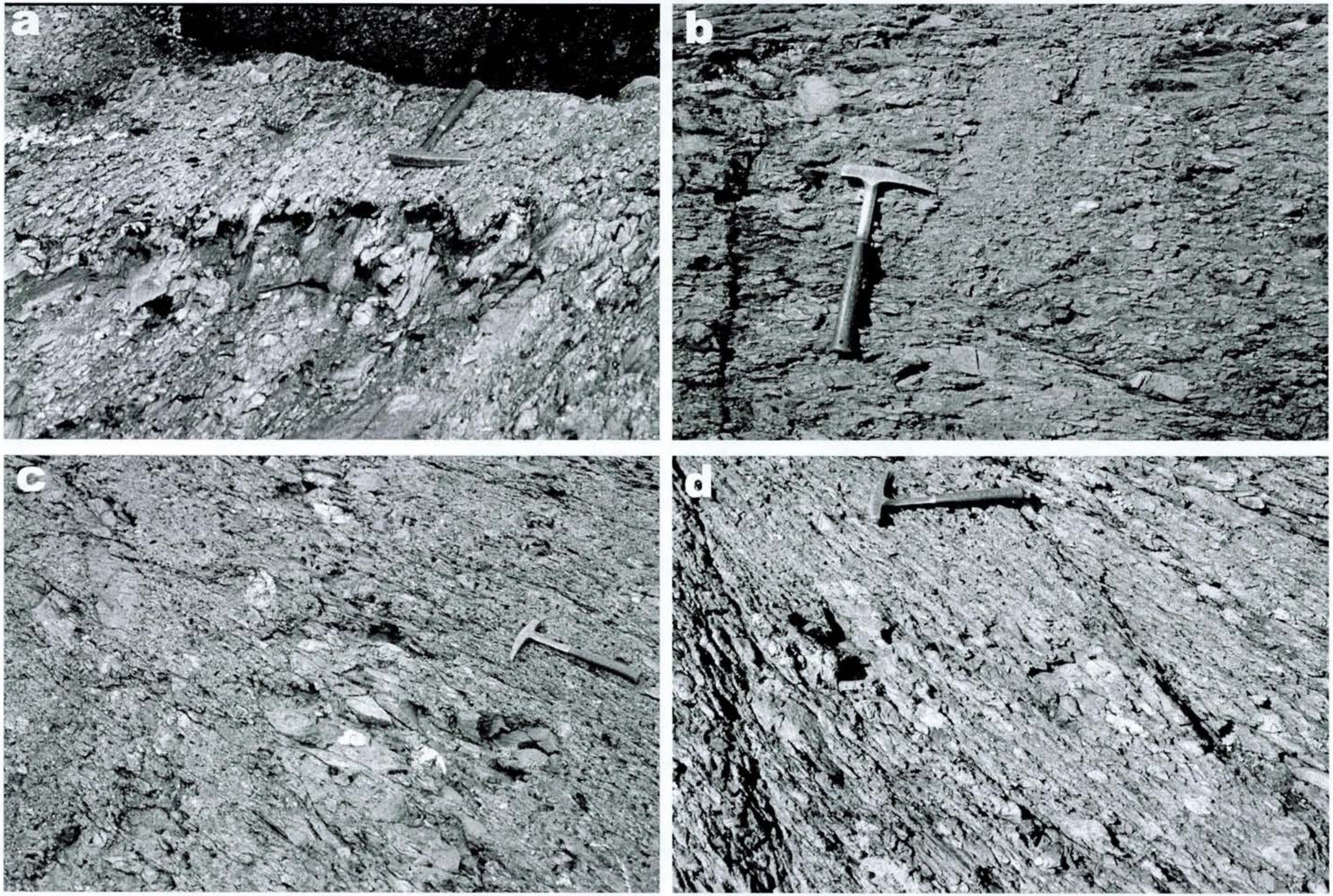

a
b
c
d

Fig. 11. (a) Photograph of a tight to isoclinal fold in the Devonian conglomerate. A pronounced cleavage is developed along the axial plane. (b) Photograph of a folded sandstone layer (parallel to hammer) in the conglomerate, which is shearedout and transposed into the cleavage in both limbs. (c) Photograph of transposed layering in the conglomerate ('vertical' = top - bottom), with an oblique angle to the pronounced cleavage. (d) Photograph of transposed layering in the conglomerate (right - left), with an oblique angle to the pronounced cleavage (lower right – upper left). The layering is entirely obliterated and transposed into the cleavage in the lower left coner.

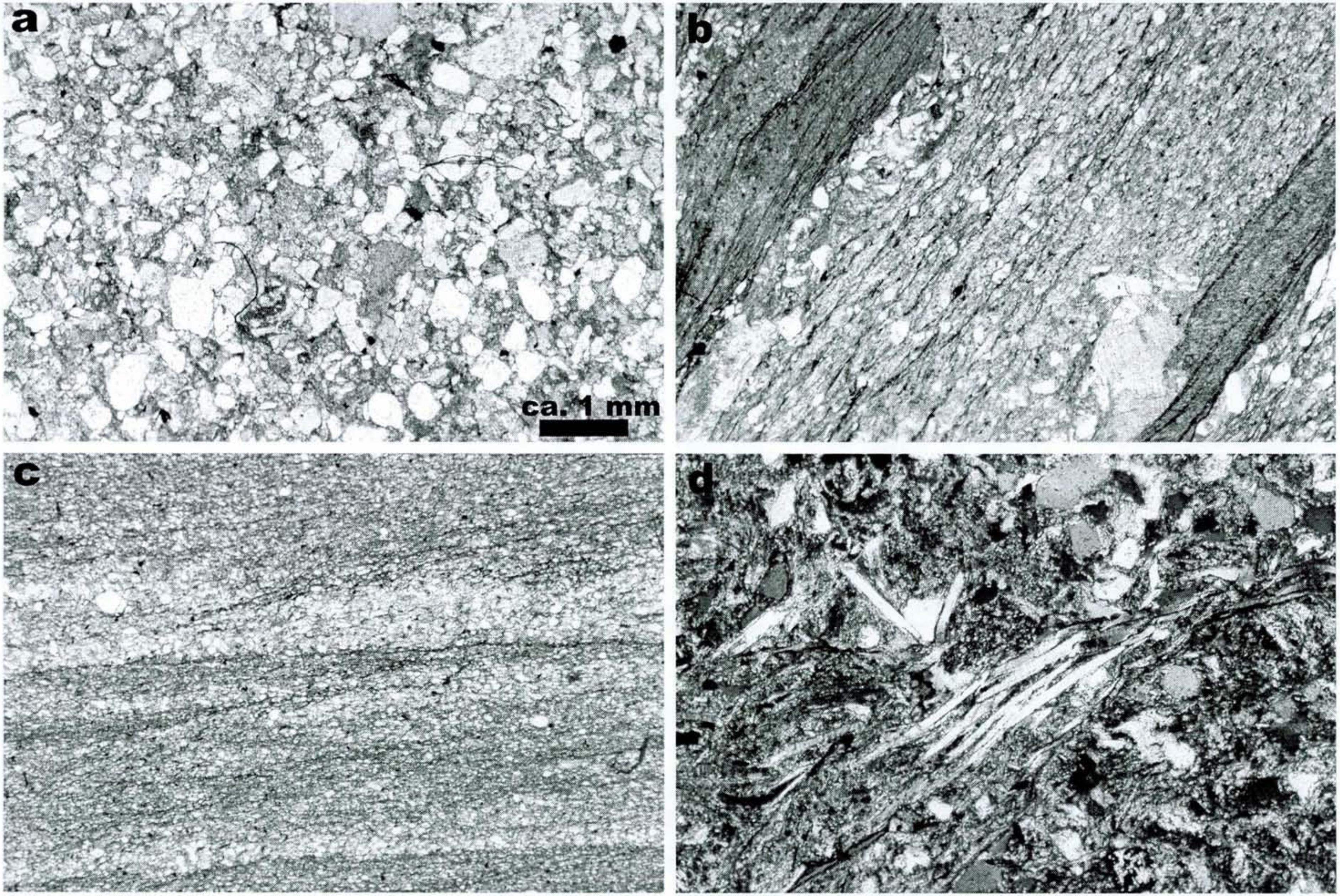
One of the most spectacular features of the deformation of the Devonian sedimentary rocks, is the degree of *transposition* of primary sedimentary features, e.g. bedding, into the cleavage (Fig. 11a, b, c, d). This transposition is so advanced that, in places, the rocks have the appearance of coarse-grained fragmentary gneisses, and the bedding is very difficult to discern (Fig. 11d). In some sandstone horizons the only visible structure is the cleavage. The effects of pressure solution are very marked and the flat, almost discoidal shapes of many of the pebbles are to a large measure a result of selective solution along cleavage surfaces. In some of the finer grained lithologies the rocks take on a crude striping parallel to the cleavage representing solution-concentrated metamorphic segregations. Locally, many quartz veins are developed and these can be seen to be both syn- and post-tectonic, in relation to the folding.

3.2 Metamorphism and metamorphic textures of the Devonian rocks

Because of the grain/clast size distribution of the Devonian rocks, thin-sections have been made of thin siltlaminæ, thin sandstone bands and gravel conglomerates. Typical undeformed varieties of sandstones and siltstones are grain supported and moderately to poorly sorted, with a tendency for bimodal grain size. They consist mainly of variably grained quartz with subrounded to angular shapes, surrounded by a very fine matrix of quartz(?), carbonate and chlorite, subordinate epidote and white mica (=phengite?) (Fig. 12a). With increasing strain, a pronounced tectonic fabric is developed (Fig. 12b, c). This fabric is developed both from the alignment of elongated clasts and of single grains, and in the surrounding sandy-silty matrix. Elongated clasts have been rotated into subparallelism with the fabric and quartz grains changed into sigmoidal shapes due to pressure solution, as shown by solution cleavage segregations. Internally, they reveal granoblastic-polygonal aggregates, and/or undulose extinction, whereas the margins generally are characterised by extensive sub-grain formation. The cleavage, although well developed in the matrix, commonly has an anatomising pattern through and around larger clasts. Locally, it also occurs in phyllosilicate-rich clasts, as a crenulation cleavage/pressure-solution cleavage. This is defined by μm-wide dark bands of very fine- to fine-grained, sub- to anhedral chlorite and quartz, the latter sometimes in rods, and in addition epidote, carbonate, phengite and opaque minerals. Typically, chlorite and phengite define a semi-schistose texture. Pressure shadows around larger grains/clasts are well developed, and show a somewhat larger grain size than that in the cleaved matrix. The pressure shadows consist mainly of subhedral chlorite and quartz and, in places, euhedral phengite. The latter also occurs as medium-sized, sub- to euhedral, cleavage-subparallel grains (Fig. 12d), and more rarely as small, medium-grained porphyroblasts, either alone or together with chlorite, epidote ± biotite. Similar pressure shadows, developed around deformed clasts, have been observed in the deformed conglomerates on Lifjell. These pressure shadows also contain small grains of phengite in the recrystallised, essentially quartz-dominated mosaic.

In summary, the tectonometamorphic fabric in the sandstones and conglomerates is semi-schistose in nature, with a cleavage defined mainly by chlorite and some phengite. Other characteristic minerals include recrystallised quartz and epidote with sporadic, small biotite porphyroblasts. This mineral paragnesis is indicative of lower greenschist-facies metamorphic conditions. The metamorphic grade and the textures developed are very similar to those recorded by Bøe et. al. (1989) from the Hitra-Smøla area.

Fig. 12. (a) Photomicrograph of well preserved pebbly sandstone from Begla island (Fig. 5). This rock is grain supported and moderately to poorly sorted, with a bimodal grain size, and shows subrounded to angular quartz grains. The surrounding matrix is very fine grained and consists of quartz(?), carbonate and chlorite, subordinate epidote and white mica (=phengite). (b) Photomicrograph of cleaved gravel conglomerate from Utvær. The dark clasts are chlorite-mica schist. Note that elongated clasts have been rotated into subparallelism with the fabric, and quartz sandgrains have sigmoidal shapes due to pressure solution, as also shown by solution-cleavage segregations. The pronounced cleavage of the matrix has an anatomising pattern through and around larger clasts. (c) Photomicrograph of cleaved pebbly sandstone from Utvær. Note the low angle between bedding and the pressure-solution cleavage. (d) Photomicrograph of cleaved sandstone from Utvær, showing a semi-schistose texture defined by euhedral phengite that occurs as medium-sized, sub- to euhedral, cleavage-subparallel grains. The photograph also shows some small, medium-grained phengite porphyroblasts.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4. DISCUSSION

Many recent accounts emphasise the extensional regime responsible for the opening of the Lower to Mid Devonian sedimentary basins (see Andersen 1998 for overview). They link this opening to upper crustal faulting above regional extensional shear zones (e.g., Nordfjord-Sogn Detachment) that rejuvenated easterly-directed Caledonian thrust zones. Recent $^{40}Ar/^{39}Ar$ thermochronology work (Fossen & Dunlap 1998; Fossen & Dallmeyer 1998) indicate that thrusting in the central part of the orogen in southern Norway ended at around 408 Ma, albeit still continuing in the foreland, and that top-to-the-west, extension-related shear commenced at around 402 Ma.

In western Norway, supra-detachment deformation of the extensional regime is recorded, for example, as an orthorhombic pattern of normal faults considered to have developed in close association with deposition in the Kvamshesten Devonian basin (Osmundsen 1996; Osmundsen et al. 1998). Osmundsen et al. (1998) suggest this to reflect chiefly E-W and subordinate N-S biaxial stretching during deposition of the upper, main parts of the succession, whereas the depositional distribution for lower parts indicates an earlier, approximately NW-SE extension. They also state that "further E-W extension was accompanied by N-S shortening, resulting in extension-parallel folds and thrusts ...". This idea of synchronous extension and shortening represents a view held by several authors, and has been explored in several recent publications that emphasise the importance of constrictional strain (Chauvet & Seranne 1994; Hartz & Andresen 1997; Osmundsen et al. 1998; Krabbendam & Dewey 1998). In this type of modelling the general geometric frame is envisaged as that of:-

(i) an extensional setting for the basins above the detachment zone,
(ii) regional and rather significant E-W folding of the same basins, and of the underlying detachment and gneiss region,
(iii) apparent minor folding of the uppermost detachment, i.e. the narrow brittle faults.

In order to fit these observations together, by claiming that they are closely related, Krabbendam & Dewey (1998), for example, proposed a regional transtensional model for exhumation of the Western Gneiss Region. According to this model, the deformation is considered to have been controlled by dominant sinistral transcurrent movement along the Møre-Trøndelag Fault Complex, whereas progressive partitioning of strain southwards resulted in combined extension and subordinate contraction. They also revived the idea that shear along the Nordfjord-Sogn Detachment initially produced a ductile mylonitic foliation. During uplift, the deformation progressively became more brittle and was finally dominated by narrow zones of cataclasites separating the Devonian basins and other hangingwall rocks from the underlying ductile detachment zone (e.g., Norton 1985; Seranne & Seguret 1987). Brittle faults truncate the regional E-W folds of the basins and the ductile detachment zone (Andersen & Jamtveit 1992; Torsvik et al. 1997; Osmundsen et al. 1998; Braathen 1999). The apparent scoop shape of some of the faults has been taken as a basis for continued N-S shortening during their formation (Krabbendam & Dewey 1998; Osmundsen et al. 1998). This scoop shape of the brittle faults, and their proposed Devonian age, has been questioned by Braathen (1999), mainly on a basis of the established age of Permian and Mesozoic fault rocks of this region (Torsvik et al. 1992; Eide et al. 1997). Braathen (1999) also addresses the apparent regional distribution of these faults, and their kinematics. Similar post-Caledonian faulting has also been established farther east in the Caledonian belt. Southeast of Sognefjorden, fault rocks in the Lærdal-Gjende (Jotun) fault zone have provided Permian and Jurassic-Cretaceous ages (Andersen et al. 1999), indicating a much wider distribution of such faulting than hitherto appreciated.

Three questions remain crucial for the validity of the synchronous extension-contraction models:

(i) Why are no angular unconformities recorded in the Devonian basins?

(ii) Could transtension with minor associated shortening produce regional tight folds, and overturned bedding and contacts in the lower and northern limbs of these folds?

(iii) How could shortening with associated metamorphic textures in the Devonian rocks be coeval with deposition of the same rocks?

So far, the answers to these questions remain ambiguous, although they would tend to discredit models for synchronous extension and N-S shortening. Hence, alternative models, bringing in the importance of metamorphism and contractional strain, may equally well fit the above outlined general observations; for example, a polyphase evolution, including a major and regional contractional phase, as explored in the following sections.

The first-order feature of such a contractional phase would be the E-W folds, recorded in western Norway (Fig. 1c) and far to the east, in the Otta and Røragen districts. Folds of ENE-WSW to NE-SW trend also affect Devonian rocks in the Hitra and Smøla areas some 200 km to the northeast. On a more local scale, and parasitic to the regional folds, is the intense folding and associated structures developed on the islands of the outer Utvær group (Figs. 5 and 7). These structures attest to the high strains operating during deformation, and not least shown by the considerable flattening which has occurred in the long limbs of the folds. The style of the tectonic structures described above is one which is normally associated with a compressional, or, at most, transpressional (Roberts 1983) mode of deformation, and not one which would be expected to develop in an extensional tectonic regime. In particular, the overturned basement-cover contact attests to this. The high degree of transposition of primary features during folding and cleavage development, together with the exceptional degree of pebble rotation attests to a fairly high level of rotational strains during the deformation. These features, combined with the highly non-cylindrical pattern exhibited by the bedding/cleavage lineation, indicate that the folding and cleavage development was accompanied or succeeded by strong flattening deformation, at least locally.

Seranne & Seguret (1987) also observed the phenomenon of pebble rotation into a tectonic cleavage, in the mainland part of the Solund field, but they described this fabric as relating to *"down dip-slip shearing of soft conglomerate"*. However, they also recognised the fact that, in the conglomerates of the southern margin of the Solund Devonian, many of the pebbles had undergone ductile deformation. The latter has also been previously featured by Nilsen (1967). Strongly deformed, elongated and flattened pebbles of very varied petrology can be observed in the near-coastal sections from Nesøy to Losna, and on the upper southern scarp slope of Lifjellet (Fig. 2). It can be observed that similar strains have affected the matrix of the conglomerates, showing that the rock succession was thoroughly indurated, and not *soft sediment*, as would be required by Seranne & Seguret (1987). These deformed pebbles include both quartzites and vein quartz showing that quartz has been deformed in a ductile maner above its temperature threshold. Furthermore, pressure shadows to such deformed pebbles contain small grains of phengite in addition to quartz, a phenomenon also recognised by Bøe et al. (1987) in the deformed conglomerates on Smøla. The mylonites beneath the greenstone slices, along the coastal section west of Lifjellet, are also greenschist-facies rocks. The strong ductile deformation exhibited by this southern zone of deformed conglomerate attests to the deformation having occurred at not inconsiderable crustal depths, i.e. below that of the brittle-ductile transition zone.

The deformational features described from the Utvær group of islands show that the Devonian rocks have been subjected to considerable tectonic strains during the greenschist-facies metamorphism. The style of structures and the syntectonic metamorphism recorded are indicative of a compressional deformational regime at intermediate crustal depths. This bears a number of resemblances to the tectonothermal development of the Devonian rocks of Hitra and Smøla (Bøe et al. 1989). In that study, it was shown that the Devonian rocks were strongly folded on both the mega- and mesoscopic scales, and that a regionally penetrative cleavage, decorated by phengite, was developed in the lower part of the greenschist-facies. PT estimates for this metamorphism are in the range 4.1-4.8 kbar and 300-350°C (Bøe et al. 1989), and preliminary K-Ar age dating indicates a Late Devonian age for the metamorphism. Metamorphic phengite has also been reported from the Håsteinen Devonian field in cleavage and shear zones (Torsvik et al. 1987). Torsvik et al. (1986) also reported phengitic white micas from the cleaved facies of the Kvamshesten Devonian field. Roberts (1974) was, in fact, the first to draw attention to the development of phengite as a characteristic feature of deformed Devonian rocks; showing how phengite developed in the tectonic cleavage of the Early Devonian sediments of Røragen, 40 km east of Røros. Until now, accounts of the uplift history of southern Norway have not incorporated the metamorphism of the Devonian basins, as well as the unroofing of their substrata, in the modelling (e.g., Dunlap & Fossen 1998).

It has now been shown in many accounts that the Devonian rocks of Norway have been affected by upper anchizone or greenschist-facies regional metamorphism (Roberts 1974, 1983; Sturt 1983; Steel et al. 1985; Torsvik et al. 1986, 1987, 1988; Bøe et al. 1989). Recently, Svendsen & Jamtveit (1999), in accepting that the Devonian rocks of the various 'basins' are affected by greenschist-facies metamorphism, have studied the various mineralised veins. The veins cut the Devonian rocks and contain mineral assemblages which are also typical of greenschist-facies. Certain veins in the Solund area are reported to contain biotite and amphibole (not specified), in addition to quartz and calcite. This accords well with the present account of widespread presence of the metamorphic assemblage phengite-chlorite-epidote in the strongly deformed rocks of the Outer Solund area. Svendsen & Jamtveit (1999), however, ascribe the vein mineralogy to a combination of load and hydrothermal metamorphism. The present authors cannot agree with this view and consider that, on the basis of the evidence presented above concerning the deformation and metamorphism of the Utvær island group, the metamorphism in the Solund and Hitra/Smøla regions is of the regional dynamothermal type. Other features of the Solund Devonian field that can be applied to support this view include:-

- the ductile deformation of conglomerates in a metamorphic matrix (see above),
- the development of phengite in pressure shadows,
- the presence of a greenschist-facies metamorphic assemblage in mylonites at the base of thrust slices on Lifjellet.

The various lines of evidence of deformation and metamorphism from the Devonian rocks of Norway indicate that the entire assemblage has undergone, to varying degrees, regional and local folding, cleavage development, thrusting and regional metamorphism in a compressional orogenic mode. This is by no means incompatible with the extensional deformation taken to be responsible for the formation of the Devonian basins, or for that which affects these and underlying rocks during Mid-Late Permian and Late Jurassic-Early Cretaceous times (Andersen et al. 1999). It implies, however, that the rocks of the Devonian fields, after their deposition and deep burial, have been involved in a comprehensive phase of tectonothermal development in a largely compressional regime - *the Solundian phase.* The implications of this are quite profound and require the siting of deformation and metamorphism at depths consistent with the metamorphic assemblages, rather than interpret them as a products of abnormal heat flow attendant on the extensional opening of sedimentary basins.

This would imply that compressional tectonics had not ceased with the emplacement of the great *thrust nappes* during the Scandian orogeny. As yet, this would appear to be non-predictable from much of the recent literature, which appeals essentially to extensional tectonic regimes to explain the vagaries of both the opening of sedimentary basins and their subsequent tectonothermal development. None of the palaeotectonic reconstructions to date allow for a continuation of subduction-related or collisional processes into Mid-Late Devonian times. This is perhaps strange as during this period the Appalachian Belt of eastern USA-Canada was virtually contiguous with the Caledonides. In the NE Appalachians, a period of regional, penetrative deformation and metamorphism occurred during latest Devonian to Early Carboniferous times (366-350 Ma), the *Neo-Acadian episode.* The tectonothermal development of this episode is uncertain, but its character is believed to favour a process of crustal delamination (Robinson et al. 1998).

At least two scenarios can be envisaged for the Late Devonian – Early Carboniferous, regional compression phase in south-central Norway. Firstly, there are no reconstructions of the NW European Caledonides that involve subduction-related features in this period. However, there is a logical candidate for a Mid-Late Devonian, subduction-related, island-arc assemblage in the strongly calc-alkaline bimodal volcanic rocks of Middle Devonian age in the sedimentary-volcanic sequences of the Walls Formation of Shetland, and in similar successions of northwest Shetland and the Eday lavas of Orkney (Mykura 1976, Thirlwall 1981, 1983, Astin 1983). Thirlwall (1983), in fact, states that geochemically the "*Shetland lavas show most of the characteristic features of modern arc volcanics*". These volcanosedimentary rocks were folded and cleaved, developing phengite, during greenschist-facies metamorphism (Torsvik et al. 1990), i.e., an almost identical situation to that of the rocks described in the present account. This folded assemblage was then cut by the Mid-Late Devonian plutonic assemblage of the West Shetland Igneous Complex, also with a strongly calc-alkaline character (Mykura 1976 a, b). Work on spores, from the Shetland volcanic sequences, indicates that they are all of Middle Devonian age, and it is well established that the Eday lavas of Orkney are Givetian (upper Middle Devonian). It is also of interest that considerable developments of Middle Devonian acid volcanic rocks are found in the Kap Franklin and Canning Land areas of SE Greenland, and that these are cut by granite plutons (Escher & Watt 1976). Unfortunately, there appears to be little modern petrochemical data published on these rocks

These rocks, together with those of Shetland, thus form an extensive belt of volcanic/plutonic complexes. As pointed out by Thirlwall (1983), "*There seems little doubt...that the Shetland ORS lavas, and the Eday lavas of Orkney, are related to subduction and probably developed relatively close to the former site of subduction*". He further suggests that the closure of Iapetus, in this region, was "*probably as late as Mid-Devonian*". Thus, a tempting scenario is that the *Solundian phase* deformation and metamorphism of the Devonian sequences of the Scandinavian Caledonides results from collision between an island arc, sited near Shetland, and the continental block of Baltica.

An alternative model focuses on regional transpressional tectonics (Roberts 1983; Sturt 1983; Braathen 1999). Braathen (1999) discusses the possibility that overall N-S compression in the Sunnfjord region was related to and controlled by sinistral transpression along the Møre-Trøndelag Fault Complex. In this scenario, contractional and mainly ductile deformation in the Sunnfjord region was progressively succeeded by brittle faulting that recorded a change from N-S shortening to synchronous shortening and E-W extension and extrusion.

5. CONCLUSIONS

The Devonian clastic succession of the islands of the Utvær group, in outer Solund, has together with its substrate been involved in strong contractional deformation under greenschist-facies metamorphic conditions. This deformation produced a series of tightly appressed folds in the sequence, and the deformation fabric is dominated by a penetrative cleavage into which the pebbles have been rotated. The metamorphic parageneses are characterised by the development of phengite and chlorite and formed in the lower temperature part of the greenschist-facies. In the authors' opinion, this deformation is the same as that which produced a well-marked cleavage with pebble rotation in the southern part of the Solund field. Along the southern margin of the Solund, considerable ductile strains were experienced by the conglomerates, again associated with greenschist-facies metamorphism. Evidence of such metamorphism is also found in syn- and post-tectonic mineralised veins. It is concluded that this metamorphism is of the dynamothermal regional type. A very similar tectonothermal development is recorded in the Devonian fields of Hitra and Smøla, where phengites indicate pressures in the range 4.1- 4.8 kbar, signifying deformation and metamorphism under an appreciable crustal cover.

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