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Steep shear zones in the basement and associated deformation of the cover sequence on Karmøy, SW Norwegian Caledonides

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Abstract—The allochthonous rocks of Karmøy, SW Norwegian Caledonides consist of three major geological units. The two oldest units (basement), the Karmøy Ophiolite intruded by the granitic rocks of the West Karmøy Igneous Complex (minimum age 445 Ma), were polyphasally deformed and metamorphosed prior to the deposition of the Skudeneset Group of Upper Ordovician/Lower Silurian age. During the end Silurian (Main Scandinavian Phase) orogenic deformation, the basement was cut by a series of linear steeply eastwards dipping shear zones with a NNW–SSE trend that can be followed on Karmøy and the off-shore islands for more than 40 km. Within the basement, mylonite zones with a well developed LS fabrics were formed, while the sediments were folded into asymmetrical folds with middle limb excision. In the sediments an axial planar cleavage and pronounced pebble orientation/elongation developed paralleling the LS fabric in the mylonites. Based on reorientation of dykes in the sheeted dyke complex of the Karmøy Ophiolite it can be shown that sinistral shear strain (γ = 6–7) was operative across the zones. For the whole of the area the sense of shear was sinistral and the eastern blocks invariably moved upwards.

INTRODUCTION

KARMØY is located on the southeastern margin of the SW Norwegian Caledonides in an allochthonous position (Fig. 1) and consists of three major geological units. The oldest unit is the Karmøy Ophiolite (Sturt & Thon 1978a, Sturt *et al.* 1979 and in press), which was deformed and metamorphosed under middle/upper greenschist facies conditions during an early Caledonian (late Cambrian/early Ordovician) orogenic phase (Sturt *et al.* in press, Furnes *et al.* in press). This deformation predated the intrusion of the granite rocks of the West Karmøy Igneous Complex (W.K.I.C.). Late granodioritic dykes yield a minimum age of 445 Ma (Rb/Sr whole rock, $\lambda Rb^{87} = 1.39 \times 10^{-11}a^{-1}$) for the emplacement of this complex. The basement represented by the ophiolite and the W.K.I.C. is overlain by a transgressive metasedimentary cover sequence, the Skudeneset Group (Fig. 1, Inset map A and Fig. 2a) of mainly coarse clastics (conglomerates and sandstones) where an Ashgill shallow marine fauna (Broch *et al.* 1940) has been identified in the Hilleslandsvatn Formation (Fig. 2a). The basal contact of the Skudeneset Group represents a major regional stratigraphic unconformity (Sturt & Thon 1978b).

During the end Silurian (Main Scandinavian Phase, Roberts & Gale 1978) orogenic deformation, the basement was cut by a series of linear steeply eastwards dipping shear zones, or rather ductile deformation zones (Mitra 1978). These have a NNW–SSE trend that can be followed on Karmøy and the off-shore islands for more than 40 km along strike (Fig. 1). Within the basement linear belts of mylonitic rocks were developed, while the Skudeneset Group was folded into a series of asymmetric folds with strong middle limb excision coinciding with the mylonite zones (Fig. 1). In the mylonite zones a variably intense LS mineral fabric developed (Fig. 1,c,d,e,g and h) and in the Skudeneset Group an axial planar cleavage, S_1, and a pebble orientation/elongation, L_1, (Fig. 1,a,c and f) in general paralleling the LS fabric in the mylonite zones. Evidence for differential simple shear across mylonite zones as outlined by Ramsay & Graham (1970) and Beach (1974) is best seen where the mylonite belts cut across the sheeted dyke complex of the Karmøy Ophiolite on Feøy (Fig. 1). Here the original vertical sheeted dykes have an original trend towards NNE (Sturt *et al.* 1979 and in press), see rosediagram on Fig. 1. The dykes become progressively rotated towards parallelism with the shear zones indicating a simple shear strain in the order of 6–7. Sinistral horizontal displacement within one zone 100 m wide then becomes 600 – 700 m. Where there is a stratigraphical control, in the Skudenset Group area, Fig. 2 (a) & (b), it can be shown that the eastern block moved upwards (between 500 and 700 m) and towards the west.

BASEMENT DEFORMATION

West Karmøy igneous complex

This consists of a series of acidic intrusions varying in composition from quartzdioritic to granitic which has undergone a polyphasal and protracted series of intrusive and deformational events (Ledru 1978 and in preparation). The W.K.I.C. is cut by a series of well developed mylonite zones with a maximum thickness of about 500 m, the most important of which can be traced from the Skudeneset Group in the south towards Mannes in the north (Fig. 1). Several such mylonite belts can be followed further west within the W.K.I.C. (Ledru 1978 and personal communication 1979), along the margin between the Karmøy Ophiolite and the W.K.I.C. and within the Karmøy Ophiolite (Fig. 1). On the regional scale the belts are linear and well defined, but in

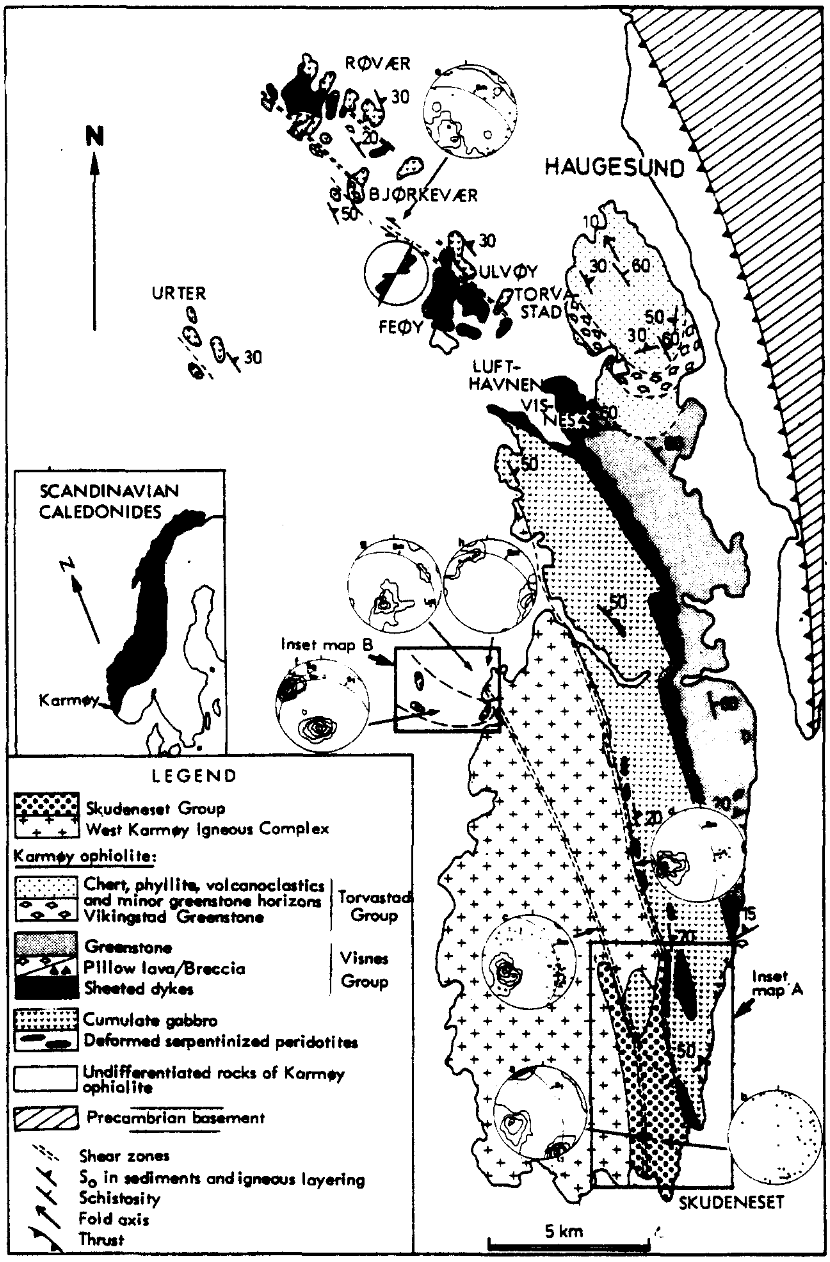

Fig. 1. Generalized geological map of Karmøy and adjacent islands (modified after Sturt *et al.* 1979). Structural diagrams are referred to as Fig. 1 a,b,c,d,e,f,g and h respectively. Structures are plotted on Lambert equal area projection, lower hemisphere. (a) Poles to S_1 cleavage in Skudeneset Group (302 obs), max S_1, 158°/53 NE. Contour intervals 1, 5, 10, 15 max 17.3%. Pebble orientation/elongation, L_1 in shear zone, Falnes Fm, (98 obs), max. 152°/13. Contour intervals 1, 5, 10, 20, 40, max. 51.5%. (b) Primary pebble orientation, Falnes Fm (43 obs). (c) mylonite foliation, S_m, Homravatn area, in West Karmøy Igneous Complex. Max. S_m, 156°/48 NE. Contour intervals 1, 5, 10, 15, 20, max. 30.8%. Pebble orientation/elongation (29 obs) in Indre Holmavatn Formation. Lineation in S_m (27 obs). (d) Mylonite foliation, S_m, along contact between Karmøy Ophiolite and West Karmøy Igneous Complex (49 obs) Max. 161°/63 NE. Contour intervals 1, 5, 10, 15, 20, max. 30.6%. Lineation in S_m (12 obs). (e) Low grade shear zones in Karmøy Ophiolite, Feøy–Røvær area (83 obs). max. S_m 124°/58. Contour intervals 1, 5, 10, max. 21.7%. Lineation in shear zone (17 obs). (f) Poles to S_1 cleavage in Skudeneset Group, islands west of Mannes (49 obs), max. S_1, 104°/44 NE. Contour intervals 1, 5, 10, 20, 35, max. 42.8% Pebble orientation/elongation, L_1 (43 obs), max. 298°/20. Contour intervals 1, 5, 10, 20, 40, max. 62.5%. (g) Mylonite foliation, S_m, Mannes–Marøyni area (69 obs) max. S_m, 127°/35. Contour intervals 1, 5, 10, 20 max. 26.5%. (h) Lineation in S_m, Mannes–Marøyni area (75 obs), max. 124°/17. Contour intervals 1, 5, 10, max. 15%. Rose diagram refers to orientations of sheeted dykes, North Feøy (324 obs). Diameter of rose diagram represent 20% concentration (after Sturt *et al.* 1979).

detail several zones of high strain are recorded, varying in thickness from a couple of cm up to 50 m. Within the belts, areas of less strain are preserved containing earlier structures. The early structures in general have a similar trend to the shear zones (Ledru 1978), but their early age is confirmed by the presence of clasts with early structures in the conglomerates of the Skudeneset Group. The early structures are often intensified and rotated into parallelism with the mylonite foliation. In the area between the main mylonite zone and the contact between the W.K.I.C. and the Karmøy Ophiolite the new schistosity is developed over a wider area with no discrete mylonite zones. The more complex pattern within the main mylonite zone is illustrated on Fig. 3(a) from the Mannes–Marøyni area.

The main fabric in the mylonite zones is a greenschist facies foliation (S_m) dipping between 45 and 70 degrees to the east-northeast, (Fig. 1,c,d & g) defined by biotite, muscovite, chlorite, epidote and lenticular aggregates of quartz and feldspar. Within the mylonite zones reduction in grain size of the original coarse (up to 2 cm) quartz and feldspar is typical. Phyllonites are locally found and here the amount of mica increases at the expense of feldspar. Thin veins of ultramylonite (up to 2 cm) are locally found within the most deformed parts. Pressure shadows around aggregates of lenticular quartz and feldspar are common. Within the mylonite foliation a shallow stretching lineation defined by lenticular quartz and feldspar is developed plunging to the southeast and northwest. This is notably developed in the Mannes–Marøyni area (Fig. 1h). Other structures developed are complex boudinage and pinch and swell structures. Locally the mylonite foliation may show the typical sigmoidal shear zone pattern (Ramsay & Graham 1970). The complex and polyphasal development of the fabric within the mylonite foliation is shown

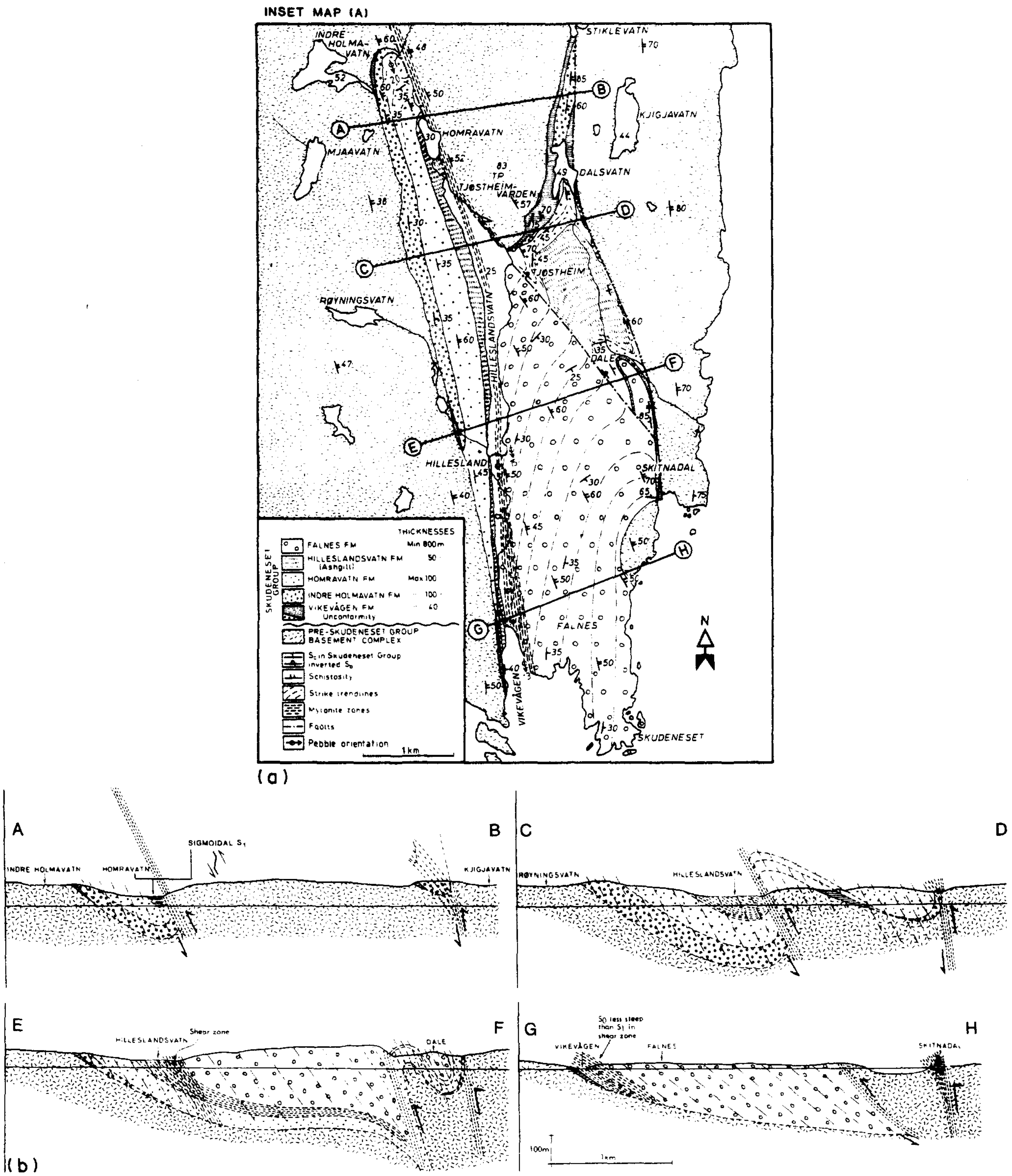

Fig. 2. (a) Inset map A, Fig. 1. Geological map of the Skudeneset Group, main area. (b) Geological cross sections, Skudeneset Group, main area.

in the area north of Mannes where Ledru (personal communication 1979) has observed late shear zones developed on the main mylonite foliation with development of new mylonites related to the shear zones indicating a movement towards the west-southwest, also with formation of local thrust zones.

Along the contact with the W.K.I.C. and the Karmøy Ophiolite the mylonite zones are steeper and the lineation has an eastwards plunge (Fig.1d). These steeper zones may be controlled by the rigid block of the Karmøy Ophiolite to the east and also by steepening of later faults.

Karmøy Ophiolite

Where the mylonite zones cut the Karmøy Ophiolite, flaser gabbros and retrograded greenschists are developed. From Fig. 1 it is clear that the mylonite zones are mainly developed along the contacts of different units within the Karmøy Ophiolite, pointing to the control of older structures by the location of the mylonite zones. Poles to the mylonite foliation in Karmøy Ophiolite are shown in Fig. 1(e). A variably developed shallow northeast–southwest mineral lineation and small scale folding is also observed within the S_m of the Karmøy Ophiolite (Fig. 1e). The best evidence for rotation during the shear zone development comes from the north Feøy region (Fig. 1). Here the vertical sheeted dykes of the Karmøy Ophiolite have a pre-shear trend to the NNE which is approximately at right angles to the shear zones (Fig. 1, rose diagram). The dykes are here progressively rotated into almost parallelism with the shear zones and chlorite schists are developed. The original dyke trend is again regained on the northeastern side. Preliminary calculations of shear strain across such zones indicate shear strain in the order of 6–7 for the most intensely deformed parts, always with a sinistral shear component. The thickest shear zone yet observed here is about 100 m, which would give a sinistral displacement in the order of 600 - 700 m. Numerous such zones, normally less than 10 m wide can be seen along the northwestern coast of Feøy.

DEFORMATION OF THE SKUDENESET GROUP

The Skudeneset Group with a minimum thickness of 1.1 km (Fig. 2a) was deposited on the polyphasally deformed and metamorphosed basement of the Karmøy Ophiolite and the W.K.I.C. Sedimentological studies (Thon in preparation) indicates that the Skudeneset Group was deposited in fault controlled basins with sediment transport from the west and northwest. The Skudeneset Group is now preserved in asymmetrical synclines in three areas (Fig. 1), i.e. the main Skudeneset area in the south (Fig. 2a & b), the islands west of Mannes and on the northwesternmost skerries in the Urter area (Fig. 1). I will here confine the discussion to the two major areas, the Skudeneset area and the islands west of Mannes.

Main Skudeneset area

The unconformity is preserved on the western limbs of the synclines (Fig. 2 a & b) and is best seen in the Hilleslandsvatn–Indre Holmavatn area and in the area north of Tjøstheim. Sedimentary structures such as erosional channels, cross bedding and grading are here well preserved. A low grade axial planar cleavage, S_1, is well developed having a similar orientation to the mylonite foliation S_m (compare Fig. 1a & c, see also profiles Fig. 2 b.) As we approach the excised limb of the fold in the Homravatn valley, the cleavage becomes increasingly sigmoidal (Fig. 2b, profile A–B) consistent with shearing out of higher units of the fold. In the most undeformed rocks the cleavage is a typical result of pressure solution and rotation of old detrital micas, the metamorphic grade is very low (chlorite grade). Within the excised limbs white mica starts to crystallize along the cleavage. Asymmetrical pressure shadows develop around former clastic quartz grains which now become lenticular quartz aggregates. Associated with the mylonite zones in the sediments is a marked pebble orientation/elongation (Fig. 1a), best seen in the conglomerates of the Falnes Formation in the Vikevågen–Hilleslandsvatn area (Fig. 2a & b). At Vikevågen an anomalous cleavage/bedding relation is observed within the mylonite zone where bedding locally is less steep than cleavage within a zone 100 m wide. The preferred orientation of conglomerate clasts is very marked in the mylonite zones and contrasts markedly with the random primary orientation of the clasts from the Falnes Formation outside the zone (Fig. 1b). In the Homravatn valley (Fig. 1c) the conglomerate is extremely flattened and elongated over an area of 150–200 m adjacent to the major mylonite belt and it is difficult to distinguish pebbles from matrix. Pebble orientation shows more variation in this zone than further south (compare Fig. 1a & c) which may reflect flattening strain superimposed on a primary pebble orientation. In the eastern outcrop of the Skudeneset Group south of Skitnadal (Fig. 2a, profile G–H) a slice of the W.K.I.C. is thrust over the conglomerate. The igneous rocks here are in an extremely brittle condition and no banded mylonites are developed along the contact, except for local bands of ultramylonite or flinty crush rock.

Where the main mylonite zone from Mannes runs into the Skudeneset Group it splays into two branches, the main branch running down Hilleslandsvatn towards Vikevågen following approximately the contact between the Hilleslandsvatn Formation and the Falnes Formation. The other branch continues with a more southeasterly trend towards Skitnadal (Fig. 2a), and when followed towards the southeast, develops into a high angle fault with minor mylonite development. The same type of fault is also found in the Urter area (Fig. 1).

Islands west of Mannes

Here the unconformity is not directly exposed and there is a gap of between 50 and 100 m between the

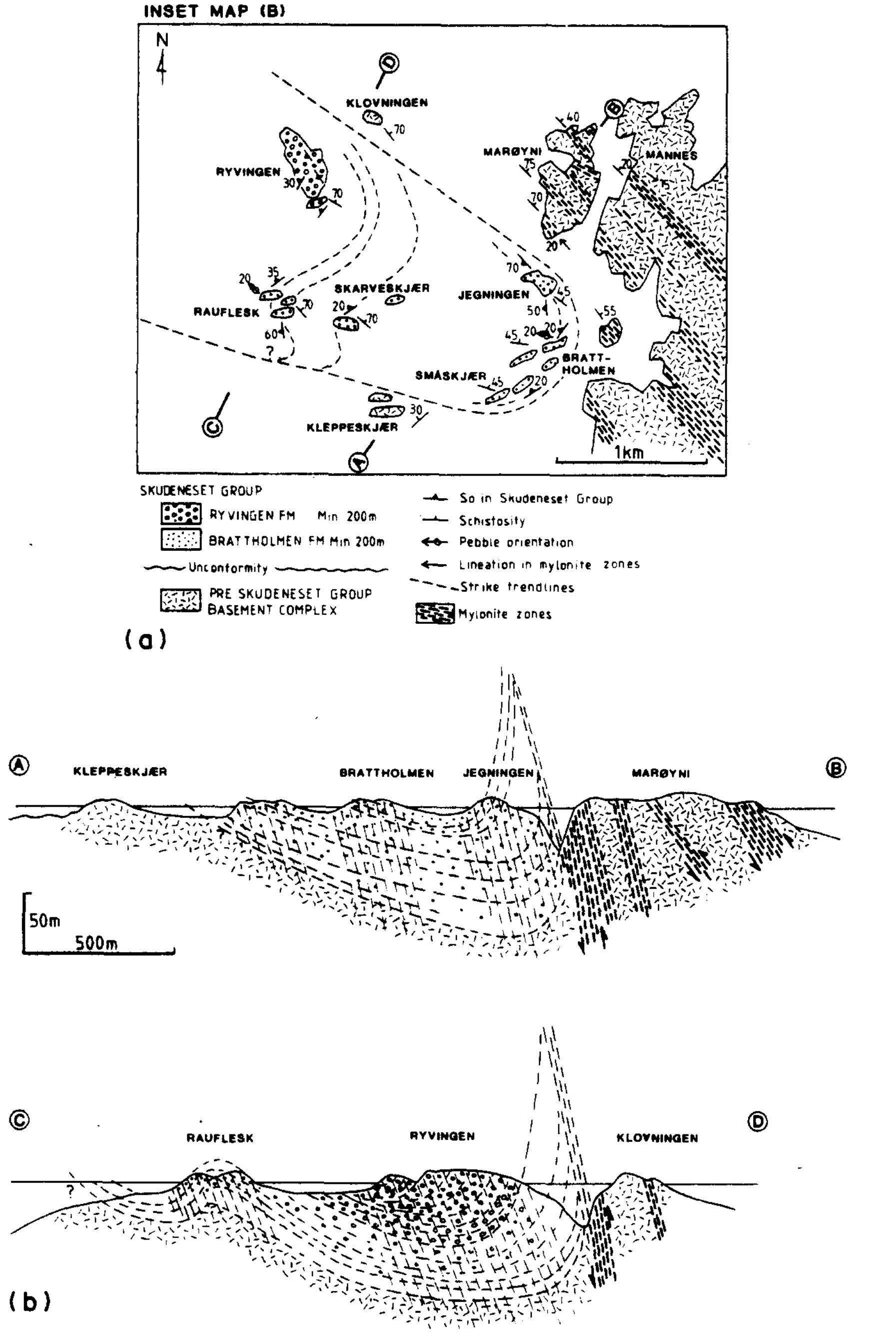

Fig. 3. (a) Inset map B, Fig. 1. Geological map of the Skudeneset Group, islands west of Mannes. (b) Geological cross sections, Skudeneset Group, islands west of Mannes.

W.K.I.C. and the Skudeneset Group. On a series of well exposed skerries the markedly asymmetric synclines are well seen (Fig. 3 a & b). Again a well developed axial planar cleavage is developed (Fig. 1 f) with a marked pebble orientation/elongation towards the west northwest. The metamorphic grade is apparently higher here than in the Skudeneset area as green biotite has crystallized along the S_1 cleavage. In the lowest formation of the Skudeneset Group in this area a series of quartz conglomerates is developed and marked pressure solution effects are observed at pebble contacts. When comparing the S_m mylonite foliation on Marøyni and Mannes with the S_1 cleavage in the sediments there is a marked difference in the trends (Fig. 1 f & g) of over 20°. At present the author has no explanation for this anomaly.

DISCUSSION AND CONCLUDING REMARKS

Ramsay & Graham (1970) showed how the LS mineral fabrics in the shear zones reflected the orientation of the finite strain ellipsoid and that the mineral lineation reflected the orientation of maximum elongation. Coward (1976) further showed how finite shear zones often depart from this ideal simple shear model and that also shortening or elongation would operate across such zones. Mitra (1978) then avoided the term shear zone and introduced the term ductile deformation zones for such belts of strongly deformed rocks. The mylonite zones of Karmøy and their associated lineation are thought to represent the result of a complex process where simple shear played an important part in the development of the structures. On the small scale typical sigmoidal schistosities developed. A major difficulty on Karmøy for the evaluation of the strain history in the mylonite belts is the presence of older structures with a trend generally similar to the mylonite zones. The strains in the cover sequence are also clearly controlled by the mylonite zones, with a maximum elongation within the shear zones and a marked linear maximum (Fig. 1 a & f). The high degree of linear parallelism in the conglomerate clasts, as contrasted with the crystalline rocks, may reflect deformation of the Skudeneset Group in an early stage i.e. prior to main consolidation.

The only strain markers which could be used for an estimation of shear strain in the Karmøy region with some degree of certainty are the sheeted dykes of Karmøy Ophiolite on Feøy. They have a geometrical form, if we do not consider variation in thickness and departure from the vertical, which will allow a calculation of the shear strain. Even here there are major difficulties. The sheeted dykes have a rather restricted distribution and also their trends are not always perpendicular to the shear zones. It is also clear from the preliminary work I have done that the shear strain in the different mylonite zones cutting the sheeted dyke complex shows strong local variation.

The complex and polyphasal development of mylonite zones is clearly shown by the work of Ledru (in preparation) in the northern part of the W.K.I.C. Here the main mylonite foliation gets reworked and new mylonites are developed in relation to new zones of simple shear. This late mylonite formation is related to local overthrusts to the west-northwest.

Taking all these limitations together it may still be concluded that the late deformation pattern on Karmøy is related to movements between rigid blocks with a sinistral shear displacement, and where the eastern blocks invariably moved upwards as seen on the geological profiles (Figs. 2b and 3b). This type of deformation probably reflects major structural weaknesses along trends with a NNW to SSE direction deeper in the crust. The older structural control can be deduced from several lines of evidence:

1. The Karmøy Ophiolite was already deformed during the early Caledonian orogenic deformation along basically similar trends as the shear zones (Sturt *et al.* 1979). This may reflect structures developed in relation to the creation of the Karmøy Ophiolite, i.e. during the oceanic stage (mid-ocean fracture systems etc.).
2. The contact between the Karmøy Ophiolite and the W.K.I.C. also has the same general trend. It seems likely that W.K.I.C. was emplaced along the early zones of weakness. This is supported from the orientation of syn-intrusion structures that also follow such trends (Ledru, in preparation).
3. Evidence for similar major mylonite zones is also found further east in the sound between Karmøy and Haugesund (Fig: 1). As we approach the sound intensely deformed rocks are developed. As yet no data exist from this area.

Evidence of this late westward movement associated with faults and shear zones is also found on the mainland to the east, where the latest set of folds always indicates a northwestward to westward movement deforming the whole nappe pile of the Hardangervidda–Ryfylke Nappe system (Anderson 1974). Evidence for the same westward movement has also been found in the pinched in synclines of the cover to the Ulriken Gneiss Complex of the Bergen Arc System (Thon in preparation) some 100 km further north.

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