The Structure of the Magerøy Nappe, Finnmark, North Norway

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Andersen, T. B. 1981: The structure av the Magerøy Nappe, Finnmark, North Norway. *Norges geol. Unders. 363*, 1–23.

The Magerøy Nappe was emplaced during the Scandinavian phase of the Caledonian orogeny, of Middle/Upper Silurian age. Two main episodes of deformation (D_1 and D_2) with attendant Barrovian-type regional metamorphism are recorded in the metasediments of Upper Ordovician/Lower Silurian age forming the Magerøy Supergroup (minimum thickness 5.5 km). The D_1 deformation produced overturned to recumbent regional folds which due to opposite vergence form a mushroom-like culmination in central Magerøy. D_1 folds east of the structural divergence zone are tight, recumbent folds with eastward vergence, while those to the west are overturned asymmetrical folds verging to the west. Textural and structural observations indicate that D_1 consisted of two deformational events (D_{1a} and D_{1b}) of which the later coincides with the final movements along the basal thrust of the nappe. The metamorphism reached its peak in the period between D_1 and D_2, and was accompanied by acid and mafic/ultramafic intrusions (417 ± 11 m.y., Finnvik Granite). D_2, which occurred under retrograde metamorphism, produced a large synformal structure, essentially coaxial with the F_1 folds, but with a subvertical axial surface. In the structural depression along the axial trace of this fold the highest structural levels of the Magerøy Nappe mushroom-structure, and an erosional klippe of a higher nappe, the Skarsvåg Nappe, are preserved. The F_2 folding of Magerøy is correlated with the late, large-scale buckling of the Finnmarkian phase nappes of the mainland in West Finnmark.

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Introduction

Studies during the last two decades in west Finnmark and northeast Troms, northern Norway, have shown that the orthotectonic Caledonides of the region comprise two major nappe sequences. These were deformed and metamorphosed through two, major, time-separated, orogenic events, which are known as the *Finnmarkian phase* (late Cambrian/early Ordovician) and the *Scandinavian phase* (middle/late Silurian) (Ramsay & Sturt 1976, Sturt et al. 1978, Sturt et al. in prep.). In the evolution of the Caledonides of northern Norway the Magerøy Nappe occupies a key position, being the only known nappe in the Finnmark sequence which records a post-Finnmarkian evolution and the tectonothermal characteristics of the Scandinavian phase. The emphasis in the present paper is placed on a description of the structural pattern of the nappe.

Geological setting and history of research

The island of Magerøy (lat. 71°N) contains three main tectono-stratigraphic units. Most of the eastern and central parts of the island (Fig. 1) are occupied by the Magerøy Nappe, underlain to the west by the Gjesvær Migmatite Complex (Ramsay & Sturt 1976) assigned to the Kalak Nappe Complex (Roberts 1974) of Finnmarkian age. In the Skarsvåg area of N.E. Magerøy a small erosional remnant of a higher nappe, the Skarsvåg Nappe, is present. This nappe represents the highest unit in the tectono-stratigraphy of Finnmark (Kjærsrud, in prep.). The junction between the Magerøy Nappe and the Gjesvær migmatites is a major thrust plane, the Magerøy Thrust (Ramsay & Sturt 1976). The Magerøy Nappe and the higher Skarsvåg Nappe have been preserved from erosion by downfaulting of the northern block on the Magerøysundet fault (Fig. 1). This fault separates Magerøy from the Porsanger Peninsula where rocks assigned to the Kalak Nappe Complex occur. The displacement along the fault is of unknown magntitude, but in addition to a dip-slip component there was probably a considerable component of dextral strike-slip.

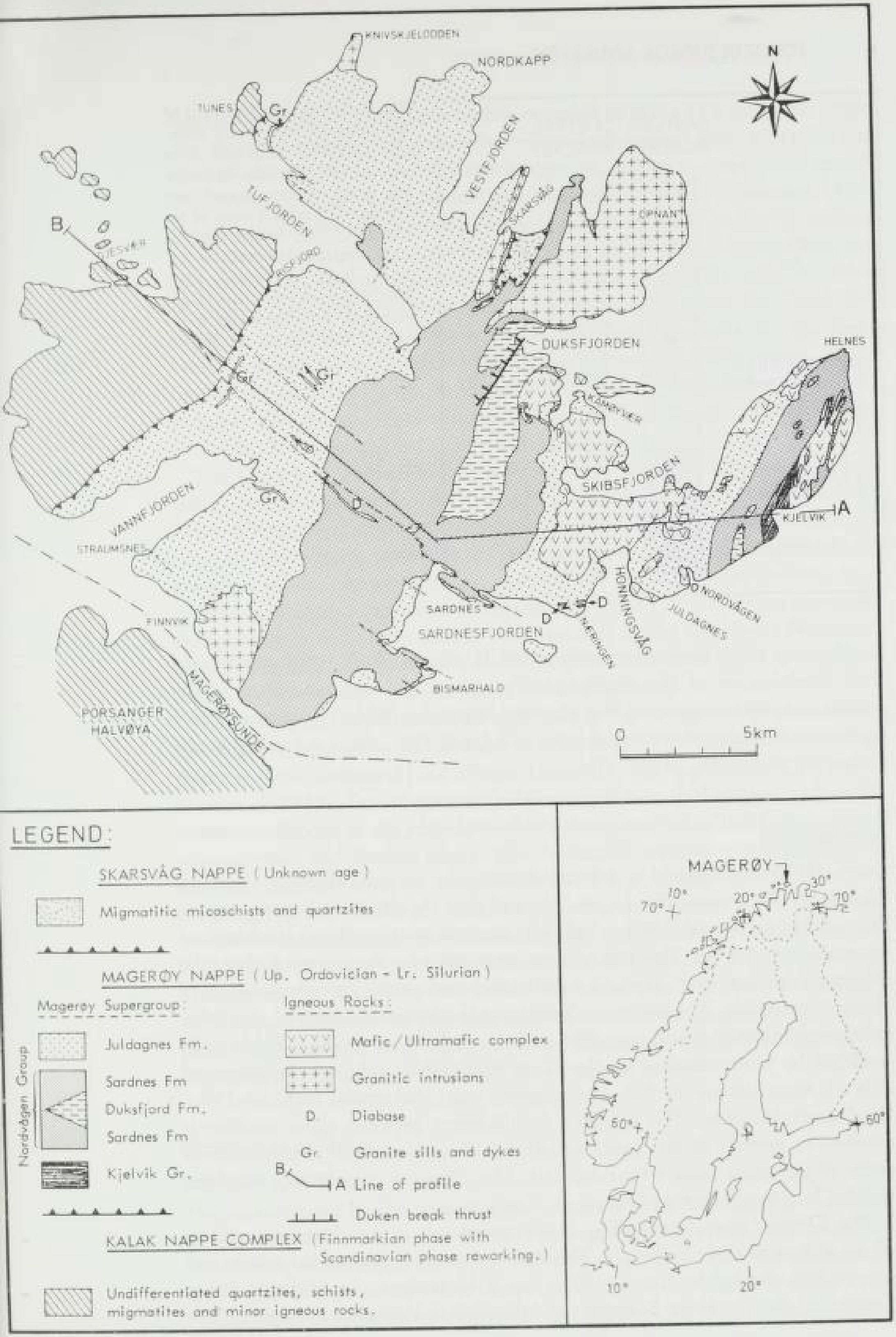
The discovery of a Lower Silurian fauna in eastern Magerøy (Henningsmoen 1961) posed a number of questions concerning the age and geological evolution of the Magerøy assemblage, which previously had been correlated with the autochthonous Eocambrian rocks of east Finnmark (Holtedahl 1944). This correlation was based on the lithological similarity between the so-called 'Duksfjord tillite' and the tillites of east Finnmark. The fossil discoveries prompted Føyn (1967) to re-examine the eastern and central parts of the island, where additional finds of fossils in the Sardnes area (Fig. 1) led him to conclude that the 'Duksfjord tillite' represented a Silurian intraformational conglomerate. This conclusion has since been supported by additional fossil-finds (D. M. Ramsay, pers. comm. in Curry (1975)).

In the late sixties and early seventies Curry (1975) carried out a more detailed study of eastern Magerøy. She established a preliminary lithostratigraphy, and on the basis of this demonstrated that the metasediments were folded in large-scale overturned to recumbent folds (D_1), resulting in extensive areas of inversion. She also recognized a second, less pervasive fold phase (D_2), and showed that the regional metamorphism was a Barrovian zonal sequence. Curry was chiefly concerned, however, with the mafic and ultramafic intrusive rocks of eastern Magerøy, which form an important syn-orogenic igneous complex.

In a study of the thrust-zone between the Magerøy Nappe and the Gjesvær migmatite complex, Ramsay & Sturt (1976) showed that the nappe was emplaced under metamorphic conditions which extended well into the amphibolite facies. They also recognized an extensive post-tectonic recrystallization of the mylonitized lithologies of the thrust zone, and concluded that the thrusting of the nappe had taken place during the D_1 event.

The work of Føyn (1967), Curry (1975) and Ramsay & Sturt (1976), together with a detailed structural analysis of a deformed conglomerate in eastern Magerøy (Ramsay & Sturt 1970), represented the only modern studies

Fig. 1. Geological map of Magerøy, compiled and simplified from the mapping by T. B. Andersen, C. J. Curry and K. Kjærsrud. The geological cross-section is shown in Fig. 3.



KNIVSKJELODDEN
NORDKAPP
N
TUNES
Gr
VESTFJORDEN
TUFJORDEN
SKARSVÅG
OPNAN
B
GJESVÆR
RISFJORD
DUKSFJORDEN
HELNES
Gr
KAMØYVÆR
SKIBSFJORDEN
KJELVIK
A
VANNFJORDEN
STRAUMSNES
HONNINGSVÅG
SARDNES
D
NORDVÅGEN
JULDAGNES
FINNVIK
SARDNESFJORDEN
NERINGEN
MAGERØYSUNDET
BISMARHALD
PORSANGER
HALVØYA
0
5km
LEGEND:
SKARSVÅG NAPPE (Unknown age)
Migmatitic micaschists and quartzites
MAGERØY NAPPE (Up. Ordovician - Lr. Silurian)
Magerøy Supergroup:
Igneous Rocks:
Nordvågen Group
Juldagnes Fm.
Mafic / Ultramafic complex
Sardnes Fm
Granitic intrusions
Duksfjord Fm.
D. Diabase
Sardnes Fm
Gr. Granite sills and dykes
Kjelvik Gr.
B A Line of profile
Duken break thrust
KALAK NAPPE COMPLEX (Finnmarkian phase with Scandinavian phase reworking.)
Undifferentiated quartzites, schists, migmatites and minor igneous rocks.
MAGERØY
10°
70°
20°
30°
70°
60°
60°
10°
20°

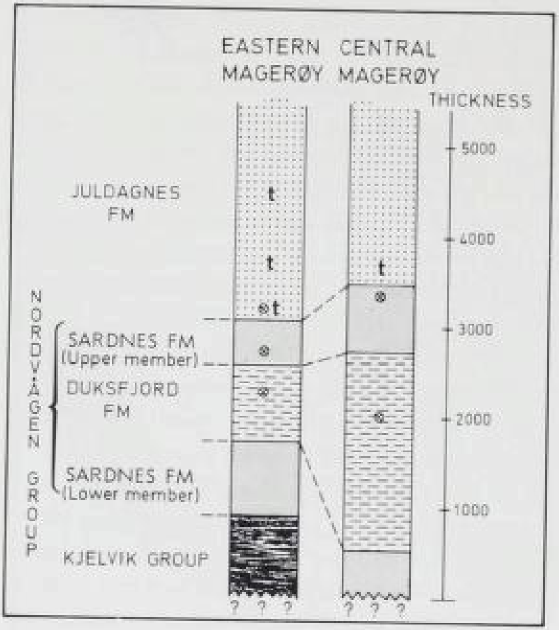


Fig. 2. Stratigraphic profiles of the Magerøy Supergroup showing thickness variations from the eastern (Kjelvik–Honningsvåg area) to the central part (Sardnes–Duksfjord area) of the island. Circled crosses and t's show stratigraphic levels at which body fossils and trace-fossils, respectively, have been recorded. All thicknesses in metres. For legend, see Fig. 1.

on Magerøy when the present author and K. Kjærsrud (in prep) commenced their investigation of the stratigraphy, structure and metamorphism in the central and western parts of the Magerøy Nappe in 1976. The present paper represents a shortened version of parts of a Cand. Real. thesis submitted at the University of Bergen, 1979.

Stratigraphy

Curry (1975) established a lithostratigraphy in eastern Magerøy, between Kjelvik and Næringen (Fig. 1), and showed that the Magerøy Supergroup (as defined by Andersen (1979)) had a minimum stratigraphical thickness of approximately 5.5 km. This area was re-investigated by the present author who effected a further stratigraphical sub-division and partial re-interpretation of Curry's succession. The sedimentological interpretation of some of the lithostratigraphical units is still uncertain, and the preliminary model is liable to be modified by future detailed studies. Two stratigraphic columns are presented (Fig. 2), from eastern (Kjelvik–Honningsvåg area) and central (Sardnes–Duksfjord area) Magerøy. The variation in thickness between these profiles is ascribed to primary lateral facies variation, although tectonic modification of some of the units cannot be ruled out. The Magerøy Supergroup has been divided into two following units:

The *Kjelvik Group* (900 m, Fig. 2) is exposed only in the immediate vicinity of the village of Kjelvik (Fig. 1). This unit consists of interbedded pelites and greywackes, divided by Curry (1975) into 3 formations, the Midttind Pelite Formation, the Transition Formaton and the Kjelvik Psammite Formation. The

Kjelvik Group was by the same author regarded as being of a turbiditic origin. The sequence displays progressively coarser and thicker greywackes towards the top (Curry 1975), and this is thought to reflect a progressive upward shallowing, possibly on a prograding submarine fan system (Andersen 1979).

The stratigraphically overlying *Nordvågen Group* (2180 m, Fig. 2) contains a complex association of metasediments. These include lensoidal bands of conglomerates, limestones, quartzites and greywackes of variable thickness. Most of the unit, however, consists of pelitic and semi-pelitic rocks. The Nordvågen Group is subdivided into 2 formations, the *Sardnes Formation* and the *Duksfjord Formation*. The Duksfjord Formation is laterally discontinuous, and in the eastern and central parts of Magerøy it divides the Sardnes Formation into an upper (500 m) and a lower member (825 m). The stratigraphic thicknesses given here are estimated from eastern Magerøy.

The Duksfjord Formation contains laterally persistent limestone horizons which, in the type locality between Nordvågen and Kjelvik, have yielded a Lower Silurian shelly fauna (Henningsmoen 1961). The fossils recorded include crinoids, brachiopods, favositids, halysitids, heliolitids and rugose corals. Interpretation of the depositional environment of the Nordvågen Group is at present inconclusive, although it appears that much of the group represents shallow-marine sediments. This is most evident in the Duksfjord Formation, where colonial corals have been found in growth position (B. A. Sturt, pers. comm. 1978) together with abundant crinoid fragments.

The *Juldagnes Formation* (2400 m, Fig.2) is the youngest unit preserved in the Magerøy succession. At the base monograptids of Lower Llandoverian age (Monograptus sandersoni) have been found (D. Skevington, pers. comm. in Sturt et al. 1975). Trace fossils are relatively common in the lower part of the formation. Species of the ichnofauna which have been identified include Protopalaeodictyon and Scolitia plana. The formation represents a typical flysch sequence with turbidites of intermediate facies type. In the type area between Honningsvåg and Nordvågen, sedimentary structures typical of turbidite sedimentation are well preserved. These include complete Bouma sequences, soft sediment deformation structures and solemarks. No variation of the depositional environment has been discerned within this formation. The flysch sediments of the Juldagnes Formation probably formed as a consequence of rapid relief-producing processes, most likely associated with early orogenic activity during the Scandinavian phase of the Caledonian orogeny.

Structural analysis

INTRODUCTION

The area mapped by the present author extends from Duksfjord in the north to Magerøysundet in the south, and covers approximately 160 km^2. Data from the adjacent areas mapped by Curry (1975) and Kjærsrud (in prep.) have been used in the interpretation of the overall structure of the Magerøy Nappe.

Two main deformational events can be discerned in the lithologies of the

Magerøy Nappe, D_1 and D_2. There is some indication that D_1 can be subdivided into two episodes of deformation D_{1a} and D_{1b}, separated by a short static interval. This is based mainly on textural evidence from the metamorphic assemblages. The following structural nomenclature symbols are used:

S_0 — Bedding.
D_1 — First deformational event.
D_{1a} — Earliest phase of D_1.
D_{1b} — Main phase of D_1.
S_{1a} — Slaty cleavage developed during D_{1a}, now preserved in cores of porphyroblasts
S_1 — Main planar structure developed during D_{1b} (schistosity in the west, slaty cleavage in the east).
F_1 — Folds developed during D_1.
L_1 — Lineations developed during D_1.
D_2 — Second deformational event.
S_2 — Cleavage (crenulation and pressure solution cleavage) developed during D_2.
F_2 — Folds developed during D_2.
L_2 — Lineations developed during D_2.

THE D_1 STRUCTURAL PATTERN OF THE MAGERØY NAPPE

Introduction

The internal D_1 structure of the Magerøy Nappe comprises 5 large overturned to recumbent folds (Fig. 3). In the eastern part of the nappe the folds verge towards east-southeast, while those in the west have a northwesterly vergence. This pattern of opposite vergence results in a domain of overall conjugate form in the central part of the island. In consequence 3 structural domains are identified:

1. East Magerøy (eastward vergence)
2. Central Magerøy (divergence of folds)
3. West Magerøy (westvard vergence)

THE D_1 STRUCTURE OF EAST MAGERØY

The D_1 structure of this domain (Fig. 3) is formed by a major coupled fold, the *Kjelvik anticline* and the *Pollneset syncline*. Curry (1975) identified the existence of both structures on stratigraphical grounds. The present author, however, disagrees with her interpretation of the geometry and facing of the structures. Curry regarded both folds as downward facing, and held that this pattern was a primary D_1 phenomenon rather than a result of refolding. The present author asserts that this is an incorrect and unnecessary complication of the structural pattern. The S_0/S_1 relations in all areas where younging and the F_2 geometry are recognized, vergence of D_1 parasite folds and the preserved main folds closures show that both of the large folds were developed as upward-facing structures. The hinge area of the Pollneset syncline was, however,

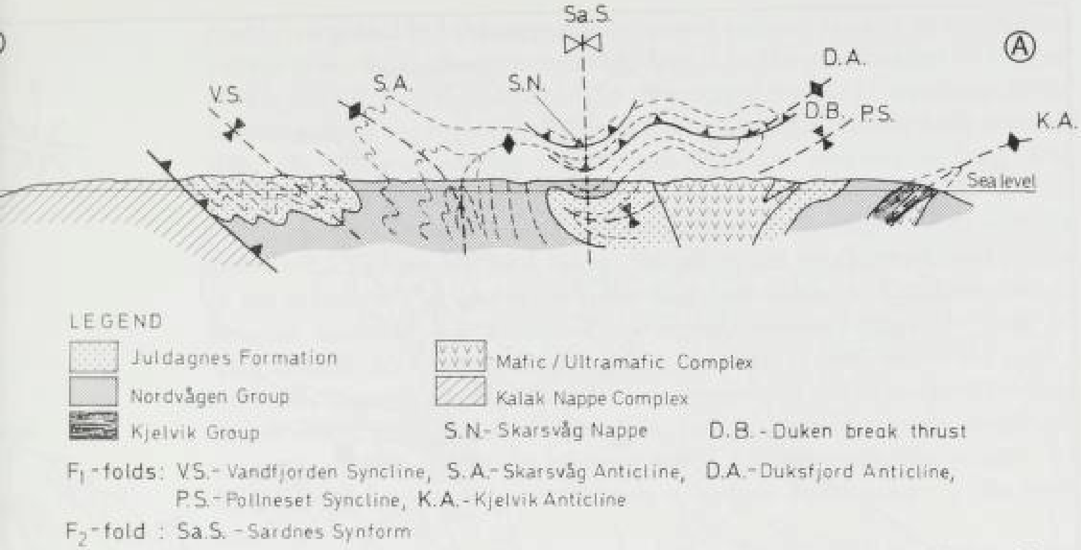


Fig. 3. Profile A–B of Fig. 1 showing the major fold structures of the Magerøy Nappe.

refolded during D_2 so that west of Sardnesfjorden (see Fig.s 3 and 4) it appears as an antiformal syncline. This is only the situation west of the axial surface of the F_2 Sardnes synform (se below and Fig. 5B) where the dip direction of S_0 and S_1 was changed during D_2.

The hinge zone of the Kjelvik anticline is located in the vicinity of the village of Kjelvik. It is not possible to observe the fully developed inverted limb because of the trend of the coastline. Parts of both the Kjelvik Group and the Nordvågen Group are, however, inverted northeast of Kjelvik. Much of the structural pattern of this area has been obliterated by the contact metamorphism associated with the gabbroic bodies of the mafic/ultramafic igneous complex. The common limb of the large coupled fold, is continuously exposed between Kjelvik and Næringen (Fig. 4). The degree of deformation varies considerably depending on the relative competence of the lithologies, as was also shown by Ramsay & Sturt (1970). The present steep dips of S_0 and S_1 are largely the result of F_2 refolding.

The D_2 deformation has considerably modified the geometry of the Kjelvik anticline, but as the F_2 folding of the area appears to be homoclinal (i.e. the original direction of dip is unchanged), the facing of the F_1 fold is preserved. By unfolding the effects of D_2, the F_1 fold appears to have been developed as an upward-facing anticline, with axial surface dipping 30° W. The plunge of the axis was 013°/7° prior to the F_2 refolding, the interlimb angle 27° and the approximate amplitude and wavelength was in the order of 7–7.5 km and 5 km, respectively. The unfolding of D_2 is an approximation as the pre-D_2 orientation of S_0 and S_1 is unknown. The easternmost area, however, is least affected by D_2 so the orientation of S_1 in this area is taken as the pre-D_2 orientation on which the unfolding is based. The reconstruction also assumes that S_1 had a subparallel development throughout the fold profile.

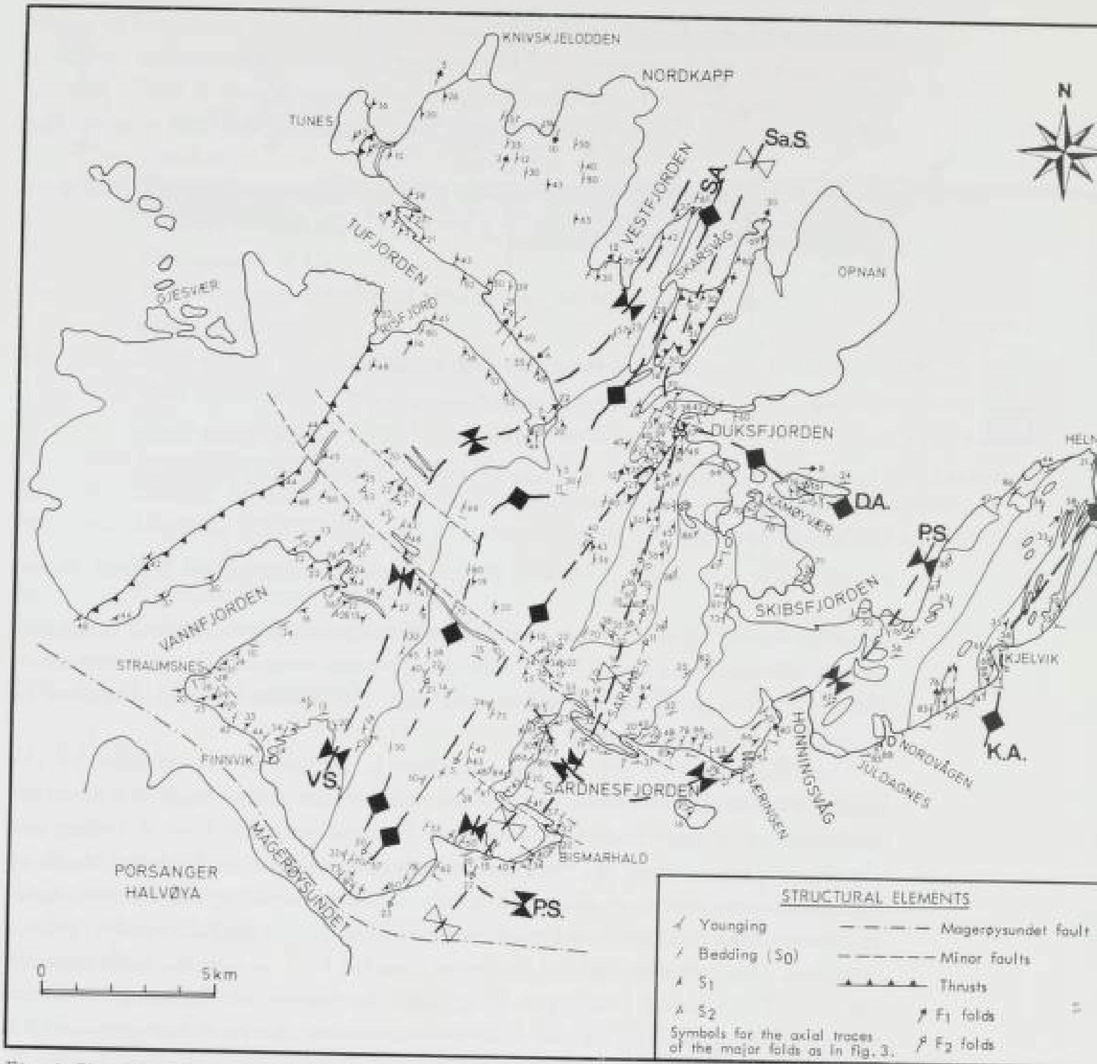


Fig. 4. Simplified map of representative structural elements in the Magerøy and Skarsvåg Nappes.

The Pollneset syncline is the complementary syncline to the Kjelvik anticline. The key area for establishing this fold is the shoreline exposure around Sardnesfjorden (Fig. 4), the hinge of the fold being well exposed in the Pollneset area, northwest of Sardnes. The existence of the structure was recognized by Curry (1975), but, as with the Kjelvik anticline, the original facing direction of the fold was misinterpreted. The relatively low metamorphic condition and deformational state of the metasediments in the Sardnes region accounts for good preservation of primary structures. This allows a good stratigraphic control around the closure of the fold from the normal to the inverted limb.

Unlike the area further to the east, the rocks of the Sardnesfjorden region have experienced strong D_2 overprinting. The D_1–D_2 interference pattern is readily recognized and the approximate co-axial surfaces produce an interference pattern (Fig. 5b, c) closely resembling *Type 3* in the classification of Ramsay (1967, p. 530). The change of the dip direction of the pre-D_2 structures in the western limb of the F_2 Sardnes synform has inverted the primary S_0/S_1 relationship. The Pollneset syncline in this area therefore now has the form of an antiformal syncline (Fig. 3).

The inverted limb of the Pollneset syncline is a common limb with the Duksfjord anticline described below. Owing to the gentle northward plunge of the axis (030°/10°), this particular fold limb forms an extensive tract of inverted strata in the Sardnes–Duksfjord–Karmøyvær region, an area of approximately 65 km². Much of the area, however, is occupied by the mafic/ultramafic igneous complex. Because of the presence of thick stratigraphic units, within which stratigraphic markers are lacking or only sparsely developed, mesoscopic parasite folds are rarely observed. Consequently, the vergence of the minor F_1 folds consistently shows a normal relationship to the main structures.

The dimensions of the Pollneset syncline are comparable to that of the Kjelvik anticline. The amplitude and wavelength are approximately 7.75 km and 5 km, respectively. Exact values for interlimb angle and attitude of axial surface are not given on account of the pronounced D_2 refolding, although it is clear that the fold is tight, i.e. interlimb angle 0–30° (Fleuty 1964), and originally approached a true recumbent fold.

THE D_1 STRUCTURE OF CENTRAL MAGERØY

Divergence of the large-scale F_1 folds in central Magerøy produced a domain of overall conjugate form. The box-fold-like polycline of this domain is formed by two, opposite-facing, overturned to recumbent anticlines; *the Duksfjord anticline* and the *Skarsvåg anticline*. The eastward-verging Duksfjord anticline is the better preserved, while the geometry of the westward-verging Skarsvåg anticline is more speculative due to the level of erosion. The structural domain of central Magerøy has an elongated NW–SE-trending shape (Fig. 1). The combination of northerly plunge of both the F_1 and the F_2 fold axes provides a section through different structural levels of the polycline from north to south, although the topographic relief never exceeds 350 km. From Duksfjord to Magerøysundet (approximately 18 km) a vertical section through 2.5 km of the polycline is exposed. The preservation of the highest levels of the D_1 structure in the Duksfjord area is largely due to the later downbuckling in the Sardnes synform (F_2).

The core zone of the polycline is best exposed along Magerøysundet and is formed by steep to vertical dipping strata of the Nordvågen Group. The D_1 deformation is strong and S_0 is transposed in the sub-vertical S_1 cleavage. The steep zone (S_0 between 50° and 90°) can be traced northwards for approximately 5 km, but poor inland exposures make detailed structural observations difficult. The strong D_1 deformation localized in this zone has destroyed most of the primary structures, and younging evidence is not preserved. There are,

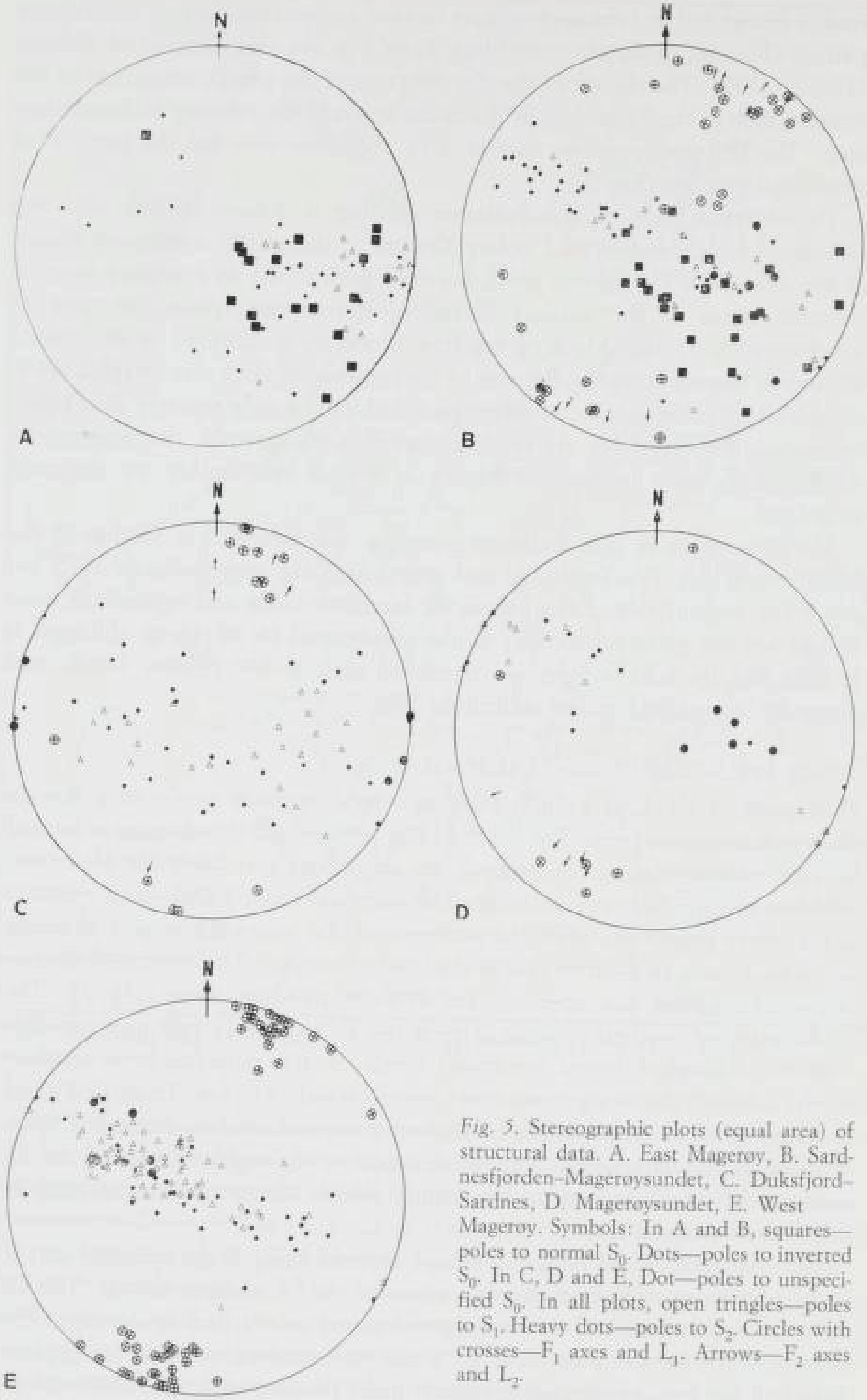


Fig. 5. Stereographic plots (equal area) of structural data. A. East Magerøy, B. Sardnesfjorden–Magerøysundet, C. Duksfjord–Sardnes, D. Magerøysundet, E. West Magerøy. Symbols: In A and B, squares—poles to normal S_0. Dots—poles to inverted S_0. In C, D and E, Dot—poles to unspecified S_0. In all plots, open tringles—poles to S_1. Heavy dots—poles to S_2. Circles with crosses—F_1 axes and L_1. Arrows—F_2 axes and L_2.

however, structures present in the transition zone between the Nordvågen Group and the Juldagnes Formation both to the east and to the west of the steep zone, which show that both stratigraphic boundaries are inverted.

In the Duksfjord area where the highest structural levels of the central polycline are preserved, the hinge of the Duksfjord anticline is highlighted by the outcrop pattern of the Duksfjord Formation. Relatively few primary structures are preserved, but the good stratigraphic markers provided by laterally persistent limestones allow correlations to be made over considerable distances. It is possible to extrapolate way-up from areas where evidence of younging can be found in close contact with the limestones. By using this method, in addition to the S_0/S_1 relationship, and taking the F_2 pattern into consideration, it can be seen that the entire area from Duksfjord to Sardnes is characterized by inverted strata on the inverted middle limb of the Pollneset syncline and the Duksfjord anticline. The lithologies cropping out to the west and north of Duksfjord form the upper, normal limb of the anticline. The outcrop pattern of the Duksfjord Formation indicates that a slide (Fig. 3) occurred between the two limbs. This tectonic break, the Duken break-thrust (Andersen 1979), was developed sub-parallel to the axial surface of the fold, enabling the upper, normal limb to translate further towards southeast over the inverted limb probably during late stages of D_1. Mylonitic fabrics are not observed, however, due to the penetrative post-D_1 recrystallisation in this part of the island.

The hinge zone of the Duksfjord anticline is characterized by a steep to sub-vertical sheet dip of S_0. Large-scale parasitic F_1 folds (amplitudes up to 500 m) have been observed in this area along the northern side of Duksfjord. In the closure of the F_2 Sardnes synform the pre-D_2 orientation of S_0 and S_1 has been retained. In this position the S_1 cleavage dips shallowly towards west. Away from the hinge of the F_1 anticline the upper and lower limbs are sub-parallel. This implies that the Duksfjord anticline had a pre-D_2, recumbent, sub-isoclinal profile. The restored axis of the Duksfjord anticline plunges at approximately 020°/15°. This is nearly coincident with the S_0/S_1 intersection lineation.

Only the lower limb of the Skarsvåg anticline is presently exposed, and this is responsible for the regionally inverted relationship between the Nordvågen Group and the Juldagnes Formation in west-central Magerøy. The sheet dip of S_0 on this limb is usually steep (40° E), while S_1 dips eastward between 20° and 30°. This S_0/S_1 relationship indicates inversion, in agreement with the evidence provided by sedimentary structures. The steep limb is strongly folded, and the long limb/short limb configuration of the parasites indicates that the main structure has a westward vergence. The abundant development of parasite folds on this limb indicates that the strain was strongly compressional. Parasitic structures of different orders of magnitude are developed, ranging in amplitude from centimetres to several metres. These folds are usually noncylindrical and have an incongruous (Ramsay & Sturt 1973) relationship to the main fold. The axis of the Skarsvåg anticline, in contrast to that of the Duksfjord anticline, appears to be sub-horizontal (020°/0°). The co-axial relation of F_1 and F_2 folds indicates that this was the primary trend of the F_1 fold. Because of the presence of the steep inverted limb with parasite folds of relatively low amplitude (compared to wavelength) it is likely that the Skarsvåg anticline was developed as an overturned, asymmetrical fold.

RECONSTRUCTION OF THE PRE-D_2 MORPHOLOGY OF THE CENTRAL POLYCLINE

The difference in geometry and fold profile development in east and west Magerøy is an important factor when trying to reconstruct the original shape of the central polycline. Several uncertainties in this reconstruction exist, particularly for the higher structural levels which have been largely removed by erosion. The F_2 refolding and poor inland exposures add further uncertainties to the accuracy of the model presented.

The coupling of the Duksfjord and the Skarsvåg anticlines produced a structural culmination with two hinges; i.e. a polyclinal anticline. Folds of this kind are normally classified as box or conjugate folds (Ramsay 1967). The two anticlines which form the conjugate structure have considerable contrast in fold profile. The Duksfjord anticline is a tight, recumbent structure, while the Skarsvåg anticline probably developed as an overturned, asymmetrical, open fold. The eastward transport of material in relation to the Duksfjord anticline was thus larger than the westward transport associated with the Skarsvåg anticline. The non-uniform geometry of the two folds resulted in an asymmetry of the profile of the polycline. The axes of the two anticlines also differ in plunge (D. A. 020°/15°, S.A. 020°/0°). This, together with the difference in fold profiles, gives the large-scale 'mushroomlike' polycline a geometry which is probably best described as a non-cylindrical asymmetrical box-fold.

THE SKARSVÅG NAPPE

East of the village of Skarsvåg a sequence of schists and quartzites crop out which are unlike the metasediments of the Magerøy Supergroup, both lithologically and in tectono-metamorphic development. This unit, the Skarsvåg Nappe, forms a relatively thin sheet-like body overlying the Magerøy Nappe. Presently it occupies a site within the core of the Sardnes synform, and in consequence of the northerly plunge of this fold it represents the highest structural level preserved on Magerøy. The lithologies of the nappe consist predominantly of variably migmatized mica schists, together with disrupted layers of quartzite. Work by K. Kjærsrud (pers. comm. 1979) indicates that these lithologies have suffered a more complex deformational history than those of the Magerøy Nappe, but a precise tectono-metamorphic history is not yet delineated. The contact with the Magerøy Nappe is characterized by high-strain fabrics. Particularly along the western margin of the Skarsvåg Nappe the lithologies have a mylonitic appearance. In this area rocks of the Magerøy Nappe, both metasediments and the granitic intrusion of Skarsvåg (Fig. 1), are strongly deformed towards the contact with the Skarsvåg Nappe. K-feldspar phenocrysts in the granitoid are augened in a strong schistosity developed parallel to the contact of the Skarsvåg Nappe. Kjærsrud (pers. comm. 1979) suggests that the intrusion of this igneous body occurred somewhat earlier (syn-D_1) than the emplacement of the Finnvik, Opnan and Knivskjelodden granites. The Scandinavian phase S_2 crenulation cleavage is penetratively developed in the Skarsvåg Nappe. The interpretation of the migmatitic mica schists and quartzites in the Skarsvåg area as a separate tectonic unit rests on the following arguments.

1) There is a strong contrast between the Magerøy Nappe metasediments and the Skarsvåg Nappe lithologies, and the present author cannot recognize these latter as part of the stratigraphy of the Magerøy Supergroup.
2) The structural development is apparently more complex and indicates a more involved tectono–metamorphic history than for the rocks of the Magerøy Supergroups.
3) The junction between the two units is the locus of high strains, which is characteristic of many thrust zones. This is best displayed along the western margin of the nappe.

Although detailed studies of these lithologies are not yet available, the present author proposes that the Skarsvåg rocks represent an individual tectono–stratigraphic unit (the Skarsvåg Nappe) separated from the Magerøy Nappe by a basal thrust zone. The Skarsvåg Nappe thus forms a higher nappe than the Magerøy Nappe in the tectono–stratigraphy of Finnmark, preserved as a small klippe within the core of the Sardnes synform.

Is is not possible to comment in absolute terms on the age of the lithologies of this nappe. Metasediments of similar character are well known from the type Sørøy succession (Ramsay 1971) of Eocambrian/Cambrian age (Holland & Sturt 1970). This sequence of metasediments forms a major constituent of the Kalak Nappe Complex. This nappe complex, however, also contains Precambrian elements (Brueckner 1973, Ramsay & Sturt 1977, Zwaan & Roberts 1978) and thus a possible Precambrian age for the rocks of the Skarsvåg Nappe cannot be ruled out.

THE D_1 STRUCTURE OF WESTERN MAGERØY

The Skarsvåg anticline forms part of the structural domain characterized by westward-verging folds. This area includes the part of Magerøy west of the central polycline, and east of the Magerøy Nappe basal thrust. The F_1 pattern is characterized by the development of macroscopic, asymmetrical to overturned, coupled folds. The most significant of these fold pairs is that formed by the above-mentioned Skarsvåg anticline and the *Vandfjorden syncline*. The fold style of this syncline can be readily identified as both limbs and the hinge are preserved. The syncline, mirrored by the minor parasite folds on the normal, long limb of the fold, is overturned and asymmetrical with an attenuated long limb and thickened, strongly folded, steep short limb. As a result of the pronounced deformation and metamorphic recrystallization, primary

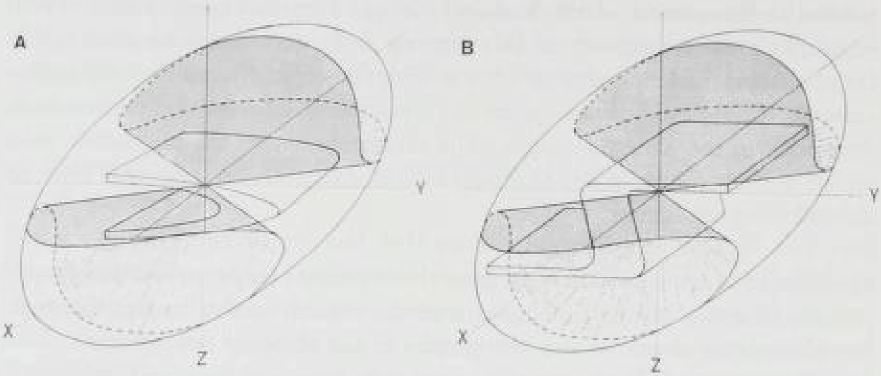


Fig. 6. A and B illustrate the difference in style of F_1 folds between eastern (A) and western (B) Magerøy. This is a result of different orientation of fold limbs in relation to the regional strain ellipsoid. The strain ellipsoids with surface of no finite longitudinal strain (shaded) shown for K-values of $\infty > K > 1$.

sedimentary structures are only sporadically preserved. Careful mapping was necessary to establish the mean dip of S_0, and thus locate the axial trace of the fold. The relatively simple F_2 refolding pattern, however, makes the S_0/S_1 relationship a valid criterion of younging. The large inter-limb angle of the large-scale asymmetrical folds produced a markedly different orientation of the limbs within the regional strain ellipsoid. This resulted in a marked contrast in the type of deformation observed in the limbs (Fig. 6). The steep short limbs were positioned in the field of compression which resulted in strong folding and tectonic thickening. The long limbs, however, were located within the extensional field and were strongly attenuated (Fig. 6b).

The structural pattern of D_1 is likely to have been produced through two successive stages with different orientation of the bulk strain ellipsoid.

1) An initial phase (early-D_1) with essentially tangential shortening with respect to the primary attitude of S_0. During this phase the present pattern of large-scale folds was set, though considerably modified during the late D_1 event.
2) The second phase (late-D_1) was characterized by strong flattening strains with attendant intense folding in the steep limbs and attenuation in the flat-lying limbs. This deformation may possibly have been associated with a process of 'gravity collapse', as a result of a combination of tectonic thickening of the nappe itself and a large overburden relating to higher nappe units.

This fold style in the western part of the Magerøy Nappe contrasts with that in the eastern part of the polycline. The development of relatively tight folds in the east produced an orientation of the limbs with approximately the same relative attitude in the bulk strain ellipsoid during the final flattening phase of strain. This resulted in a similar deformational pattern in both limbs of the

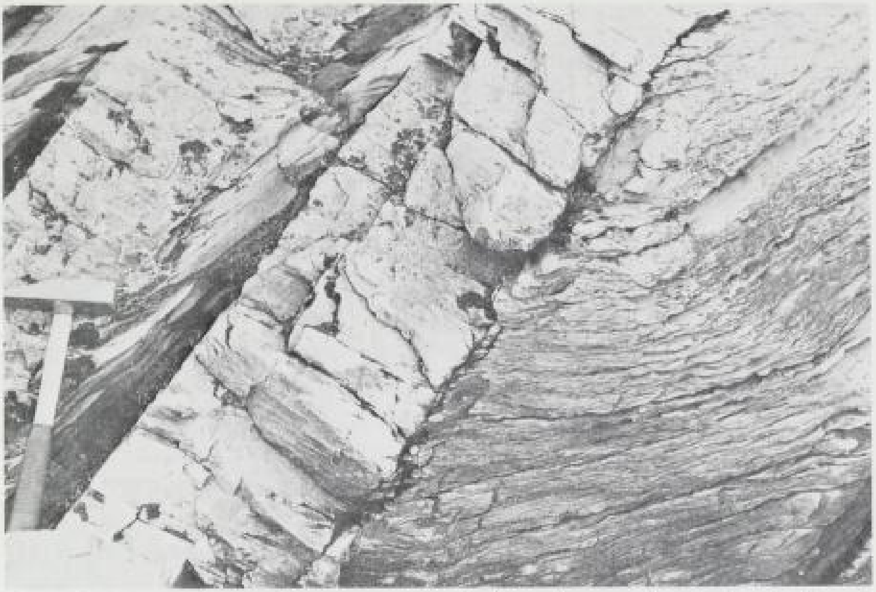


Fig. 7. S_1 cleavage refraction between coarse-grained sandstones and pelites/semi-pelites of the Sardnes Formation near the hinge of the Pollneset syncline, 2 km northwest of Sardnes.

D_1 folds. Accordingly, there is, apart from facing, no difference in fold style of the parasite folds in the normal and inverted limbs of the large-scale D_1 folds developed in eastern Magerøy.

THE D_1 EVENT: DISCUSSION

Based on mineralogical and textural studies it can be shown that the metamorphic conditions progressively increased during the D_1 event. In the east the metamorphic grade never exceeded biotite grade, the assemblages characterizing most of east Magerøy during D_1 probably belonged to the chlorite zone of low greenschist facies, and a slaty cleavage developed in the pelitic lithologies (Fig. 7). The study of the minerals characterizing the S_1 axial planar foliation indicates that the syn-D_1 metamorphism continuously increased towards the west, and by the closing stages of D_1 had attained the staurolite/kyanite zone of the amphibolite facies. This late stage of D_1 coincides with the final movements along the Magerøy Nappe basal thrust, and the emplacement of the nappe thus occurred during D_1 (Ramsay & Sturt 1976).

The study of inclusion patterns in syn-D_1 porphyroblasts, particularly garnets, suggests that the D_1 event was not a simple and continuous rhythm of rising and waning stress, but consisted of two discrete periods of active stress. These were separated by a short static interval. This suggestion is based essentially on the geometry of the syntectonic (Powell & Treagus 1970) garnet inclusion fabric, but is also supported by structural observations on the early boudinage pattern and its relationship to the stretching lineation in the Sardnesfjorden area (see p. 17). Where it is best developed the garnet inclusion

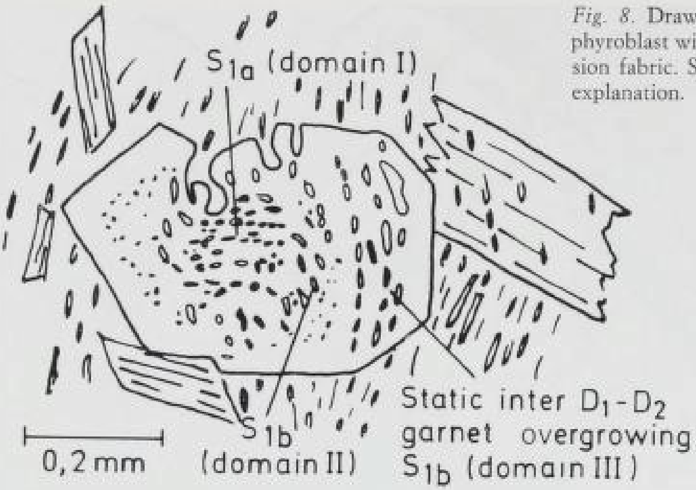


Fig. 8. Drawing of garnet porphyroblast with composite inclusion fabric. See text for further explanation.

pattern defines three domains within the porphyroblasts. These are illustrated in Fig. 8 and their characteristics can be summarized as:

Domain I. The inclusions are formed by quartz and opaque dust and are aligned in straight lines.

Domain II. The inclusions define curves, and are coarsened compared to those in domain I.

Domain III. The inclusions are further coarsened and are again, as in domain I, aligned in straight lines. These are parallel to the S_1 cleavage developed in the matrix.

The sequence of formation of this pattern of inclusions in garnets is considered to have originated as follows:

1. Tectonic stress produced an early planar structure (S_{1a}) in the rock prior to garnet crystallization. This structure S_{1a} is preserved as relics in the core of porphyroblasts (Fig. 8).
2. The regional temperature increased and garnet growth was initiated. These porphyroblasts overgrew the S_{1a} without rotation, probably in a static interval. The groundmass fabric gradually coarsened and this is reflected in the size of the individual inclusions. This stage of garnet crystallization is represented by domain I.
2. Further temperature increase under active stress caused rotational growth (syntectonic) of the garnets. This was accompanied by a general coarsening of the fabric, and represents domain II in the porphyroblasts.
4. The outer domain III was produced under static crystallization post-D_1. The garnets overgrew the S_1 cleavage, and the inclusions define straight lines parallel to the external S_1 cleavage.

Other explanations for the observed pattern are possible. A very rapid crystallization of garnet during the initial stage of growth, so that rotation was not recorded, may explain the straight inclusion trains of domain I. Electron microprobe analysis of garnets (Andersen 1979), however, shows a strong normal zonation (Atherton 1968) also within the innermost domain of the garnet porphyroblasts. This zonation is also continuous with that in the outer part of the porphyroblasts. There is therefore no evidence for particularly rapid growth of individual garnets in the early stages of their formation. The observed pattern of domains I, II and III is thus probably most satisfactorily explained through the stages 1 to 4 outlined above.

In the Sardnesfjorden area a pattern of boudinage in the competent sandstone beds is observed in which the boudin necks are aligned parallel to the axis of the Pollneset syncline. Boudinage in two directions (Chocolate-tablet boudinage, Ramsay (1967) has not been observed. This indicates that the k-values (Ramsay 1967) were considerably thigher than $k = 0$. The Sardnesfjorden boudin orientation appears to indicate that the principal direction of extension during the stage of the deformation history at which the boudins formed was at a high angle to the axis of the Pollneset syncline. This observation is in contradiction to other observations of stretching direction from the same area. The long axes of pebbles in deformed conglomerates, as well as the general mineral stretsching lineation, parallel the axis of the large-scale syncline. The rock-element stretching lineation thus indicates that the principal extensional axis was parallel to the fold axis. Examination of hydrothermal quartz in boudin necks also shows a rodding of quartz parallel to the F_1 fold axis.

When viewed in context with the observed inclusion pattern in garnet porphyroblasts, it is believed that the boudinage pattern in the Sardnesfjorden area has originated as a result of a polyphasal deformation history of the main D_1 event.

I) At early (low T) stages of D_1 (D_{1a}), the principal direction of extension was oriented at a high angle to the fold axis, indicated by the pattern of early boudins.
II) At later stages of D_1 (D_{1b}), the X-axis of the strain ellipsoid was orientated parallel to the axis of the main folds. Growth of minerals and deformation/rotation of pebbles took place under this phase of D_1 which occurred at more elevated T-conditions as seen from the syn-tectonic mineral assemblages.

The polyphasal pattern of D_1 is only detectable in the area of Magerøy with eastward vergence of the large-scale folds. If this pattern developed in the west it appears to have been completely obliterated by the late-D_1 deformation and subsequent metamorphic recrystallization. The significantly higher syn-D_1 metamorphic conditions in the west show a different and deeper crustal level for this part of the nappe during D_1. The difference in crustal level might be attributed to a continued stacking of higher nappe from the west on to the Magerøy

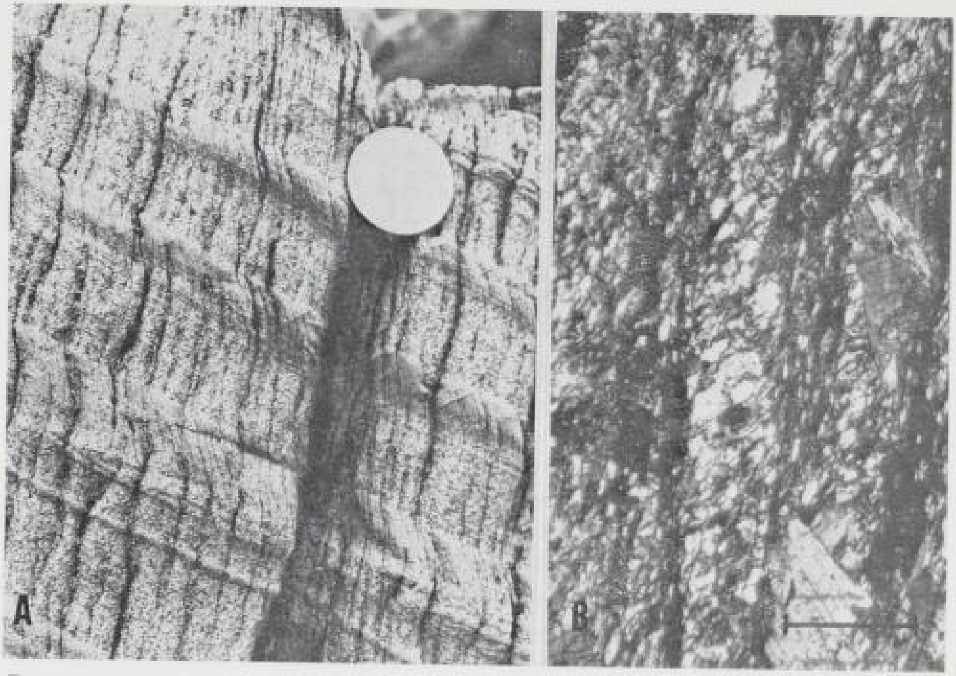


Fig. 9. (A) S_2 cleavage showing refraction in an alternating shale and sandstone lithology of the Juldagnes Formation, from the west side of Sardnesfjord. The coin measures 3 cm. (B) Photomicrograph of the pelite in (A) showing the S_2 pressure solution cleavage. The microlithons contain a relict S_1 cleavage and interkinematic (post-D_1/pre-D_2) biotite porphyroblasts. Bar scale, 0.2 mm.

Nappe which immediately overlies the Finnmarkian basement, as indicated by the presence of the Skarsvåg Nappe. These higher grade conditions were further amplified during the inter D_1–D_2 period. The difference in both deformational pattern and metamorphism between the western and eastern parts of the nappe is thus attributed to difference in crustal level for the two parts of the nappe

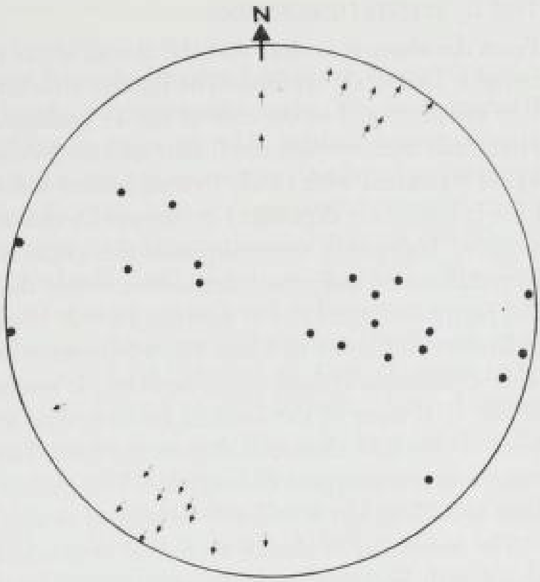
STRUCTURAL PATTERN PRODUCED DURING D_2

The second major fold phase (D_2) affecting the Ordovician–Silurian metasediments and also the igneous rocks which were intruded inter D_1–D_2, was less penetrative than D_1. The deformation took place under waning metamorphic conditions, which nowhere in Magerøy exceeded middle greenschist facies. The folds that developed form a set of essentially upright open structures. The S_2 crenulation and pressure solution cleavage is developed with a variable intensity (Fig. 9). The most intense D_2 strains are localized in the relatively incompetent lithologies of the Nordvågen Group, particularly in the Duksfjord Formation, which has a spatial distribution along the core of the Sardnes synform.

THE SARDNES SYNFORM

The dominant D_2 structure on Magerøy is the Sardnes synform. Although large

Fig. 10. Stereographic plot (equal area) of D_2 structural elements from southern Magerøy. The variation in S_2 orientation is a result of macroscopic convergent cleavage fanning across the Sardnes synform. Symbols: Dots—poles to S_2. Arrows—F_2 axes and L_2.



F_2 folds exist both east and west of the axial trace of this structure they are developed as parasitic folds on the large-scale central synform. This parasite/host relationship is illustrated by the overall attitude of S_2, which forms a macroscopic convergent cleavage fan (Fig. 10). The axial trend of the Sardnes synform is on average sub-parallel to that of the major F_1 folds. Locally, however, the trend of the axis varies considerably between 045° and 350°. For most of its observable distance the trend is approximately 010°–020°. The local deflections of the axis probably result from a primary non-plane, non-cylindrical folding of an inhomogeneous rock body. This inhomogeneity is expressed by variable competence of the sediments and also by the presence of the intrusive Skarsvåg and Opnan granitoids. There is no sign of later folding, and the irregularities in direction and plunge of the axis have probably developed as a primary feature of the synform. The axial surface of the synform is vertical to steeply westward dipping (80°–90°). The gentle eastward overturning of the synform is most pronounced in the southern segment of the area towards Magerøysundet (Fig. 4).

Several major F_2 folds can be discerned on both limbs of the main synform. On the eastern limb Curry (1975) recognized two major F_2 folds forming an asymmetrical fold pair. This is mirrored in the western limb. The long limb/short limb relationship of these flexures relative to the Sardnes synform is consistent with a normal parasite/host fold relationship. Curry (1975) showed the asymmetrical fold pair on the eastern limb to have a non-coaxial relationship to the host. Those developed on the western limb are essentially co-axial, but die out when traced along their axes in the northerly direction.

THE D_2 EVENT: DISCUSSION

From the above it is clear that the overall effect of D_2 was the formation of an upright, large-scale synform. The highest structural levels of the D_1 fold structure are preserved in the core of the F_2 synform. This event took place under retrograde metamorphic conditions and the locally intense S_2 crenulation cleavage is associated with newly formed biotite and white mica. The development of S_2 is essentially dependent on the pre-D_2 characteristics of the lithologies. In areas of high-grade metamorphism the grain coarsening produced by static recrystallization and neomineralization during the metamorphic peak (inter D_1–D_2) partly destroyed the S_1 foliation, which is necessary for a subsequent crenulation cleavage to develop. Fig. 10 shows a non-uniform orientation of S_2. This variation in attitude of S_2, however, is systematic in the sense that S_2 east of the axial trace of the Sardnes synform dips towards the west while to the west of this fold closure it dips to the east. The cleavage, therefore, forms a macroscopic convergent cleavage fan. This pattern is not explicable in terms of later re-folding, but is probably developed as a primary D_2 feature.

The formation of the D_2 synformal structure is probably a result of large-wavelength buckling in the basement. This folding produced open antiforms and synforms with axes trending approximately 010°–030°. The Magerøy Nappe and the Skarsvåg Nappe, which represent the highest tectonic units in the nappe sequences in Finnmark (Sturt et al. 1978, Kjærsrud, in prep.) are situated within the core of the major Sardnes synform. As such they partly owe their preservation from erosion to this folding, although more important is the downfaulting of the northern block on the Magerøysundet fault. A relatively extensive tract of Finnmarkian basement is exposed in the Gjesvær area (Fig. 1). This area represents a preserved part of a complementary antiform to the west of the F_2 Sardnes synform. The basal thrust of the Magerøy Nappe was thus folded during F_2 into its present attitude with a dip of 40°–50° to the southeast.

None of the major structures, D_1 or D_2, can be directly correlated across the Magerøysundet fault. There has been a considerable post-D_2 movement along this structure. This involves both normal dip-slip and also dextral strike-slip components (Zwaan & Roberts 1978). It is not possible, however, to quantify this movement. On the mainland in west Finnmark there are recorded several large-scale flexures. These structures post-date the Finnmarkian D_2 event, and fold the Finnmarkian thrust planes (Sturt, pers. comm. 1979). Associated with this late folding there are kink bands that cut all Finnmarkian structures (Jansen 1976). It is suggested that the folds of this generation form the dome-like structures in which the windows of low-grade Karelian rocks are exposed (Komagfjord and Alta–Kvænangen windows).

Both trend and style of the late folds of the mainland closely correspond with the D_2 pattern observed in the Magerøy Nappe and its substrate in western Magerøy. It is therefore suggested that the late buckling of the Finnmarkian nappes and substrate in west Finnmark occurred during the Scandinavian phase of the Caledonian orogeny, and probably at a late stage of this phase.

Faulting

The Magerøy Nappe is separated from the Finnmarkian Kalak Nappe Complex of Porsangerhalvøya (Fig. 1) by the Magerøysundet fault. This fault transects and thus post-dates the Scandinavian phase F_2 folds in the Magerøy Nappe. Faults of similar trend and relative age are commonly developed on Magerøy north of the main fault. The trend of this fault set is essentially parallel to the major fault in the Varanger area of east Finnmark known as the Trollfjord–Komagelv fault (Siedlecka & Siedlecki 1967, Kjøde et al. 1978). The final large-scale movements along this structure are believed to have occurred before late Devonian times. This conclusion is based on K/Ar dating (Beckinsale et al. 1975) of dolerite dykes that occur on both sides of the fault (Roberts 1975) and which have given ages of around 355 ± 10 m.y. A mafic dyke of similar characteristics and which post-dates the movement along faults parallel to the Magerøysundet fault occurs in central Magerøy. Although no conclusive evidence is available concerning the age of the faulting, the similarity to the Trollfjord–Komagelv fault situation is evident. It is therefore likely that the Magerøysundet fault forms part of an extensive fault system related to the Trollfjord–Komagelv structure.

Summary and conclusion

The emplacement of the Magerøy Nappe occurred during the Silurian, Scandinavian phase of the Caledonian orogeny (Ramsay & Sturt 1976). The earliest orogenic activity which relates to this phase is probably represented by the development of the 2.4 km-thick flysch sequence of the Juldagnes Formation.

The tectono–metamorphic features of this orogenic phase are imprinted on the lithologies of the nappe as two deformational events with attendant regional metamorphism. The metamorphism reached its peak during the interkinematic period (D_1–D_2), and was accompanied by important syn-orogenic magmatism. This included both acid and mafic/ultramafic intrusions. The Finnvik granite, intruded coevally with the metamorphic peak, has given a Rb/Sr whole rock isochron age of 417 ± 11 m.y. B.P. ($Rb^{87} = 1.42 \times 10^{-11}$). As such, it dates the age of the Scandinavian phase metamorphism (Sturt et al. in prep.). Recent geochronological studies from the Gjesvær migmatite complex (H. Austrheim, pers. comm. 1979) indicate that this metamorphism also resulted in an isotopic homogenization in the Finnmarkian basement, as shown by a Rb/Sr whole rock isochron of 409 ± 28 m.y. for this complex. The high Sr^{87}/Sr^{86} ratios, 0.7111 for the Finnvik granite and the exceptionally high 0.7547 for the Gjesvær migmatites, imply a long crustal history prior to the final isotope homogenization.

There are indications of early low-T deformation during the initial stages of D_1. The increasing regional metamorphism which accompanied D_1 shows that the lithologies were depressed to progressively deeper crustal levels. This is considered by the author to be the result of a continued stacking of higher nappe units onto the Magerøy Nappe, such as is represented by the Skarsvåg Nappe. The strong metamorphic zonation which had developed at the closing stages of D_1, and which was further amplified in the inter D_1–D_2 period, indicates that the western basal parts of the nappe were positioned at deeper crustal levels than the eastern parts. This may have been a result of a combination of a relatively steep westward dip of the thrust and therefore a considerable overburden from the higher structural levels of the Magerøy Nappe and probably also from nappes in a structurally more elevated position.

The tectono–thermal environment during the second deformational event, D_2, was clearly different from that which prevailed during D_1. By the onset of D_2 the temperatures had dropped to a level characterized by lower greenschist facies metamorphism. This event, producing the open, upright folds, probably occurred during the early stages of the uplift-cooling history of the area. The basal thrust plane developed its present orientation, with a dip towards the southeast, as a result of strong upbuckling of the Finnmarkian basement to the west.

Acknowledgements. – The author is particularly grateful for the critical advice and help given by Prof. B. A. Sturt, Univ. of Bergen, during the course of this work. Thanks also to Prof. D. M. Ramsay, Univ. of Dundee, and Cand. Real. A. Thon, Univ. of Bergen, for their critical reading and improvement of the manuscript. E. Irgens and J. Ellingsen are thanked for the drafting of maps and illustrations.

International Geological Correlation Programme.
Norwegian contribution No. 38 to Project Caledonian Orogen.

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