The structure of Mellene and Heggeberg, Valdres

By
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Contents

Abstract

Structural study of the Valdres Sparagmite and Mellsenn Formation in their type region between the Jotunheim crystalline rocks and the frontal quartzite nappes of the central southern Norwegian Caledonides has revealed that: 1. the Valdres is recumbently folded and allochthonous within a previously unrecognized, major, nappe-salient which was thrust over structurally discordant Ordovician phyllites and Cambrian slates and arenites, 2. elongation lineations trending azimuth 70-145, oblique to the general NE strike of the Caledonides, are parallel to cleavage-bedding intersections and folds axes of first generation bedding folds that have been overturned toward the south and southwest on the southern margin of the salient, 3. the allochthonous Valdres Sparagmite and conformably underlying Mellsenn Formation are overturned in their type section and are, respectively, Eocambrian and Cambrian-Lower Ordovician of different sedimentary facies from rocks of the same age below, 4. the Valdres Sparagmite at two localities was fold-thrusted to its present position along with Precambrian Jotun rocks

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upon which it was initially deposited. Previous interpretations were that the Valdres Sparagmite is an autochthonous Ordovicion-Silurian orogenic deposit derived from early Caledonide tectonic elements and that the elongation lineations are parallel to directions of tectonic transport in nappes comprised largely of imbricately faulted, upright, sedimentary sequences. The present structural interpretation of the Jotunheim mountains, the Lower Jotun nappe in the southern Valdres district, and the tectonic and sedimentary relations between the Valdres Sparagmite an the main Eocambrian Sparagmite Basin to the east must be reconsidered in the light of these new findings.

INTRODUCTION

Structural data of great importance in establishing the regional structure and stratigraphic position of the Mellsenn Formation and Valdres Sparagmite were collected during the summers of 1965 and 1966 in Mellene, central southern Norway. Because of the clear relationship and stratigraphic conformity here between the Valdres and the fossiliferous Mellsenn, Mellene has come to be the type area of the two formations (Strand, 1938, 1951, 1959). The age of the Valdres Sparagmite established in Mellene and the interpreted structural position of the Valdres between the Lower Jotun nappe and Upper Jotun nappe as seen in the surrounding Valdres district have been the basis for establishing the early Caledonian history of central southern Norway (Strand, 1961, p. 167). Mellsenn-Valdres structural and stratigraphic relationships in Mellene are thus critical in the structural and historical interpretation of the Valdres district, the Jotunheim Mountain area, and the rest of southern Norway.

This paper describes the structure of the area, discusses the tectonic implications of the data, and briefly lists stratigraphic units used in mapping. For complete correlations the reader should refer to the accompanying complementary paper of Dr. Jörg Loeschke. Owing to past discussion (Strand, 1959, 1962; Kulling, 1961) regarding the stratigraphic position of the Valdres Sparagmite and the relations between the Valdres and the Mellsenn Formation, exposed in its type section along the south-facing slope of Mellene, the primary (sedimentary) and secondary (structural) evidence bearing upon the primary up-direction of beds is given emphasis in this paper.

Mellene and Heggeberg comprise an area of approximately 130 square kilometers, apparent on the 1960 Geologisk Kart over Norge as a peninsula of Valdres Sparagmite projecting south from the southwest side of the main region of Valdres exposure (see Index map, Fig. 1). My interest in the structural problems of this region was aroused by the publications of Professor T. Strand (1938, 1944, 1951, 1954) and by his able guidance in the field during the 21st International Geological Congress (Strand and Holmsen, 1960). Earlier work of importance in formulating our present interpretation of the structure and

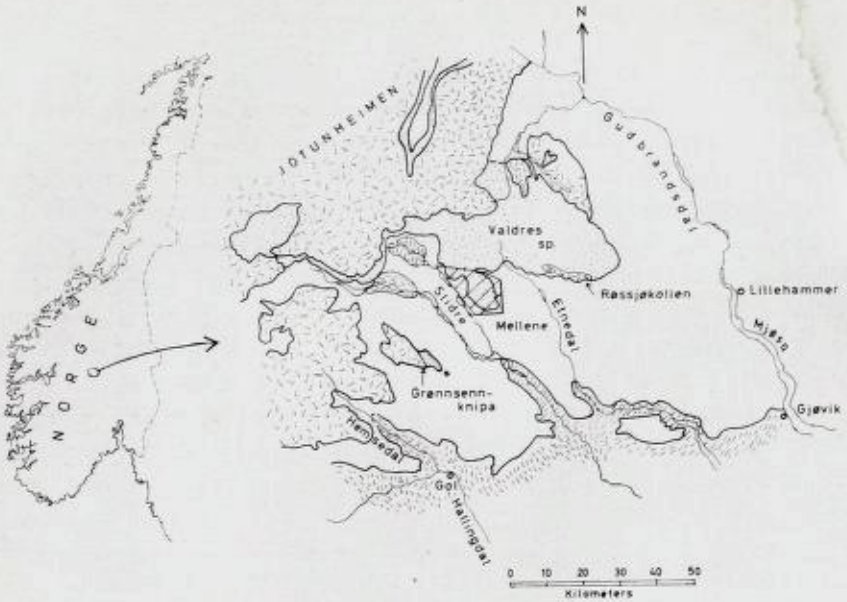

Fig. 1. Index map of central southern Norway

geologic history was that of Goldschmidt (1916) and Björlykke (1884, 1905). During 1965 I worked in the Grønsennknipa area from July 1 - August 10 and in Mellene from August 30 - November 1. Field work was continued during 1966 in Mellene and Heggeberg from June 27 to July 21. Geologic mapping was facilitated by the accurate outcrop maps of Professor Strand (Slidre and Nordre Etnedal sheets) and the geologic map (fig. 10) should be studied in conjunction with these previously published maps. In Mellene, mapping was done at a scale of 1 : 50,000 on the Fullsenn (sheet 1717 IIII) and Slidre (sheet 1617 II) quadrangles of Series M711, or at a scale of 1 : 25,000 on photographic enlargements of the above maps. In addition, thirty critical localities within these map areas were mapped by pace and compass methods at an approximate scale of 1 : 5000. Air photos of the region at a scale of ca. 1 : 40,000 flown in 1955 by the AMS were essential to the structural interpretations given below. Compass readings were recorded in 360° and the data in figures 2 and 3 were plotted in the lower hemisphere of a Schmidt net.

ACKNOWLEDGEMENTS

This paper has been greatly improved by discussions and field excursions with Dr. Jörg Loeschke, who has been working in the same areas on related geologic problems. His warm friendship and free exchange of ideas have made this work both stimulating and pleasurable. It is also a pleasure to acknowledge: the help and interest in the progress of this work shown by Professor Trygve Strand, the facilities placed at my disposal by the Institutt for Geologi, Blindern, the aid in preparing the acetate peel of figure 4 received from Amanuensis Knut Björlykke, the photographic work of A. Wisth, the constructive comments and stimulating discussions of Professors O. Holtedahl, Anders Kvale and Chr. Oftedahl on problems of Norwegian tectonics. My research in Norway was made possible by a NATO Fellowship and through a leave of absence and financial grant from Bucknell University, Lewisburg, Pennsylvania, U.S.A. Finally, loan of air photos during 1966 from the Norges Geologiske Undersökelse greatly faciliated my work.

CLASSICAL STRATIGRAPHY

Strand and Holmsen (1960, p. 4) have given the following stratigraphic sequence in the area surrounding Mellene, listed in ascending order:

1. Eocambrian quartz sandstone.
2. Lower Cambrian alternation of shale, siltstone and sandstone perhaps 200 m thick,
3. Middle and Upper Cambrian alum shales and Lower Ordovician shales,
4. Phyllite Formation of dark fine-grained phyllites which has yielded graptolites indicating Llanvirian, Llandeilian and possibly lowermost Caradocian horizons; perhaps 300 m. thick,
5. Mellsenn Formation, comprised of basal dark-colored slates and sandstones and upper greenish, reddish and purplish slates and light colored sandstones, up to 200 m. thick,
6. Valdres Sparagmite, a thick sequence of arkoses (sparagmites) and conglomerates.

The Valdres Sparagmite in Mellene and the rest of the Valdres district has traditionally been interpreted as autochonous in normal stratigraphic position over the Mellsenn Formation and Phyllite Formation upon which it rests (Strand, 1938, p. 47). As summarized by Strand (1959, p. 186—191, 197), the Phyllite Formation, bearing Lower Ordovician (3b and 3c) Arenigian graptolites, is overlain by the Mellsenn Formation containing, in its topographically lowest part, Middle Ordovician (4a) Llandeilan graptolites. The Mellsenn Formation grades upward into the Valdres Sparagmite, and this part of the sec-

tion has been interpreted as Caradocian or younger with the Valdres Sparagmite perhaps being partially equivalent to Lower Silurian Llanoverian sandstone in the northwest part of the Oslo region (Strand, 1951, p. 197). However, Holtedahl (1959) has shown in the nearby Grönsennknipa area that the Valdres is allochthonhonous, resting upon a nearly flat thrust above Phyllite Formation, and Kulling (1961) has suggested that the Valdres Sparagmite in Mellene is Eocambrian. Parts of the sequence of Cambrian sandstones, slates and shales, occurring in normal stratigraphic succession beneath the Phyllite Formation, show lateral facies changes to the east. To the southwest of Mellene in the Östre Slidre valley, Strand (1951) has described a section comprised of Middle and Upper Cambrian alum shales and Lower Ordovician shales, underlain by Lower Cambrian gray interbedded shale, siltstone and sandstone. To the southwest of Mellene, only 10 kilometers east of Östre Slidre, the Middle and Upper Cambrian dark bituminous alum shales persist but red or green slates interbedded with sandstones occur in the Lower Cambrian. These red or green slates are irregular in occurrence but extend to the east border of the Nordre Etnedal map area (Strand, 1938, p. 17—18). Coarse-grained, dark gray, Eocambrian quartz sandstone is exposed in the lowest part of the Östre Slidre valley in normal stratigraphic succession beneath the Cambrian. The quartz sandstone and all other stratigraphic units up to the Mellsenn Formation are presumably allochthonous as part of the «quartz sandstone nappe» which has been traced to the vicinity of Fagernes, only 12 kilometers south of Mellene (Strand, 1954).

Changes in this stratigraphy resulting from the present work and that of J. Loeschke are discussed under «Revised Stratigraphy» after the evidence for the revision has been presented.

GENERAL STRUCTURAL DESCRIPTION

The Valdres Sparagmite of the Valdres district lies between the two main groups of Caledonide nappes described by Strand (1961, p. 163) in his summary of the Scandinavian Caledonides. To the southeast lie nappes composed of rocks of Eocambrian and Cambro-Silurian age and to the northwest lie higher nappes composed of sediments of western eugeosynclinal facies and basement crystalline rocks. In view of this, it was particularly interesting to discover that the whole Mellene plateau and Heggeberg are part of an intermediate nappe, here named the Mellene nappe, underlain by a large, essentially flat, overthrust (the Mellene thrust) ranging in altitude from 700 to 1000 meters. Gross structural relations are the same as reported by Holtedahl (1959, 1960) at Grönsennknipa and it is clear that this is one of a group

major tectonic breaks, here named the Valdres nappes (following Kulling, 1961), along which the sandy-textured Valdres Sparagmite and Mellsenn Formation have been thrust over phyllites of the Phyllite Formation. Imbricate slices rise off the basal thrust as shown by relations north and south of Rundemellen (Section I, figure 11). Here the basal thrust north of Rundemellen cuts up through the Valdres Sparagmite and overrides the allochthonous Valdres of Skarvemellen to the south, while the basal thrust to the south rises and is truncated by the Rundemellen slice. These two silces, both parts of the Mellene nappe, show similar stratigraphy and have been described and named the Rundemellen schuppe and Skarvemellen schuppe by J. Loeschke.

The following structural relations at the Mellene thrust have been observed in Mellene and Heggeberg:

1. Overturned Mellsenn Formation conformably underlying Valdres Sparagmite and thrust over Phyllite Formation. Such relations occur for 8 km along the south slope of Mellene.
2. Overturned Valdres Sparagmite in thrust contact above overturned Mellsenn Formation which is in turn thrust over Phyllite Formation. At such places the Mellsenn Formation exists as slices stretched and broken along the Mellene thrust zone such as may be seen at localities labeled 2 on figure 10:
   a. north and south of Rundemellen, b. at Rennsenn seter, c. at Vangsjöen, d. at Heggeberg.
3. Overturned Valdres Sparagmite in thrust contact above Phyllite Formation such as may be seen at localities labeled 3 on figure 10:
   a. north of Bergo, b. in northwestern Mellene.

The Mellsenn Formation in Mellene and Heggeberg is always associated with the Mellene thrust at the base of the Mellene nappe either, as in 1 above, overturned above the thrust in conformable sedimentary sequence beneath overturned Valdres, or, as in 2 above, bounded above and below by thrusts separating it from the underlying Phyllite and the overlying Valdres. Where these thrusts come together the Mellsenn is pinched out and the Valdres directly overlies Phyllite Formation as in 3 above. The Mellsenn thus is overturned, stretched, broken and, in places, absent in the Mellene thrust zone beneath the Mellene nappe, showing features common in middle stretched and broken limbs in recumbent anticline-syncline combinations.

This paper is primarily concerned with the structure of the allochthonous Valdres within the Mellene nappe, consisting of a number of northwest-southeast to east trending, overturned or recumbent folds that are overturned to-

ward the south and southwest. On the geologic map (fig. 10) and the structure sections (fig. 11) several major folds can be traced throughout the area. These structures have been labeled for easy reference with letters A—G on the structure sections of figure 11. The Skarvemellen recumbent anticline (A) is well shown at the south and southwest margin of Mellene in the air photo of figure 8 and in structure sections I, II, III, and IV of figure 11. The next major structure to the northeast is the Öyangen overturned syncline (B) which is well-exposed on three peninsulas along the north shore of Lake Öyangen (fig. 10) and may be seen on structure sections III and IV of Figure 11. Northeast of Öyangen lies a complex belt of smaller scale overturned and recumbent folds that cover the area north to the northeast border of Mellene. Within this complex there appears to be an anticlinorium (C) followed to the northeast by a synclinal area (D) passing through Rennsenn vann. At the northeast limit of Mellene, as shown on sections II, III, and IV (fig. 11) there is a general steepening or overturning (E) which extends as a prominent ridge from Rennsenn seter northwest through Rolistöl to Vindaasen, northeast of Heggeberg (fig. 10). The structure to the northeast of this steep zone can be seen on the northeast extension of structure section V through Heggeberg. Structure section V northeast to Gravfjellet (off the map area) shows the existence of an overturned anticline (F) followed to the northeast by an overturned syncline (G) at the southwest base of Gravfjellet.

Not all major structures can be traced from eastern Mellene to Heggeberg on the northwest. Owing to the east plunge in southern Mellene, the area of structure section II is structurally higher than structure sections II, III, and IV and, in the northern half of section I, only steep to overturned dips occur. Folds B, C and D cannot be traced east to structure section I. Except for the continuity of the steep limb (E), connections between Mellene (structure section IV) and Heggeberg (structure section V) are uncertain because of the poor exposures between the two areas. The plunge here is to the northwest and many of the folds are cut off against the Mellene thrust leaving only the nearly horizontal Valdres Sparagmite of Heggeberg as a thin plate above thrust. The structure of Heggeberg cannot be traced to the southeast and although I believe the Valdres Sparagmite of Heggeberg is overturned, no primary evidence of the overturning was found.

However, the Mellsenn Formation below the Valdres Sparagmite on Heggeberg is definitely overturned as proven by overturned Mellsenn stratigraphy in sections on the north, west, and east slopes of Heggeberg. The best section is exposed on the extreme eastern point of the summit of Heggeberg, near

the 2 on the geologic map (fig. 10). Here, in ascending order above the thrust separating the Mellsenn Formation from the Phyllite Formation below, the following overturned sequence is found:

1. Gray slate (2 m.) (Unit 1 or 2, Table I)
2. Dark gray quartzite, «Blauquarz» (20 m.) (Unit 3, Table I)
3. Greenish gray slate, «Dachschiefer» (10 m.) (Unit 6, Table I)
4. White quartzite, «Mellsenn quartzite» (10 m.) (Unit 7—9, Table I)
5. White, chalky, sheared feldspathic quartzite, Valdres Sparagmite in a movement zone or thrust
6. Sheared, pebbly, green Valdres Sparagmite

Some Mellsenn stratigraphic units are missing and all units present are sheared and tectonically thinned as is typical wherever the Mellsenn Formation is seen north of the type section on the south slope of Mellene. The contact between the Mellsenn and the Valdres seems to be a thrust or zone of intense shearing and movement. Owing to uncertainty about the true nature of this zone, it has not been shown as a fault on the geologic map (fig. 10).

To demonstrate the structural relations between the allochthonous Valdres Sparagmite of Mellene and the underlying Phyllite Formation and Cambrian rocks, structure section III was extended southwest across the bottom of the Östre Slidre valley. The Cambrian rocks are brought to the surface in this valley along an asymmetric anticline which plunges azimuth 325 toward the northwest as shown on the Slidre map sheet of Strand (1951) and figures 10 and 11 of this paper. Reconnaissance in areas to the south of Mellene, inspection of air photos, and study of maps of Strand (Slidre, 1951; Nordre tnedal, 1938; Aurdal, 1954) has shown that this is a consistent trend and plunge direction for folds in the Phyllite Formation, Cambrian rocks, and Eocambrian quartz sandstone in the «quartz sandstone nappe» near Fagernes. The southeast to east plunging folds of the allochthonous Valdres Sparagmite in the southern part of the Mellene nappe are thus structurally discordant with the northwest plunging folds in the Eocambrian quartz sandstone, Cambrian rocks, and Phyllite Formation below the Mellene thrust.

STRUCTURAL ELEMENTS

Structural elements occurring here include planes and lineations. Planes are bedding (S_0), slaty cleavage (S_1) and slip cleavage (S_2). Generally, the rocks are low-grade metamorphic rocks with well-preserved relic bedding and primary sedimentary structures in all arenites and with predominant secondary foliation (slaty and slip cleavage) in argillaceous sediments. Slaty cleavage is readily visible in all arenites containing more than 10 % metamorphically

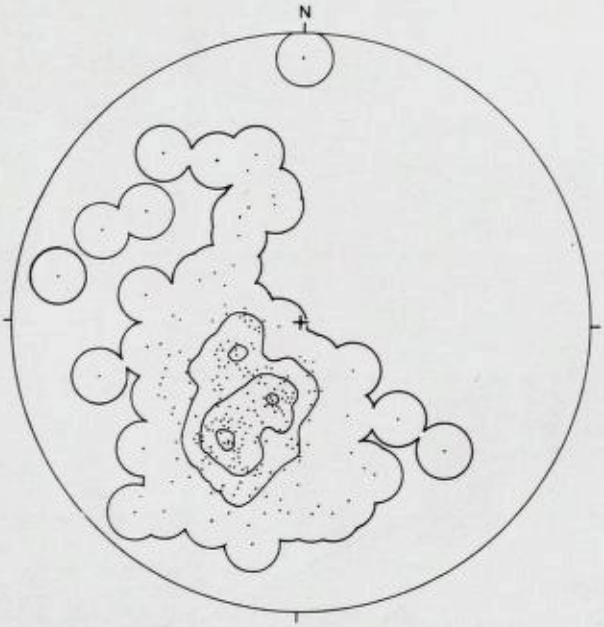

Fig. 2. Poles to slaty cleavage in Mellene
236 poles plotted; contours: 4,5,10,15 % per one% area

recrystallized and oriented argillaceous matrix and may, in places, be seen as planes of grain distortion in purer arenites. Most slates and phyllites show bedding in addition to slaty and slip cleavage but correct identification of primary and secondary S-planes is, in places, difficult. Slaty cleavage predominantly strikes northwest and dips northeast throughout Mellene (see fig. 2). As slaty cleavage approximately parallels the axial planes of folds, dipping more steeply on right-side-up limbs and less steeply on overturned limbs, the center of concentration of slaty cleavage poles on figure 2 is assumed to approximate the pole of the regional axial plane. This regional «average» axial plane strikes NW (approximate aximuth 300°) and dips 20—40° NE. In detail each fold of the region has its own axial plane diverging somewhat in both strike and dip from this average, but it is helpful to visualize the folds of the region with this model. Viewed in company with the recorded bedding attitudes, such an axial plane requires that folds be overturned or recumbent.

Slip cleavage is visible only in slates and phyllites so few measurements could be made in the Valdres Sparagmite. In the Mellsenn and Phyllite Formations, slip cleavage strikes E and dips steeply. To the north in the vicinity of Heggeberg (structure section V, fig. 11) slip cleavage is prominent and

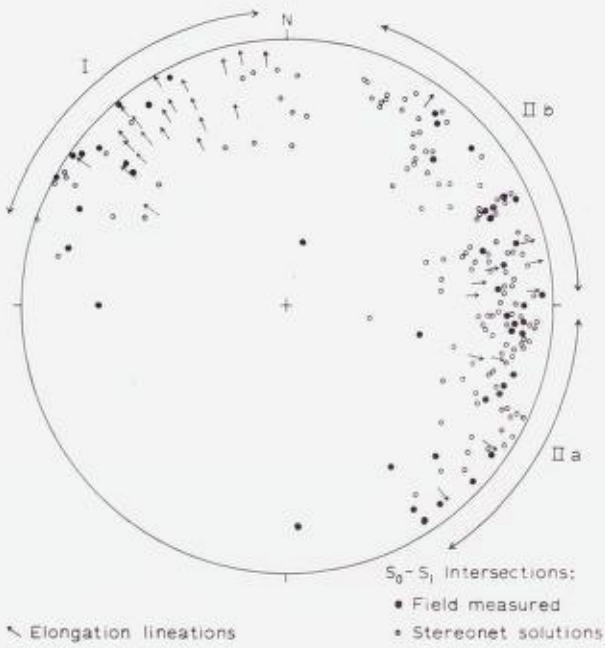

Fig. 3. Lineations in Mellene and Heggeberg
45 bedding (S_0)- slaty cleavage (S_1) intersections measured in the field
130 bedding (S_0) slaty cleavage (S_1) intersections determined on stereonet from field measurements of S_0 and S_1
32 elongation lineations

oriented parallel to the axial plane of late folds of bedding and slaty cleavage but in most of this region it is indistinct and expressed only as intersection lineations on S-planes of earlier origin.

Lineations of three descriptive classes (intersection, elongation, crinkling) and two periods occur in Mellene and Heggeberg. Quantitatively most important are lineations produced by intersections of S-planes:

L_1 — intersections of bedding (S_0) and slaty cleavage (S_1)

L_2 — intersections of slaty cleavage (S_1) and slip cleavage (S_2)

Such intersection lineations are commonly associated with and parallel to lineations of another descriptive class produced by small-scale folds or crinkles of either bedding (S_0) or slaty cleavage (S_1). L_1 lineations of both intersection and minor fold type are inferred to be parallel to major fold axes. No major structures paralleling L_2 lineations were recognized in the area surrounding Mellene, but in the Phyllite Formation surrounding Heggeberg large folds of bedding (S_0) and slaty cleavage (S_1) with slip cleavage (S_2) axial planes were

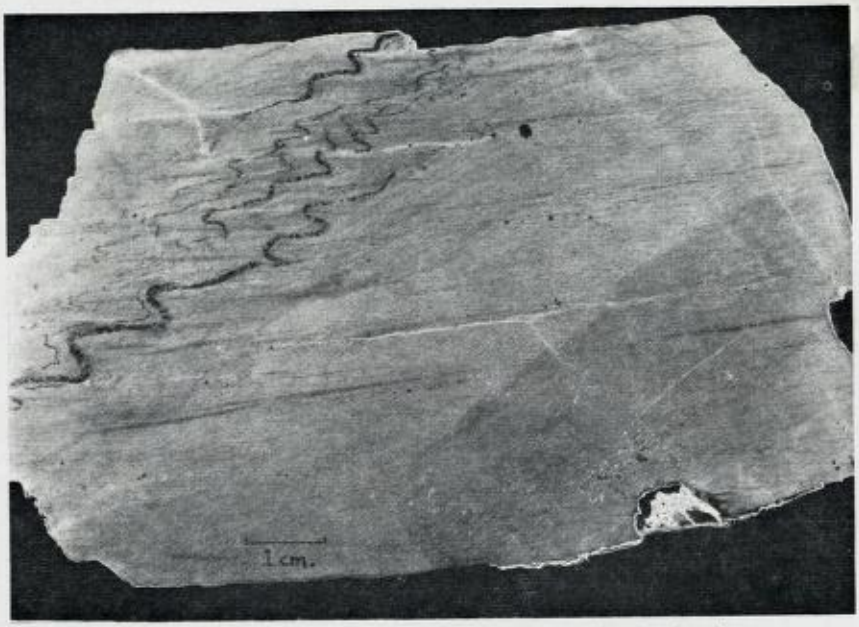

Fig. 4. Acetate peel from etched slab of slate collected at locality illustrated in figure 5. Shows slaty cleavage (E-W) and overturned bedding with parallel quartz veins (NE-SW). Parasitic bedding folds show «S» sense common to all E and NE plunging L_1 folds of the area.

seen (structure section V, fig. 11). These L_2 folds trend generally east-west and appear as warps in the bedding of the Valdres Sparagmite on Heggeberg as well as in the phyllites below. More study is needed at Heggeberg and to the north to establish the extent and significance of this L_2 fold system.

Cross sections of L_1 folds are concentric„ grading to similar, with thinning of limbs and thickening of hinges as shown in figure 4, but cross sections of L_2 folds are more nearly chevron or V-shaped. Both L_1 and L_2 folds are of «S» sense when viewed down the most common easterly plunge direction (see, for example, small scale, «S» sense, L_1 folds in figure 4).

In Mellene, the least commonly observed lineations are elongation lineations, seen in slaty cleavage planes at only 12 localities as grains of quartz or feldspar with elongation ratios of approximately 1.5 : 1 to 2 : 1. Some elongated feldspars are broken by open tension cracks perpendicular to the elongation lineation. Elongation lineations are parallel to L_1 slaty cleavage-bedding intersections and minor folds and presumably of similar age. In the more intensely deformed rocks of Heggeberg, elongation lineations with elongation ratios of

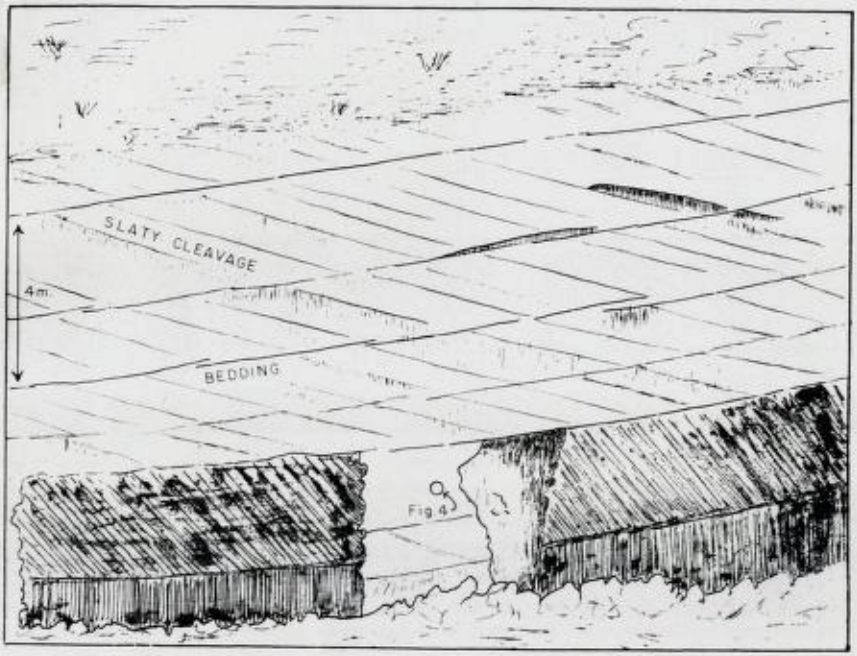

Fig. 5. Sketch of westernmost Valdres skiferbrudd showing slaty cleavage and overturned bedding. Circle shows locality of specimen illustrated in fig. 4.

2 : 1 to 4 : 1 were seen at nearly every outcrop of Valdres Sparagmite, but no folds could be mapped. Thus the relations between elongation lineations, and fold axes or cleavage-bedding intersections could not be determined, but, as the elongation lineations of Heggeberg parallel the bearing and plunge of the elongation lineations of northwestern Mellene, they are inferred to possess similar geometric relations.

Relations between planes, lines, and folds described above are summarized below:

L_1 = intersection of bedding (S_0) and slaty cleavage (S_1) = minor sinistral concentric to similar folds of bedding = elongation lineations = fold axes of major overturned and recumbent folds with slaty cleavage as the approximate axial plane = *b* of the 1st deformation phase.

L_2 = intersection of slaty cleavage (S_1) and slip cleavage (S_2) = minor sinistral chevron folds of slaty cleavage with slip cleavage as axial plane = *b* of the second, minor, deformation phase.

L_1 lineations plunge northwest, southeast, east, and northeast (fig. 3) but all lie approximately in the axial planes of the region as shown by comparison

of plots of lineations and poles to slaty cleavage in figure 3 and figure 2. Note that poles to slaty cleavage are grouped near the stereonet center in the southwest quadrant of figure 2 whereas lineations plot near the periphery of the northwest, northeast and southeast quadrants of figure 3. When the geologic map position of different lineations (fig. 10) is compared with their stereonet position (fig. 3), two subgroups within the broad band of lineations can be delimited. Lineations in the northern part of Mellene and in Heggeberg plunge northwest, giving rise to subgroup I in the northwest quadrant of figure 3. Lineations and folds in the Skarvemellen anticline and Öyangen syncline plunge southeast, giving rise to subgroup IIa in the east and southeast quadrant of figure 3. In the eastern recumbent part of the Skarvemellen anticline, and in the weak Mellsenn slates of the slate quarries along the south slope of Mellene, L_1 lineations and folds plunge northeast and north, giving rise to subgroup IIb. Inspection of the geologic map thus shows that different lineation orientations within Subgroup II are a function of different positions on the Skarvemellen recumbent fold and perhaps different rock types and their different response to folding and flowage. However, all L_1 lineations are *b* lineations despite their diversity in orientation.

CRITERIA FOR ESTABLISHING PRIMARY UP-DIRECTION OF BEDS

Rigorous structural analysis of overturned to recumbent folds in sedimentary strata requires evidence of the primary up-direction of beds, particularly in areas like Mellene where there has been prior discussion about the age of the sedimentary sequence and where the trend of fold axes, transverse to the regional strike of the Caledonian mountain range, allows no simple inference about directions of overturning from the general assymmetry of the range. As demonstrated below, after the primary up direction has been proven at a small number of key localities, secondary structural evidence can be used with confidence to trace the structure throughout the area.

Primary sedimentary structures

The Mellsenn Formation and Valdres Sparagmite occur in an unbroken, conformable, north-dipping, sequence along the south-facing slope of Mellene, (Strand, 1959, p. 188) so evidence of primary up direction in either stratigraphic unit may be extended to the other. Unequivocal primary sedimentary evidence of the up-direction has been found in both units but is most common and best preserved in the Valdres Sparagmite. Cross-bedding and, at one locality, oscillation ripple marks, show the Valdres Sparagmite along the upper

Fig. 6. Overturned oscillation ripple marks in the Valdres Sparagmite of Skarvemellen

part of the south-facing slope of Mellene to be overturned, so the Mellsenn Formation is also overturned.

Best exposures of cross-bedding occur on Skarvemellen, where cross-bedded units in light-colored Valdres Sparagmite are tabular or wedge-shaped and 1-4 feet thick with sets of cross-strata nearly straight, meeting both bounding bedding planes at approximately equal angles. This cross-bedding is most like the planar cross-bedding of McKee and Wier (1953, p. 387) and is difficult to utilize in determining facing directions (Strand, 1962). However, a few localities show cross-stratification with erosional truncations facing down and to the south in beds striking approximately E-W and dipping 25 - 50° N. These localities, interpreted as proving overturning, are marked with a symbol showing the up direction on the geologic map (fig. 10). Curvature of cross-bedding laminae within cross-bed units occurs in some places and is invariably concave down to the south, supporting the contention that the section is overturned.

Overturned oscillation ripple marks on the under side of a bedding plane striking N 70 E and dipping 66° NW on Skarvemellen are additional evidence of overturning (fig. 6). This exposure is marked in the field with a cairn and has been marked with a symbol on the geologic map; it is regarded as unequivocal primary proof of overturning of the Valdres and Mellsenn sections in southern Mellene.

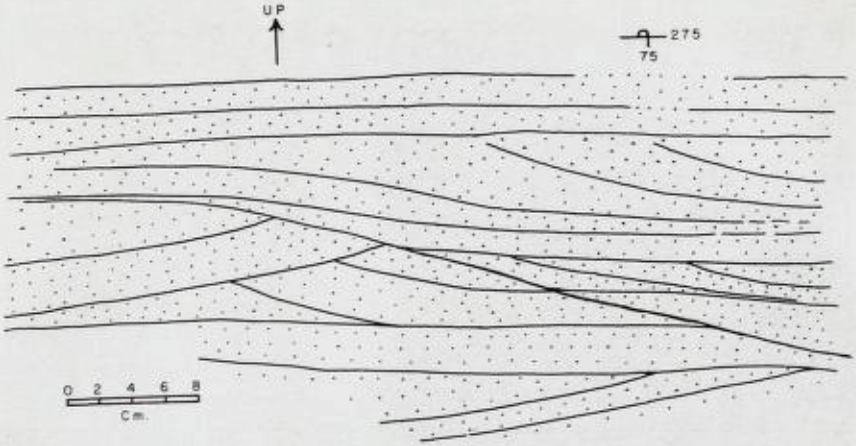

Fig. 7. Cross bedding in a Mellsenn quartzite

In a white Mellsenn quartzite (Unit 9, Table I) up slope from the eastern quarry of the Valdres skiferbrudd the cross-bedding illustrated in figure 7 also shows the up direction to be south, supporting the evidence from the Valdres Sparagmite that the Mellsenn-Valdres section on the south-facing slope of Mellene is overturned.

Secondary structural evidence

Three different lines of structural evidence show overturning of the Valdres and Mellsenn along the south-facing slope of Mellene:

1. slaty cleavage - bedding relations.
2. «S» sense of parasitic folds.
3. bedding attitudes in the Skarvemellen recumbent anticline.

Slaty cleavage-bedding relations indicating overturning are illustrated in figure 5, a view of the westernmost Valdres skiferbrudd looking northeaast down the plunge of minor L_1 folds and slaty cleavage-bedding intersections. Overturned bedding on the lower limb of the Skarvemellen recumbent anticline dips north more steeply than the northeast-dipping slaty cleavage, a common relationship in overturned beds throughout the region. On the right-side up limb of the Skarvemellen recumbent anticline, southwest of Rundemellen, bedding dips northeast less steeply than cleavage, in a relationship typical of right-side up beds in the region. Numerous other outcrops demonstrate the validity of hese cleavage-bedding relations in proving up directions of beds.

The sense of parasitic folds viewed down-plunge in overturned beds of the

Fig. 8. Air photo of southern Mellene showing trace of Mellene thrust, Rundemellen schuppe, and Skarvemellen recumbent anticline

region is demonstrated by figure 4, a polished slab cut perpendicular to L_1 lineations from the slate quarry illustrated in figure 5. In figure 4 cleavage-bedding relations are the same as shown at a different scale in figure 5 and parasitic folds are of «S» sense, the sense to be expected in the overturned limb of a fold with the orientation of the Skarvemellen recumbent anticline.

Overturning of the Valdres and Mellsenn formations along the south-facing slope of Mellene is also proven by the map of bedding attitudes in the Skarvemellen recumbent anticline. In the superbly exposed area between Skarvemellen and Rundemellen, bedding can be traced continuously around the nose of the northeast-plunging Skarvemellen recumbent anticline, leaving no doubt of the shape of the fold in this area (figure 8, 10, 11). Bedding attitudes in the Öyangen overturned syncline, well-exposed on three peninsulas along the north shore of Öyangen, also demonstrate the fold pattern of the region, and by extension, prove the existence of great overturning. Throughout the map area, up direction of beds as determined by cross-bedding in the Valdres Sparagmite (see symbols on geological map, fig. 10) has agreed with independent determination of up direction based upon secondary structural evidence. The resulting structural synthesis has been discussed above and is shown on the geologic map (fig. 10) and the structure sections (fig. 11).

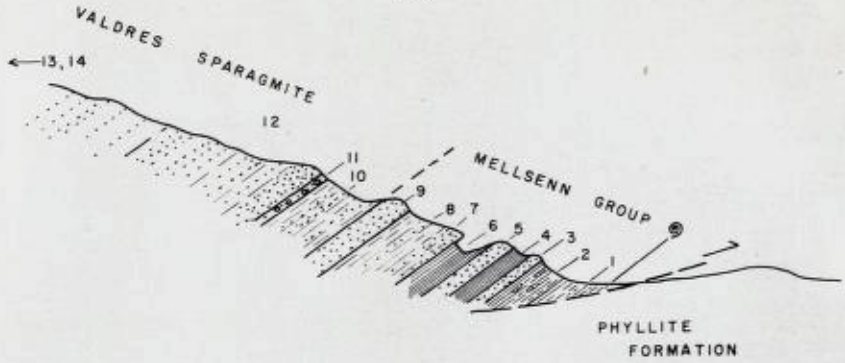

Fig. 9. Schematic, composite section showing stratigraphic units on the south slope of Mellene

REVISED STRATIGRAPHY

Mellene stratigraphy is illustrated in figure 9 ,a schematic composite section showing stratigraphic units as they occur in the overturned section along the south face of Mellene, and in Table I, a list and brief field description of the same lithologic units in correct stratigraphic position. This stratigraphy is more completely described in an accompanying paper by Dr. Jörg Loeschke.

If the evidence for up direction of beds is accepted, it is certain that the Valdres Sparagmite is stratigraphically below the Mellsenn Group (new designation of J. Loeschke) at the overturned section on the south slope of Mellene. As this is the type section for the Mellsenn Group and the one place in the region were an unbroken sedimentary transition between the Mellsenn and Valdres exists, it serves to establish the relationship between Mellsenn and Valdres. In the topographically lowest and stratigraphically highest part of the Mellsenn Group at Mellsenn seter in this section, Björlykke (1905, p. 466, discussed in Strand, 1938, p. 22-23) found graptolites belonging to division 4a of the standard Lower Paleozoic sequence of the Oslo region. Thus, most of the Mellsenn Group and all of the Valdres Sparagmite must be older than middle Ordovician. The 4a fossils at the overturned stratigraphic top of the Mellsenn Group are allochthonous and have been thrust above older fossils (dated as 3a-3b, (Strand, 1938, p. 21)) collected by Björlykke (1905, p. 462-466) in the Phyllite Formation nearby. The new data on the thrust underlying Mellene and the overturning of the Mellsenn-Valdres section above the thrust thus confuses what was previously thought to be a normal unbroken succession from older to younger rocks. It is probable that the Valdres Sparagmite is Eocambrian as has previously been suggested, on different ground, by Kulling (1961). The following arguments support an Eocambrian age for the Valdres Sparagmite:

Table I — *Composite stratigraphic section — southern Mellene*
Compiled from my observations and from data of J. Loeschke

Unit	*Description*	*Equivalent units of J. Loeschke*	*Björlykke, 1905, p. 466*	
1	Dark gray or grayish black slate. Graptolites collected here by Björlykke (1905, p. 466) at Mellsenn Seter stated by Strand (1938, p. 23) to belong to division 4a, lower Middle Ordovician	Mellsenn-schiefer	2	Mellsenn Group
2	Dark gray slate with brownish-weathering impure limestone lenses and beds		3	
3	Massive, medium to dark gray, coarse-grained «blue quartz» quartzite		5	
4	Thinly-laminated medium gray and light gray slate. Laminations less than 1 mm. thick	Mellsenn-	4	
5	Massive, light to medium gray, coarse-grained, quartzite with some «blue-quartz» beds. This unit and 3 produce a prominent ridge down slope from the slate quarries	Blauquartz	5	
6	Greenish gray and grayish red purple slate with one thin bed of dololutite. Main quarry horizon of the Valdres skiferbrudd	Mellsenn-Dachschiefer	6	
7	Light greenish gray, medium-grained, thinly-bedded quartzite			
8	Interbedded grayish red purple slate and fine-grained grayish red purple sandstone or grayish green sandstone	Mellsenn-Quartzite	7	
9	Massive, white, medium-grained quartzite forming a prominent ridge above the Valdres skiferbrudd			
10	A complex, poorly exposed unit comprised of interbedded grayish red purple and greenish gray silty slate, fine to medium grained sandstone and sparagmite			Valdres Sparagmite
11	Grayish red tilloid conglomerate with nonlaminated matrix and boulders of granite and basic plutonic rocks to 20 cm. maximum dimension. This unit is less than 2 meters thick but differs from all other rock types of the area in containing abundant matrix and exotic boulders	K 3		
12	Grayish pink to light brownish gray, medium grained feldspathic quartzite, approximately 650 m. thick, containing near the middle a quartzite conglomerate (K 2) with some boulders of rhyolite	Rundemellen type K 2	8	
13	Greenish gray, dark gray and pink or red, pebbly to conglomeratic «trikolorsparagmite» varying from meta-arkose to meta-graywacke, approximately 1350 m. thick with quartzite and quartz-feldspar conglomerate (K 1) at top	Rognslifjell type K 1		
14	Grayish green, pink and gray coarse-grained meta-arkose and meta-graywacke, at least 1000 m. thick.	Rabalsmellen type		

1. In Mellene, where the base of the Valdres Sparagmite is not exposed, Loeschke has described a Valdres section approximately 3000 meters thick, measured down from the Mellsenn Group along the northern half of structure section I, figure 11. On the basis of structural interpretations presented in structure section I-V of figure 11, this must be considered a minimum value for the thickness of the Valdres Sparagmite in this area. Note that folds F and G on the northeast end of structure section V are interpreted to occur in Valdres Sparagmite stratigraphically below the Valdres section exposed in Mellene. The unfaulted base of the Valdres Sparagmite has been described only on southern Grönsennknipa (Goldschmidt, 1916: Holtedahl. 1959) where the Valdres Sparagmite, with a quartzite-boulder conglomerate near the bottom, rests upon crystalline Jotun rocks. Contrary to the observations of Goldschmidt (1916, fig. 2), only at or near the locality illustrated by Holtedahl in figure 8 (1959, p. 102) is an unequivocal sedimentary contact presently exposed, and even here the contact has been slightly disturbed (Holtedahl, 1959, p. 102) during simultaneous folding of the Valdres and Jotun rocks. This contact establishes the nonconformity between Jotun rocks and the Valdres Sparagmite but there is no compelling reason for accepting Goldschmidt's view (1916, p. 40, 56) that the Valdres conglomerate was deposited on or in front of the eastward sloping surface of the Jotun rocks during their forward movement. Now that it is certain that the Valdres is allochthonous and older than middle Ordovician it is logical to suggest as originally proposed by Kulling (1961), that both the Valdres and Jotun rocks were thrust to their present position together after Eocambrian deposition of the Valdres upon Precambrian Jotun rocks.

   In summary, the Valdres Sparagmite is a thick clastic unit, nonconformable on Precambrian Jotun crystalline rocks and folded and thrust to its present position together with Jotun rocks. Even if the upper part of the Valdres is interpreted as Cambrian or Lower Ordovician, it is probable that the great mass of Valdres is Eocambrian since similar thick clastic sections are known only in the Eocambrian and Devonian of Norway.
2. As reported by J. Loeschke in an accompanying paper, the Mellsenn-Valdres section in Mellene shows similarity of rock types and sequence to classic sections near the Eocambrian-Cambrian boundary in the Sparagmite basin to the east, and in the lower Paleozoic of Hardingervidda. Refer to the Loeschke paper for suggested correlations to other Norwegian sections made possible by overturning the Mellsenn-Valdres section. Most striking similarities known to the writer occur between:

1. the thin, lensing, tilloid conglomerate (Unit 11, Table I) and the Eocambrian Moelv tillite of the Sparagmite basin,
2. the Mellsenn quartzite (Unit 7, 8, 9, Table I), Mellsenn slate (Unit 6, Table I) and Cambrian units of the eastern part of Nordre Etnedal and Gausdal.

If these correlations are valid, the Mellsenn Group is Cambrian and Lower Ordovician and the Valdres Sparagmite is Eocambrian.

SUMMARY AND CONCLUSIONS

Stratigraphy and Geologic History

The type section of the Mellsenn Group and Valdres Sparagmite on the south slope of Mellene is overturned and both formations must be older than 4a, Lower Middle Ordovician. The great thickness of the Valdres section, the structural and stratigraphic relationships of the Valdres to crystalline Jotun rocks at Grönsennknipa, and the new correlations of the inverted Mellsenn-Valdres section to other Norwegian sections suggested by Dr. Jörg Loeschke all point to an Eocambrian age for the Valdres Sparagmite and a Cambrian-Lower Ordovician age for the Mellsenn Group. The Mellsenn Group is an allochthonous Cambro-Ordovician facies unlike the Cambro-Ordovician section exposed below Mellene in Östre Slidre. From what little is known about detailed Cambrian facies variations in south-central Norway it seems most likely that the Mellsenn Cambrian facies was deposited to the east or northeast of its present location. This hypothesis is in accord with the south to southwest overturning of folds in the Mellene nappe which implies transport from the north or northeast.

It has been suggested above that the Valdres Sparagmite was deposited during Eocambrian upon Precambrian crystalline Jotun rocks, and then, during the Caledonian orogeny, thrust to its present location along with the Jotun rocks. This hypothesis is based upon:

1. recognition that the Valdres sparagmite must be older than 4a (Lower Middle Ordovician) and is probably Eocambrian,
2. interpretation of the contact at Grönsennknipa between Valdres and Jotun crystalline rocks as a slightly distorted sedimentary contact (Holtedahl 1959, p. 102),
3. structural conformity of Valdres and Jotun rocks in Grönsennknipa,
4. recognition that the Valdres and Jotun crystalline rocks at Grönsennknipa and the Valdres at Mellene-Heggeberg are part of a new, intermediate, allochthonous, tectonic unit, called the Valdres nappe by Kulling (1961), which is separated from the underlying Cambro-Ordovician sediments and the overlying Upper Jotun nappe by major thrusts.

This hypothesis contrasts with the earlier view that the Valdres is an autochthonous Ordovician-Silurian deposit, partially derived from Jotun crystalline rocks of the Lower Jotun nappe, which were brought to their location in the basin by early Caledonian, (Taconic) orogenic movements (Goldschmidt, 1916; Strand, 1961, p. 167). If the Valdres is accepted as Eocambrian and if the associated Precambrian Jotun crystalline rocks are recognized as part of the Valdres nappes, there is no evidence for the existence of the Taconic phase, Lower Jotun nappe in this part of the Valdres district. Although the crystalline Jotun rocks may have served as one of the sources of the Valdres Sparagmite, they did so in Eocambrian time before both rocks were thrust to their present location.

Structure and Tectonics

Major structural contributions of my work and that of Dr. Jörg Loeschke in Mellene are:

1. the discovery of the Mellene nappe of allochthonous Valdres Sparagmite thrust over Phyllite Formation,
2. within the Mellene nappe, the mapping of an arcuate system of northwest, southeast, and east to northeast plunging L_1 folds that are overturned or recumbent to the southwest or south,
3. data on the orientation of elongation lineations proving that all such lineations in Mellene and Heggeberg are *b*-lineations parallel to the fold axes of the L_1 folds described in 2 above.

Nearly horizontal thrusts, overlain by nappes comprised of Valdres Sparagmite, Jotun crystalline rocks, or Mellsenn Group and underlain by Phyllite Formation have been recognized from Grönsennknipa on the southwest (Holtedahl, 1959, 1961), to Mellene-Heggeberg (this paper), and to Rössjökollen at the eastern bordrer of Nordre Etnedal (fig 1; Strand, 1938, p. 11. section through Skjellbreidskampen; Goldschmidt, 1916, p. 38, section through Dyptjernfjeld; Björlykke, 1905, p. 455, profile of Rödsjökampen). These nappe segments, which can be traced discontinuously northeast along the Norwegian Caledonides for a distance of 60 kilometers, are clearly parts of a major tectonic unit as important as the «quartz sandstone» nappe to the southeast or the Upper Jotun nappe to the northeast. Kulling (1961) first applied the name «Valdres nappe» to a tectonic unit in this structural position and I accept his term, using it in the plural to include all of the nappe segments recognized above (thus *Valdres nappes*). Until continuity between the nappes in Grönsennknipa, Mellene-Heggeberg, and Nordre Etnedal are established, it is better to use local names for the nappe in each area. Thus in Mellene-Heggeberg.

the nappe is referred to locally as the Mellene nappe (local unit) of the Valdres nappes (regional unit). Although the Mellene thrust is essentially a break between allochthonous, commonly overturned, Valdres and Phyllite Formation, it is a striking fact that all exposures of Mellsenn Group are associated with the thrust. The Mellsenn at the thrust occurs overturned in the allochthonous sequence immediately above the thrust as in the type section on Mellene and in slices and larger patches scattered along the thrust zone between the Valdres and the Phyllite as may be seen at numerous localities on the east and west slopes of Mellene and east of Heggeberg. The constant association of the Mellsenn Group with the thrust suggests that it occupies the middle, overturned, stretched, and broken limb of a recumbent anticlinorium-synclinorium combination with minimum fold amplitude of approximately 15 kilometers. Fifteen kilometers is the horizontal distance across the northwest strike of fold axes through which the Mellsenn Group is distributed along the thrust zone (data from Strand, 1938, 1951, Nordre Etnedal and Slidre map areas). The overriding recumbent anticlinorium occurs in the Valdres Sparagmite above the thrust and the underlying recumbent synclinorium is lost in the Phyllite Formation beneath the thrust, far to the northeast of Mellene.

Axial planes of the stack of overturned to recumbent folds within the Valdres Sparagmite of Mellene dip northeast and fold axes are arcuate in plan, bending from northwest or southeast plunging, to east plunging to northeast plunging when traced from northwest to southeast in the area. Overturning of folds is toward the southwest, south, and locally, southeast suggesting transport in a southwest or south direction. In the Valdres of Grönsennknipa, recumbent to overturned folds with the same axial plane and southeast plunging axes were also mapped by the writer and it is concluded that the tectonic pattern is characteristic of the region. Overturning and recumbent fold tectonics have also been observed by Björlykke (1905, p. 453, 463), Strand (1938, p. 17, 51) and Dietrichson (1945, fig. 2; 1950,fig. 2).

Elongation lineations parallel fold axes of the recumbent fold system and are thus *b* lineations. Arcuation in strike of fold axes and elongation lineations certainly brings some of them parallel to the direction of thrusting or the direction of flow on foliation planes, but, no constant direction of lineation across fold axes was recognized. The lineations apparently result from flattening in the planes of slaty cleavage and stretching in *b* due to arcuation of the fold system. Even though the elongation lineations trend generally azimuth 110° (northwest-southeast) transverse to the main strike of the Norwegian Caledonides, they clearly do not mark the local direction of transport of the nappes or the folds. The direction of transport is unknown but is more likely toward

the southwest or south in the direction of overfolding of the L_1 folds. Mellene lies on the southwest margin of a salient which may embrace the whole Sparagmite basin to the east (see Skjeseth, 1963, fig. 38 for a regional map). Viewed in such regional perspective, the southwest to south overfolding of Mellene is seen to be merely a marginal spreading on a much larger salient that has probably moved southeast. Although the northwest-oriented elongation lineations of Mellene may accidentally parallel the major transport direction of the large Mellene-Sparagmite basin salient, the local lineation orientation does not parallel the local transport direction.

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STRUCTURE MAP OF MELLENE-HEGGEBERG

Geology by R. Nickelsen, 1965-66

Location of conglomerate beds from J. Loeschke

3 km. to V''

V'

Vindaasen

To Bygdin

Heggeberg

Rolistøl

Hegge-fjorden

Volbufjord

Slidre Sheet 1617 II

Fullsenn Sheet 1717 III

Rennsenn-vann

Røyri

Øyangen

Rognslifjell

Rundemellen

Skorvemellen

Mellsenn

Vangs-sjøen

Rabbis-vann

N

MN 5°

LEGEND

Stratigraphy:

- Phyllite formation — P
- Mellsenn formation — M
- Valdres sparagmite — V

Primary evidence of facing of beds:

- Up direction shown by black dot

Strike and dip of bedding - S_0:

- Overturned
- Vertical
- Horizontal

Strike and dip of slaty cleavage - S_1:

Bearing and plunge of lineations - L_1:

- Intersection of S_0 and S_1
- Elongations of particles

Geology by R. Nickelsen, 1965-66

Location of conglomerate beds from J. Loeschke

LEGEND

ratigraphy:

Phyllite formation	P
Mellsenn formation	M
Valdres sparagmite	V

imary evidence of facing of beds:

Up direction shown by black dot

rike and dip of bedding - S_0 :

Overturned

Vertical

Horizontal

rike and dip of slaty cleavage - S_1 :

aring and plunge of lineations - L_1 :

Intersection of S_0 and S_1

Elongations of particles

Axes of folds with sense or shape of fold viewed down plunge

ults

pographic base map from 1:50000. Slidre (1617 II) nd Fullsenn (1717 III) maps of series M 711

Hegge-fjorden

Volbufjord

Heggeberg

Rollstøl

Rennsennvann

Røyri

Øyangen

Rabalsvann

Rundemellen

Rognslifjell

Skarvemellen

Mellsenn

Nervann

Hovsfjord

Cambrian

To Fagernes

N

MN 5°

0 1 2 3

Kilometers

Fig. 11. Geologic structure sections (I—V)
Letters A—G mark folds that can be traced throughout Mellene-Heggeberg