Sedimentary, Tectonic and Metamorphic Features of the Devonian of Røragen, Sør-Trøndelag

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An outline is given of the depositional environment of these Lower Devonian rocks following the discovery of various primary sedimentary structures which have provided some evidence of palaeocurrent directions. Tectonic structures are described and it is shown that an early deformation phase, apparently along E–W axes, was accompanied by an uneven weak metamorphism; further extensional strain locally produced phyllonites. Some of the less competent lithologies were then mesoscopically folded along approximately NE–SW axes, and this deformation was followed by local thrusting, shearing and faulting. These late Caledonian diastrophic events are most probably of Svalbardian (lowermost Upper Devonian) age, and it is suggested that the main folding of the Oslo region Cambro–Downtonian succession as well as some of the sparagmite basin deformation of south-east Norway may date to the same phase of orogenic movement.

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Introduction

Despite its isolation and restricted areal extent the Devonian of Røragen constitutes an important element in the Palaeozoic geological history of Norway. Our knowledge of these sediments derives largely from the investigations of Goldschmidt (1913), who discovered a wealth of plant fossils to which a Lower Devonian age was subsequently ascribed (Halle 1916, Høeg 1936). Holmsen (1963) later reported the presence of folds within parts of the sequence and noted that these deformed rocks displayed features indicative of a low-grade metamorphism; thrusting was also considered to have affected the complex. These observations clearly rejected Goldschmidt's (1913) view that faulting alone had produced the present-day disposition of the Devonian sediments.

The present contribution is based on just over one week's investigation, in 1971, of deformation features within this sequence, aimed at providing some quantitative data on the folding and thrusting as well as enabling comparisons to be made with tectonic structures occurring in the allochthonous Cambro–Silurian succession of the Trondheim region. During the course of this study it became apparent that diverse primary sedimentary structures were also represented within the Devonian sequence, and these are mentioned briefly in the account which follows.

Lithostratigraphy and sedimentary features

Goldschmidt's (1913) mapping showed that the Devonian succession to the south-west of Røragen lake differed somewhat from that occurring to the north-east (Fig. 1). As only the basal part of the sequence is common to both sub-areas it is difficult to establish a continuous succession, but nevertheless the strike attitudes and geographical distribution of individual units do permit the tabulation of a general lithostratigraphy. This comprises: (1) Basal polymict conglomerate, 10–80 m thick; (2) grey sandstone and shale with red sandstone higher up, 140–220 m; (3) serpentinite conglomerate and breccia, locally over 200 m thick; and (4) polymict conglomerate and breccia, with grey and red sandstone and shale intercalations, over 700 m. Detailed descriptions may be found in Goldschmidt (1913).

From field investigations it seems fairly clear that lateral thickness and rapid facies changes formed an integral part of the sedimentation picture, even though the true extent of these is unknown. With such discontinuity the erection of a formal stratigraphic scheme would normally be problematical. In this case, however, to facilitate the present description it is here proposed to introduce three formational names (see Appendix): the *Lerbekk Formation,* comprising the sandstone and shale sequence with the basal conglomerate; the *Svartberg Conglomerate*, for the serpentinite conglomerate or breccia occurring on the south-west side of Røragen lake; and the *Brekkefjell Conglomerate,* for the coarse polymict conglomerate occurring to the north-east of Røragen. It is further proposed that the term *Røragen Group* be employed for the complete succession, which totals between 1100 m and 1200 m in thickness.

At this stage it is worth reflecting on the fact that Goldschmidt's (1913) geological map was drawn without the aid of aerial photographs and is based on an old and not particularly accurate map series. Holmsen (1963) was able to point out some small errors in Goldschmidt's mapping. Another inaccuracy concerns the small area of 'sandstone and shale' on the north-west side of Geitberget (Fig. 1): Goldschmidt indicated these rocks as constituting part of his 'Abteilung 2' – part of the present Lerbekk Formation – whereas they form a local discontinuous unit occurring actually within the Brekkefjell Conglomerate.

On examining the lithologies which constitute the Lerbekk Formation it is clear that a great variety of rock-types is present, such that one has a wide range from conglomerates through various grain-sizes of sandstone to siltstones and shales. In addition, metamorphic features are noticeable in many of the finer grained rocks which have taken on an incipient phyllite aspect. It is this formation which has provided most of the examples of primary sedimentary structures so far observed, chiefly in the exposures of plant-fossiliferous shales and siltstones up the stream Lerbekken south-east of the lake Aursunden (Fig. 1). In this small area one finds penecontemporaneous slump structures (Fig. 2), slump balls, load casts and other sole markings, and in certain sandstone horizons small-scale unimodal cross-bedding and

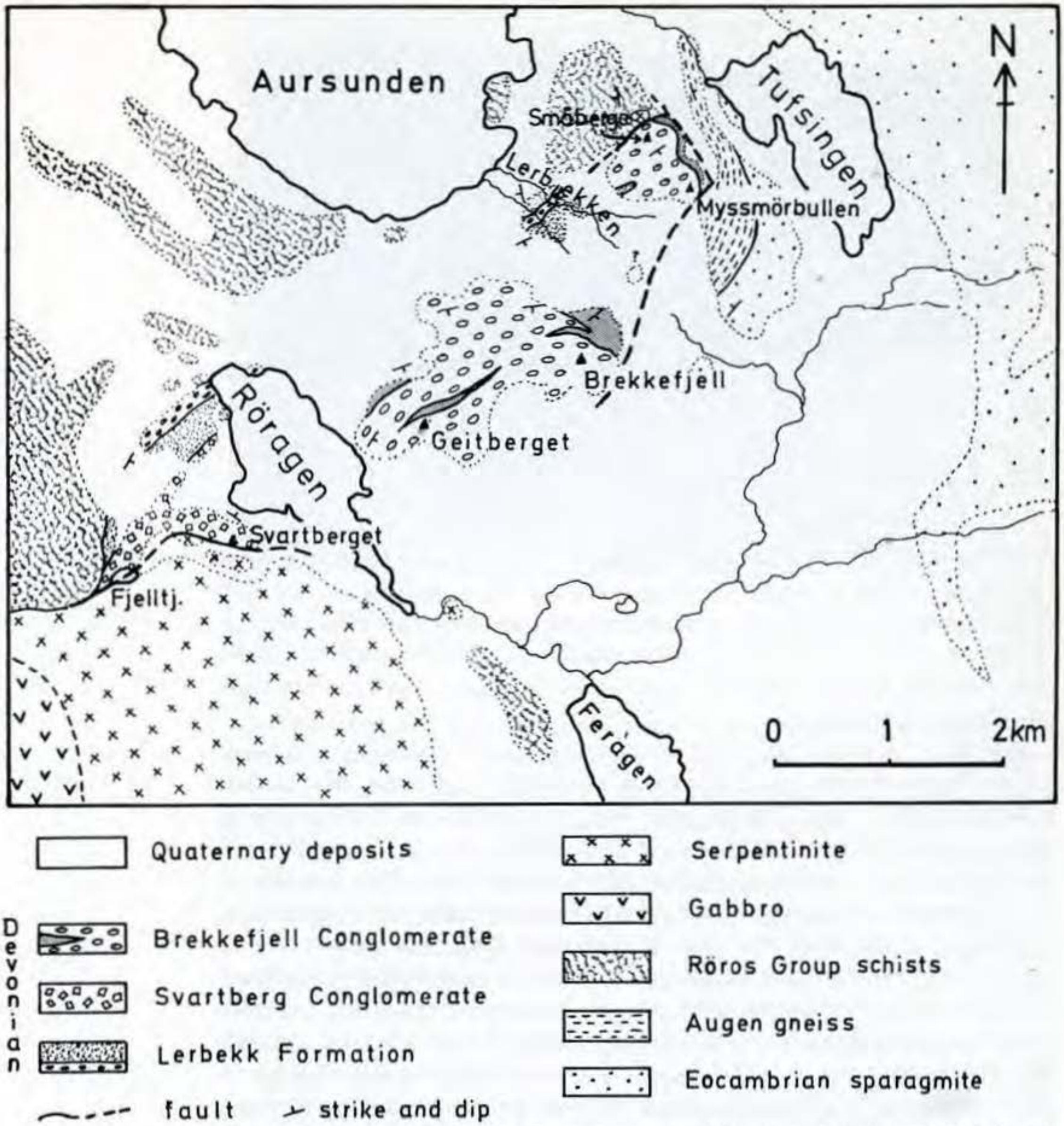

Fig. 1. Geological map of the Røragen area, modified from Goldschmidt (1913) and Holmsen (1963) and based on the new 1:50,000 topographical map 'Brekken'.

possible current ripples. The occurrence of worm burrows in some silty shales (Fig. 3) is of additional interest. To the writer's knowledge biogenic structures have not before been reported from the Norwegian intramontane Devonian.

Primary structures also occur within the silty sandstone and shale unit on the north-west side of Geitberget. These include thin, tabular cross-bedded layers in a prominent, 20 cm-thick, grey siltstone horizon. The attitude of the

Fig. 2. Penecontemporaneous slump structures in silty sandstone and shale, Lerbekk Formation, Lerbekken. Specimen 13 cm in length.

foresets in this locality denotes that currents were directed towards a NE–ENE point. Traces of worm burrowing have also been observed in this NW Geitberget area as well as sole structures resembling small-scale flute casts. In addition it may be noted that possible indications of clast imbrication have been observed in the Brekkefjell Conglomerate but this feature has not been investigated in any detail.

Discussion of the depositional environment of the Devonian sediments cannot be more than brief, since this is a topic which requires further sedimentological study. The present field observations do, however, lend support to Holtedahl's (1960) and Bryhni's (1964) view that crustal movements must have occurred during the period of deposition. The character of the sediments, with particularly coarse conglomerates higher up, suggests that a subsiding, partly fault-controlled, intramontane basin was present at that time. Minor, low-angle unconformities within the Brekkefjell Conglomerate sequence in the north-easternmost part of the area denote periodic, slight, intraformational tilting of strata towards a south-easterly point and possible clast imbrication suggests a SE-directed current flow. Current directions noted earlier in siltstones within the same formation at Geitberget are somewhat oblique to this NW–SE trend, but in terrigenous alluvial fan deposits such as we have here transport of material cannot be expected to be unidirectional except over very small areas. In addition, it may be noted that boundary relationships between the Brekkefjell Conglomerate and the sandstone and siltstone of the Lerbekk Formation on the NW side of Småberga display an angular unconformity which indicates that the underlying sediments were tilted towards a north-westerly point before deposition of the conglomerate.

Further indications of sediment dispersal patterns may be inferred from conglomerate character and thickness. The basal conglomerate of the Lerbekk Formation, for example, thins markedly towards the north-east and pebble

Fig. 3. Horizontal and vertical worm burrows in silty shales, Lerbekk Formation, Lerbekken. Some plant-fossil fragments are present near the bottom of the photograph. Scale division, 1 mm.

size diminishes. The disappearance of the Svartberg Conglomerate is even more rapid and spectacular, again towards a general north to north-easterly point. Holmen's (1963) interpretation, that on Svartberget this breccia or conglomerate derives from the adjacent serpentinite across a steeply inclined fault, is almost certainly correct. This implies that the breccia here represents locally produced scree material. A little further north the thinning serpentinite conglomerate lies directly upon red sandstone of the Lerbekk Formation (Fig. 1). This relationship, and the local presence of a sandstone and shale layer in the conglomerate (p. 108), clearly refute Nilsen's (1973a) suggestion that this particular conglomerate may not be of Devonian age. The pre-Devonian chromite-bearing serpentinite bodies of this area, showing imprints of the main Silurian deformation and metamorphism, were exposed to erosion, in part by faulting, sometime during Lower Devonian time. Bjørlykke (1974) has recently reported the presence of chromite grains compositionally similar to the chromites from the Røragen serpentinite in upper Middle Ordovician sediments from the Oslo region, thus providing additional evidence for a pre-Upper Ordovician age for these ultramafic bodies (Strand 1960, Rui 1972) and at the same time rejecting Wolff's (1967) suggestion that they are of Devonian emplacement. The local N–NE transport associated with the deposition of the Svartberg Conglomerate was subsequently replaced by a more E–SE-directed dispersal; this change of transport direction seems clear if only from the fact that serpentinitic material is minimal in the succeeding Brekkefjell Conglomerate (cf. Goldschmidt 1913).

From the above observations the conclusion is that although we now have some indications at least of probable palaeocurrent directions, there is a definite need for a thorough reinvestigation and sedimentological study of these Devonian sediments as well as for a careful remapping of the complex on accurate base maps. It cannot be hoped that even half as much detail will be accumulated as, for example, in Nilsen's (1968) study of the Devonian of the Solund area of west Norway. Although the Røragen Devonian was probably much thicker and more extensive at one time, the small size of this 10–12 km^2 outlier presents severe limitations on any attempt to establish a history of east Norwegian Devonian sedimentation.

A note may be added here that investigations of spores from the fossil plants are now being carried out by Dr. K. Allen of the Department of Botany, University of Bristol. Preliminary study of some of the material has shown that the state of preservation of the microflora is very poor: no conclusions may be reached at present but there are indications that the spores studied so far belong to a Lower Devonian assemblage (Dr. K. Allen, pers. comm.).

Tectonic structures

The most noticeable structural feature of this small area of Devonian rocks is the fairly regular south-easterly dip of strata at some 40°–70°. Goldschmidt (1913) held the view that the sediments had been simply tilted during downfaulting, but as noted earlier Holmsen (1963) was able to show that some folding and minor thrusting had also been involved in their deformation. It is convenient, for descriptive purposes, to outline the deformation history of these rocks by first reconsidering the folds which Holmsen (1963, p. 130) reported from the north-east side of Brekkefjell and then discussing these in relation to other structural elements.

Folds. Folded Devonian strata, principally interbanded phyllitic shales and siltstones and small-pebble varieties of conglomerate, occur in the area between Brekkefjell and Myssmørbullen. Although a good deal of the pelite is clearly present as primary intercalations in the Brekkefjell Conglomerate, general tectonic relationships do not exclude the possibility that some of it may belong to the Lerbekk Formation: poverty of exposure is largely responsible for this uncertainty. Folds are also observed in a thin-bedded, alternating, quartzitic sandstone and dark phyllitic shale (Holmsen 1963, p. 132). The position of this lithology in the stratigraphy is unknown; it could conceivably be pre-Devonian.

The folds are open to close asymmetrical structures (Figs. 4 and 5) with amplitudes ranging up to ca. 1.5 m and axial surface separations up to ca. 1 m. Hinges vary from sharp to well-rounded often in contiguous folds and sometimes also along individual axial surfaces. Observations in the Myssmørbullen area have shown that the essentially parallel folds may be arranged *en échelon*, thus producing diverging axial trends and plunge values. No cleavage is asso-

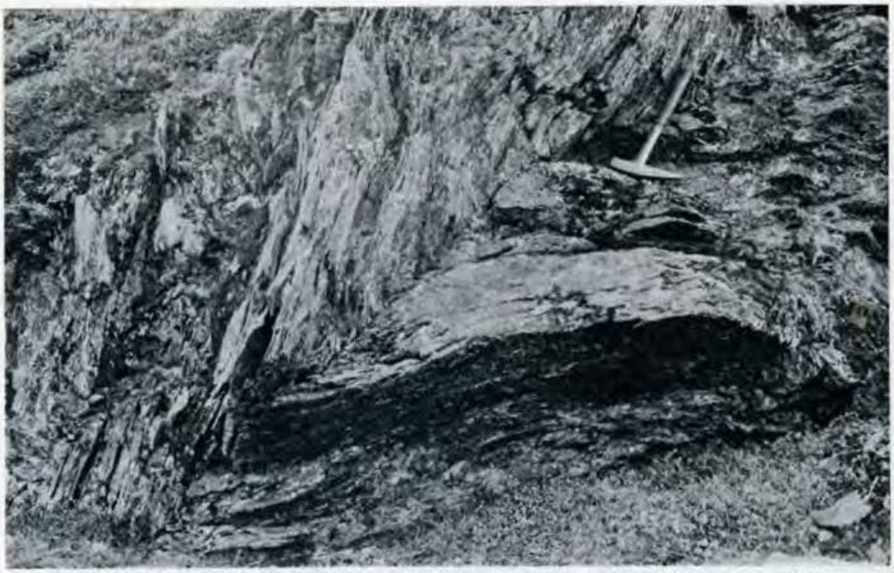

Fig. 4. Fold in closely banded phyllite and siltstone with angular hinge zone and disrupted axial surface; horizon within the Brekkefjell Conglomerate, NE Brekkefjell. Looking ca. SSW.

Fig. 5. Folds in interbanded phyllite and phyllonitic siltstone showing varying shape; horizon within Brekkefjell Conglomerate, NE Brekkefjell. Looking ca. SW.

ciated with the folds though in some instances the axial surfaces of sharp-hinged structures may develop into dislocations; some short limbs of microscopic folds may also show a progressive destruction and transformation into shear surfaces.

Fold axes display an appreciable variability of trend (Fig. 6), a feature already noted by Holmsen (1963) and which in part is due to the essentially

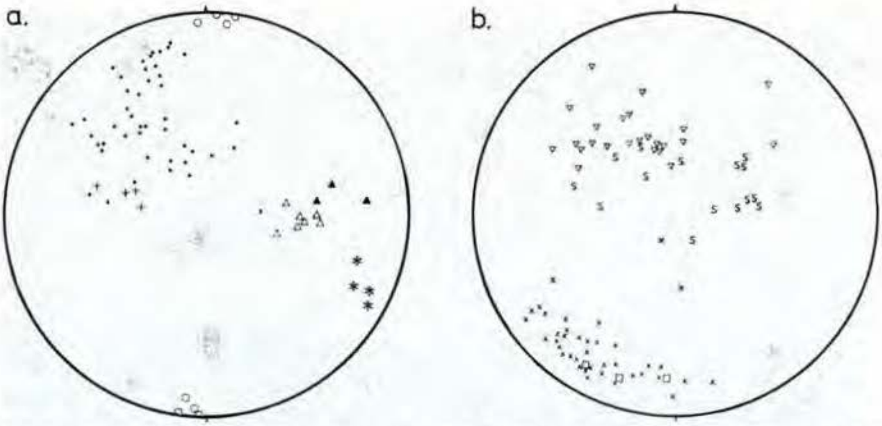

Fig. 6. Structural data, Lower Devonian, Røragen. Schmidt net, lower hemisphere. (a) Dots – poles to bedding: circles – poles to early cleavage: open triangles – early β-axes: filled triangles – early crinkle lineation: crosses – fabric lineation in Røros Group schists: asterisks – lineation in augen gneiss.

(b) Inverted triangles – poles to axial planes of post-cleavage folds: X – axes of post-cleavage folds: S – poles to prominent shear planes: squares – shear boudins or shear-plane intersection lineation.

non-cylindrical character of the folding. The folds are 'plunging inclined' structures with axial trends towards a point between south-west and south, rarely south-southeast. In a few cases plunges are near-orthogonal to the axial plane strike, i.e., the pitch is close to 90°, and the folds are thus 'reclined'. No geographical distribution of fold type, trend or plunge values has been detected such that refolding can be discounted as a possible reason for axial trend irregularity.

Overturning of the folds is generally towards a north-westerly point, the axial surfaces dipping more steeply than bedding. As folds are absent in the steeper dipping parts of the sequence, this fold axial surface/bedding relationship is unfortunately not readily detectable in the stereographic plots (Fig. 6). The only exception to this overturning relationship is found in a narrow zone trending north-east from Brekkefjell in which axial surfaces are shallower than bedding; this merely represents a local tectonic inversion of the sequence within the short limb of a slightly larger scale structure. Overall, however, the asymmetry of the folds and their consistent SW–S plunge denotes an approximately NW-directed movement during the development of these structures.

Earlier structural elements. Examination of the folded lithologies shows that the folds are in many cases deforming slaty, phyllitic or phyllonitic rock-types which under the microscope are seen to possess lepidoblastic textures. From this it is deduced that the folding described above is not the oldest diastrophic element to have been imprinted on these Devonian sediments.

Where folding is well developed, as at the localities on NE Brekkefjell and Myssmørbullen, it is virtually impossible to recognise any angular

Fig. 7. Cleavage developed oblique to bedding in an intraformational red silty 'shale' and sandstone unit within the Brekkefjell Conglomerate on the top of Geitberget. The hammer shaft lies parallel to the cleavage.

disparity between this early planar fabric and the original bedding. On the top of Geitberget and north-east towards Brekkefjell, however, a crude cleavage can be observed in pelitic and silty layers within the Brekkefjell Conglomerate. This cleavage, confirmed by petrographic examination as a preferred orientation of phyllosilicates, is clearly disposed oblique to bedding (Fig. 7). It is also steeper than the bedding, agreeing with the sedimentary structural evidence that the succession is the right way up. Constructed cleavage/bedding intersection lineations plunge at some 50° towards the east (Fig. 6a); these are subparallel to a rarely developed microcrinkle lineation. The only minor fold which could possibly belong to this deformation episode is present in the banded quartzitic sandstone and phyllite lithology in a crag between Brekkefjell and Myssmørbullen. This is a tight, partially sheared out structure; the axis was not measurable.

Although linear elements associated with this early movement phase are few and far between, the limited data do tend to suggest the possible development of major folding along ca. E–W axes. The rocks of the Røragen Group have acquired their general south-easterly dip mainly during these movements, positioned as they are theoretically on the southern limb of an easterly plunging open anticline. The syn-depositional basinal tilting to the south-east referred to earlier (p. 92) would not have contributed to any significant extent to this present-day stratal dip. A note may be made here that extensional features associated with the local production of phyllonitic lithologies can be dated to a late stage of this early deformation: this is discussed a little more fully later (p. 102). No tectonic elongation of pebbles has been detected in the conglomerates.

Other tectonic features. Holmsen (1963) noted that the Devonian strata were possibly locally affected by thrusting, and referred to observations made by Professor Chr. Oftedahl that shear planes were also present within these rocks.

Shearing is an important microscopic and mesoscopic element in the structural picture and is most prominently developed within the folded pelitic lithologies at Myssmørbullen and on NE Brekkefjell. Shear planes may parallel the axial surfaces of the folds, as mentioned earlier, but other notable trends are SE and SSE with gentle to moderate dips towards a south-westerly point (Fig. 6b). At Myssmørbullen a conjugate set of shears locally produces boudin-like features with the axes of the lenticles paralleling the local fold trend. Constructed intersections of other master shear surfaces also plunge towards the SSW. In all these cases the shearing has developed during the main folding but also transects the folds. Locally, at Myssmørbullen, pyrite has been observed along certain shear surfaces.

Thrusting is present on a mesoscopic scale, again at Brekkefjell and Myssmørbullen; as shears are seen to develop into thrusts it is difficult to know where to draw the dividing line between these features. Surfaces along which displacive and disruptive movement has obviously occurred only rarely display localised brecciation or mylonitisation, and slip-striae may be absent. Fortunately the flexing of strata adjacent to the thrust surface often provides evidence of the relative direction of movement (Fig. 8); this denotes a general NW–N translation of upper blocks relative to the overridden strata. Relationships at Myssmørbullen show that the thrusting there was syn- to post-folding.

Evidence of major thrusting of the Devonian rocks has not been detected during the present study, agreeing with Holmsen's (1963) conclusions. Considering the contact relationships in Lerbekken where the Lerbekk Formation basal conglomerate rests with marked angular unconformity upon the Røros Group[1] schists and phyllites (Goldschmidt 1913, Holmsen 1963) it is difficult to conceive that the Devonian strata are anything other than autochthonous. At this locality, however, the Røros metasediments are locally flexed within a 30 cm wide zone immediately subjacent to the actual unconformity (Fig. 8c) denoting that some minor, post-lithification thrust movement, effectively towards a NW–N point, has occurred along this primary surface. As no mylonite, slip-striae or segregatory quartz can be observed, this movement was in all probability only of very local significance.

Relationships along the south-eastern margin of the Devonian field are unfortunately obscured beneath Quaternary deposits. Holmsen (1963) first indicated the presence of a local thrust, although in the appendix to his paper he appears to rescind this view. Bearing in mind the consistent SE dip of the Brekkefjell Conglomerate even in its south-easternmost exposures, including

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[1] For current usage of this term, see Wolff (1967).

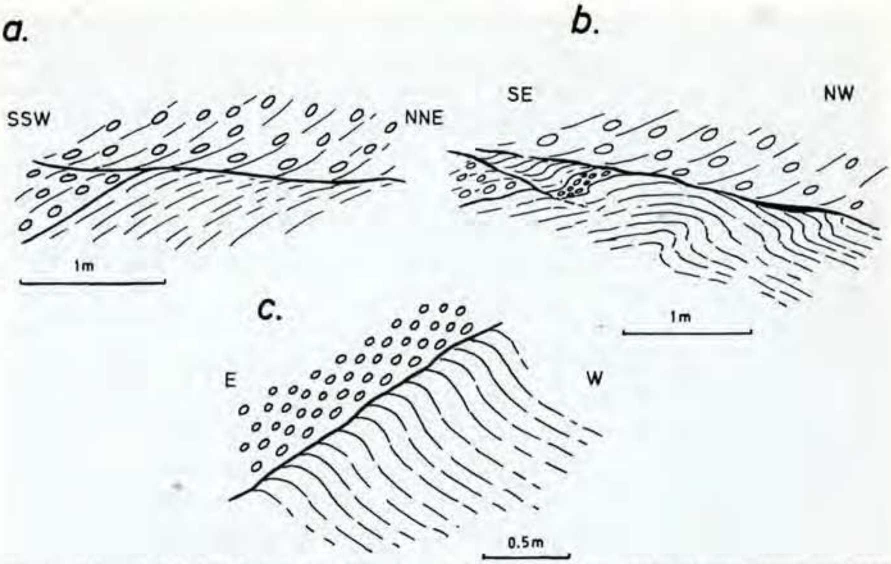

Fig. 8. (a) and (b). Field sketches showing relative movements along minor thrust surfaces within the Devonian rocks (conglomerate, phyllite, siltstone): a – NE Brekkefjell; b – Myssmørbullen. (c) Sketch showing the disturbed nature of the unconformable boundary between Lerbekk Formation basal conglomerate and the underlying Røros Group phyllitic schists, Lerbekken. Strike/dip in Devonian 032°/52° (SE), in Røros schists 135°/32° (SW).

the locality depicted in Holmsen's (1963, p. 130) Fig. 2, it is possible that Goldschmidt's (1913) interpretation of a fault positioned along this margin may be correct. Angles of dip do tend to shallow out on Brekkefjell, a feature which could be associated with the nearby presence of a NE–SW dislocation downfaulting the Devonian. A shallow-level drilling programme would perhaps afford the only means of solving this problem.

Faulting would appear to have contributed to the deformation of the Røragen Devonian, though not as significantly as envisaged by Goldschmidt (1913). Apart from the possible normal fault along the south-eastern margin, another NE–SW fracture juxtaposes Røros Group metasediments (with a small serpentinite body) and Devonian conglomerate on the north side of Småberga (Fig. 1). Direct evidence in favour of a NW–SE normal fault along the north-east flanks of Småberga and Myssmørbullen is lacking; stratal disposition does, however, suggest the presence of a dislocation beneath the superficial deposits in this area.

These faults, observed or inferred, are all post-lithification fractures and younger than the folding which deforms the Devonian rocks. The only probable syn-depositional fault is that separating the Svartberg Conglomerate from the serpentinite south-west of Røragen lake, but as noted earlier there are many sedimentological features which favour the view that active uplift of the nearby source areas, assisted by faulting, was concurrent with Devonian sedimentation. Other penecontemporaneous Devonian faults may therefore be present outside the immediate Røragen area, particularly to the west and south-west. The possibility also exists that some of the suggested post-lithification faults may represent reactivated Lower Devonian fracures. In this regard it would be interesting to trace the E–W Svartberg fault eastwards; it could link up with the postulated fault along the SE margin of the Devonian field.

A systematic study of *jointing* was not attempted in the time available, although the master joints were measured at most observation points. Tensional fractures normal and parallel to the main fold axial trend appear to be the most prominent joints and these are sometimes quartz- or calcite-filled.

Structural elements in the pre-Devonian rocks. Examination and measurement of structures occurring in the surrounding augen gneiss, Røros Group metasediments, serpentinites and Eocambrian psammites confirm Holmsen's (1963) observations that these are quite different in character from tectonic elements within the Devonian rocks. In the grey-green Røros phyllitic schists a prominent mineral and fabric lineation with quartz rodding plunges steeply towards WNW (Fig. 6a), and this is deformed by small-scale, ca. NNW–SSE trending (NNW plunging) folds which possess a fairly flat-lying, weakly developed, axial plane crenulation cleavage.

A later deformation in these rocks is represented locally by ESE–NW trending dextral kink bands. In the Tufsingen augen gneiss a prominent ESE-plunging lineation is present. None of these structures is developed in the Devonian rocks and, conversely, the structures observed in the Røragen Group rocks are seemingly absent from the Røros metasediments, with the exception of some shear planes. Interestingly, one sinistral kink band and other microscopic kinks have been observed in the Devonian phyllites, these also showing an ESE–WNW trend; it is therefore possible that some of the late brittle structures in the Cambro–Silurian metasediments may have developed during post-Lower Devonian shortening along the Caledonian orogen.

Metamorphic features

Indications that a low-grade metamorphism has effected recrystallisation of certain 'shales' on the north-east side of Brekkefjell were first reported by Holmsen (1963). He remarked that, at this locality, the pelites resembled phyllonites and posed the question as to whether or not recrystallisation features might be present elsewhere in the Devonian complex. The present study has, in fact, shown that slaty or phyllitic argillites and siltstones do occur rather more extensively although the degree of recrystallisation diminishes away from the north-easternmost parts of the area.

In hand-specimens, the phyllitic rocks and finer-grained siltstones of the Brekkefjell and Myssmørbullen areas are various shades of grey, occasionally black, and display lustrous foliation surfaces. On the microscopic scale, in the more homogeneous pelites the texture is characterized by a lepidoblastic felt of tiny, colourless, phyllosilicate flakes with scattered dimensionally orientated

Fig. 9. Phyllite or quartz phyllite showing variable texture depending on grain-size, lepidoblastic towards bottom right, anastomosing phyllosilicate foliae in centre. NE Brekkefjell: plane polarised light.

quartz grains and authigenic ore mineral particles; unresolvable carbonaceous matter is often present. X-ray powder patterns show the mica to be the 2M polymorph of muscovite. Starting from this lithological 'end member' a variety of subtle textural changes can be observed depending on the amount of detrital quartz incorporated in the sediment, and also on the extent to which this has been recrystallised and/or orientated. The otherwise parallel finely crystalline micas envelop the quartzes and other clastic grains thus producing a slightly sinuous anastomosing pattern of discrete pelitic foliae (Fig. 9). Apart from quartz the interfolial material includes detrital muscovite, biotite and chlorite and sporadic tourmaline, zircon and ore mineral grains. The opaques and the tourmalines have frequently developed pressure shadows or fringes consisting of neocrystallised chlorite, sericite and quartz. Interfolial quartzes are generally recognisably detrital except for the more finely crystalline particles, which are recrystallised and dimensionally orientated. In rare cases, overgrowths of quartz on quartz grains are seen.

With increasing grain-size, in which pelites gradually become more silty, the phyllosilicate foliae are more discrete, their spacing increases and the essentially clastic nature of the quartzes is more obvious (Fig. 10). Chlorite is occasionally present within the mica foliae; this appears to be recrystallised in contrast to the bent detrital flakes in the interfolial fabric. Textures in lithologies of the siltstone–sandstone range are less clearly metamorphic as grain-size increases. Matrix phyllosilicates may still show a good preferred orientation but more often than not this is a result of mechanical rotation as the muscovite and chlorite flakes may be flexed and show irregular wavy extinctions: in the same rock, however, recrystallised micas are oriented either

Fig. 10. Slightly metamorphosed siltstone with phyllosilicate foliae enveloping detrital quartz, muscovite, biotite and some plagioclase. Lerbekk Formation, Lerbekken; plane polarised light.

parallel or at a slight angle to the mechanically aligned flakes. Another difference from the more phyllitic lithologies is that the larger detrital grains, e.g., opaque minerals, do not develop any pressure shadow minerals.

Returning to the finer grained pelites and siltstones one often finds evidence, particularly on NE Brekkefjell and at Myssmørbullen, denoting that a fairly considerable extensional strain has occurred within the foliation surfaces, seemingly at a late stage in this early deformation episode. Thin layers and laminae of siltstone in pelite have been stretched and dissected and the lenticular segments pulled apart and sometimes partially rotated, and shearing has been concentrated along siltstone/pelite interfaces. It is in this type of lithology that pressure shadow crystallisation around ore grains, etc., is most prominent. Where siltstone lenticles are particularly numerous and well developed the rock takes on a phyllonitic aspect. Concerning the relative age of this extensional deformation and phyllonitisation it can be shown that it predated the formation of the common asymmetric folds (Fig. 11); it is therefore not directly associated with the thrusting (p. 98), which is post-folding. Local, thin mylonitisation occurring along some thrust surfaces is clearly younger than the development of pervasive lepidoblastic textures and phyllonitisation.

In the western and north-western parts of the area in Lerbekk Formation rocks the degree of metamorphic recrystallisation in the argillites is minimal and a good deal of the preferred orientation of the tiny phyllosilicates is considered to have taken place during compaction. Certain niveaux do, however, show evidence of mimetic growth of muscovite; this may be related temporally to the phase of extensional strain seen elsewhere in the Devonian pelites.

Fig. 11. Lithology approaching a phyllonite, derived from phyllite and siltstone laminae; deformed by micro-scale brittle folds. NE Brekkefjell: plane polarised light.

Infrequent, thin, quartz veins penetrate the phyllite and phyllonite in the north-eastern part of the area. Field observations denote that these were emplaced either just prior to or actually during the phase of phyllonitisation.

In trying to establish the physical conditions of metamorphism of the Røragen Group sediments an upper limit of quartz–albite–muscovite–chlorite sub-facies is imposed by the absence of recrystallised biotite even in rocks in which detrital biotite is fairly common. This does not necessarily imply that the lowest of the three greenschist subfacies is automatically represented; indeed, the wide range of textures and varying degree of recrystallisation present within these rocks warrants a consideration of sub-greenschist facies conditions for a good part of the sequence. In the phyllites and phyllonites the occurrence of 2M mica as the finely crystalline material suggests that temperatures well in excess of 300°C were attained, and more probably in or above the 360°–390°C range just outside the upper stability limits of the clay minerals (Winkler 1967), i.e., well into the pumpellyite–prehnite–quartz facies. The local presence of chlorite is not especially diagnostic as this is also common in sub-greenschist facies assemblages at appropriate bulk rock compositions. Considering both the textural and the restricted mineral assemblage evidence, the conclusion is therefore that metamorphic conditions probably extended up into the very lowermost part of greenschist facies in the north-eastern area during the earliest post-Lower Devonian deformation phase. Movements within the foliation associated with the phase of extensional strain probably generated additional heat, which enabled recrystallisation to occur more pervasively in the pelites.

A possible mechanism to be considered for the actual initiation of a preferred orientation of the phyllosilicates is that of tectonic dewatering of the argillites (cf. Maxwell 1962). Assuming a rapid burial of sediments in this intramontane basin environment, pore water would be very easily trapped in the argillites and with the onset of deformation pore pressures would rapidly increase in these essentially unlithified layers and eventually exceed the lithostatic pressure. The ensuing instability and dewatering promotes a re-orientation of platy phyllosilicates into parallelism with the flow direction of the escaping fluids. With continued external stress, lithification and increasing temperature, recrystallisation would accentuate or modify this fabric. The all-important criterion supporting this mechanism of cleavage initiation is the presence of intrusive clastic dykes parallel to the cleavage. In the Røragen Devonian rocks no such clastic dykes have yet been observed, but a detailed sedimentological study may reveal further data which would either support or reject the feasibility of this process of cleavage initiation. It must be stressed, however, that the present fabric in the phyllitic lithologies is a tectono–metamorphic derivative. The query is over whether or not this conceals evidence of phyllosilicate orientation by dewatering prior to final lithification. Since recrystallisation textures are minimal in pelites in the western part of the area, it would appear that at least some of the preferred orientation of micas may be ascribed to processes of lithification or diagenesis.

Age of diastrophism

Limitations are imposed in determining the age of these parorogenic movements and metamorphism by the occurrence of flat-lying Lower Permian sediments and lavas in the Oslo region, and by the fact that the youngest Devonian sediments in the west Norwegian basins are of Middle Devonian age. Before Holmsen's (1963) discovery of folding at Røragen opinion varied as to the age of the post-Lower Devonian faulting; Holtedahl (1952, 1960) considered the dislocations to be Permian whereas Vogt (1928) presented cogent arguments suggesting a probable early Upper Devonian age – his Svalbardian movements. Radiometric age determinations on some of the phyllites and phyllonites would be of great help in resolving this uncertainty, but nevertheless it is possible from a consideration of the regional geological evidence to suggest the most likely age for the Røragen diastrophism.

In the Oslo region, Jura-type, concentric folding along E–W to NE–SW axes (Strand 1972) affects a Lower Palaeozoic sequence which extends up into the Downtonian on the island of Jeløya (Henningsmoen 1960). The folded succession was peneplaned before the deposition of the flat-lying, unfolded Permian rocks. Both Vogt (1933, 1954) and Holtedahl (1952) were of the view that the pre-Permian folding was probably late- or post-Downtonian but pre-Dittonian ,i.e., of Gedinnian age. Recently, Gee & Wilson (1974) have also suggested an early Devonian age, while Strand (1972) was cautious in not tying down the folding too closely.

Turning to Røragen, the very fact that these Lower Devonian rocks are folded and metamorphically altered would clearly argue against a Permian age for these movements, although this does not dismiss the possibility that Permian, or later, faulting is represented in the area. In west Norway and on the NW side of the Trondheim region Devonian strata ranging up into upper Middle Devonian are folded along E–W to NE–SW axes and locally thrust and mylonitized, movements which have usually been ascribed to the Svalbardian tectonism (Vogt 1928, Nilsen 1968, 1973a, 1973b, Høisæter 1971, Skjerlie 1971, Siedlecka & Siedlecki 1972, Strand 1972). The Røragen folding – along probable early E–W axes with later NE–SW trends – and thrusting fits into this general pattern without difficulty and would almost certainly appear to be of a similar Svalbardian (Frasnian) age.

Comparing the major E–W and mesoscopic NE–SE folds of the east Norwegian Devonian, now represented only by the Røragen outlier, with the character, style and axial trends of the Oslo folding it is tempting to suggest that the post-Downtonian pre-Permian Oslo deformation is also of lowermost Upper Devonian, viz. Svalbardian, age. Between Røragen and the Oslo area is the vast sparagmite basin region in which major and minor, open to tight, concentric folding along approximate E–W axes is ubiquitous (and which post-dates nappe emplacement) and is known to be post-Wenlockian (Skjeseth 1963, Englund 1972). To the present writer it would also seem plausible that a good deal of this post-nappe emplacement folding and local imbrication in the Eocambrian–Silurian sequence of this area could be of approximate Svalbardian age (cf. Oftedahl 1954). In this connection it is interesting to observe that the metamorphism of the sparagmitic rocks locally reached the lower part of greenschist facies in the northern parts of the area whereas only a waning mechanical alteration is recognised towards the south nearer the Oslo region (Englund 1973).

The question arises as to whether or not it is wise to continue using Vogt's (1928) local term 'Svalbardian' for these southern Norwegian late Caledonian movements. There is obviously no reason to expect perfect time concordance over large areas and it may be preferable in the future to introduce local terms, e.g., Røragenian for east and south-east Norway, when speaking of particular deformation events in restricted areas.

Summary of tectonic and metamorphic history

The principal features of the deformation and metamorphic alteration of the Røragen Devonian sediments, which were evidently laid down in a subsiding, partially fault-controlled, intramontane basin following the evorogenic Silurian deformation (Wilson et al. 1973), may be summarized as follows:

1. Diagenetic transformation of the sediments was succeeded by the imposition of tectonic stresses which resulted in the development of a marked lepidoblastic fabric in most of the more pelitic rocks, and produced the southeasterly dip of strata. Slaty cleavage/bedding relationships and minor lineations indicate that the principal compressive stress was oriented

roughly N–S. If sizeable folds of this deformation episode ever existed in the region they would have had E–W axial trends: the entire Røragen sequence is itself positioned theoretically on the southern limb of a large anticlinal structure.

2. In the later stages of this deformation considerable extension occurred within the foliation in the pelites, locally producing phyllonites. Metamorphic conditions ranged up into the lowermost part of the greenschist facies.
3. Mesoscopic, asymmetrical, parallel folds then developed in suitably incompetent lithologies in the north-eastern part of the area. Fold axial plunges are generally between SW and S and overturning is fairly consistently to the north-west implying NW-directed compression.
4. During the folding episode, shearing and minor thrusting were initiated; these disruptive movements reached their peak after folding had ceased. Thrust translation was towards a NW–N point.
5. Normal faults, observed or inferred, post-date the folding and thrusting; some may be rejuvenated syn-depositional fractures. Joints, some of which are filled with quartz and calcite, are also essentially post-folding features.
6. Rare kink bands of ca. ESE–WNE trend represent a late tectonic strain and indicate a continuation of roughly N–S horizontal shortening. Based on the situation obtaining in the west Norwegian Devonian areas, the folding, thrusting and weak metamorphism of the Røragen Group rocks is thought to be of approximate Svalbardian (lowermost Upper Devonian) age. A similar age is proposed for the folding of the Cambro–Downtonian sequence in the Oslo area as well as for the later deformation of the nappe structures in the sparagmite basin region of eastern Norway.

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Appendix

In the introduction (p. 90) the name Røragen Group was proposed for the entire Devonian succession of conglomerates, breccias, sandstones, siltstones and phyllitic shales in this area. The group is divided into three formations which are formally designated as follows:

1. *Lerbekk Formation.*

Name: Lerbekken is a small stream draining the area between Brekkefjellet and Småberga and running into the lake Aursunden. A *type profile* in this and an adjacent unnamed stream has been described by Goldschmidt (1913, pp. 14–16) who noted the *thickness* of exposed beds as ca. 230 m. *Lithology*: the formation consists of interbedded grey sandstone, siltstone and plant-fossiliferous shale (slightly phyllitic) with some thin, intraformational, small-pebble conglomerates. A polymict conglomerate occurs at the base. In addition some horizons of red sandstone are found, particularly near the top of the sequence. For details see Goldschmidt (1913). The *lower boundary* is placed below the basal polymict conglomerate which rests with primary unconformity upon Ordovician Røros Group metasediments. The *upper junction* is recognised to the west of Røragen lake as the base of the overlying serpentinite conglomerate.

2. *Svartberg Conglomerate.*
Name: Svartberget is a small, 751 m hill 200–300 m SW of Røragen lake. It is difficult to name a *type profile*, but a *type area* is that of Svartberget and the area around and to the north of Fjelltjern. The maximum *thickness* was estimated by Goldschmidt (1913, p. 12) as at least 200 m: near the NW end of Røragen lake only a 5 m-thickness is exposed: NE of the lake this conglomerate has not been found. *Lithology*: this comprises a coarse conglomerate or breccia of cobbles, pebbles or angular fragments of serpentinite in a serpentine-rich groundmass. A 10 m-thick unit of grey sandstone and shale occurs within the conglomerate just west of Fjelltjern. Details are given in Goldschmidt (1913, p. 12). The *lower boundary* is the base of the conglomerate, above the red sandstones of the Lerbekk Formation. An *upper boundary* has not been found.

3. *Brekkefjell Conglomerate.*
Name: Brekkefjellet is a prominent 928 m hill almost midway between the Røragen and Tufsingen lakes. A *type area* is that of Brekkefjellet and Geitberget. A *type profile* is difficult to name or measure, but could be taken as a NW–SE traverse half-way between Geitberget and Brekkefjellet. The *thickness* was estimated by Goldschmidt (1913) at over 700 m, but it is probably greater than 800 m. *Lithology*: the formation consists predominantly of a coarse polymict conglomerate or breccia with fragments of Røros Group phyllites and schists as well as quartzites, chert ,sandstone, metagraywacke, vein quartz and other rock-types. Clast size is extremely variable, locally up to 6 dm; the larger fragments are more angular than the cm-sized pebbles. Grey and red sandstone, siltstone and plant-fossiliferous phyllitic shale intercalations occur within this formation. For details, see the papers by Goldschmidt (1913) and Holmsen (1963). The *lower boundary* is only poorly exposed: on the NW side of Småberga it is taken as the base of the polymict conglomerate above Lerbekk Formation lithologies. No *upper boundary* has been found.

South-west of Røragen lake the Lerbekk Formation is overlain by the Svartberg Conglomerate. NW of Røragen the Brekkefjell Conglomerate overlies the Lerbekk Formation. It has generally been assumed that the Brekkefjell Conglomerate is the youngest member of the Devonian sequence, and although this is probably the case there is no direct evidence for this assumption. A possible alternative interpretation is that the Svartberg Conglomerate could be a facies variant of the Brekkefjell Conglomerate, but general lithological characteristics and preliminary palaeocurrent observations do not favour this idea.