THE RELATIVE CHRONOLOGY OF FOLD PHASES, METAMORPHISM, AND THRUST MOVEMENTS IN THE CALEDONIDES OF TROMS, NORTH NORWAY

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The stratigraphy, structural geology, and metamorphism of an area of inner Troms, North Norway are described. Precambrian rocks are overlain by a thin sedimentary cover, possibly of Cambrian age, and overthrust by Caledonian rocks. Five fold phases are established. The second one resulted in the formation of major recumbent folds with axial plane schistosity and a mineral lineation parallel to the axes of the folds, the direction of which is WNW-ESE. The regional distribution of metamorphic facies is described. The peak of metamorphism is shown to coincide with the second fold phase.

It is concluded that the mineral lineation has no relation to the large scale thrusting of the Caledonides from NW to SE and that this thrusting took place at a very late stage in the structural evolution.

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Introduction

During the summers of 1965, 1966, and 1967 the author carried out geological studies, in close collaboration with colleagues from the Department of Geology at Aarhus University, in the Caledonides of inner Troms in North Norway. This work formed part of an exploration programme of the mining company A/S Sydvaranger, Oslo. The leader of the group in 1965 was Prof. A. Berthelsen from Copenhagen, and in 1966 and 1967 Dr. F. Kalsbeek from Aarhus was leader. During the programme a large part of the Caledonides of Troms was mapped. A preliminary note on this work has already been published (Kalsbeek & Olesen 1967).

The author mapped an area of about 350 km^2 between the river valleys of Målselva, Kirkeselva, and Divielva (Fig. 1). The area has been named Langedalen.

Stratigraphy

Fig. 1 is a simplified litho-stratigraphic map of the Langedalen area (for a more detailed description of the geology of this area, see Olesen 1968). Two major tectonic units are separated by the basal Caledonian thrust plane.

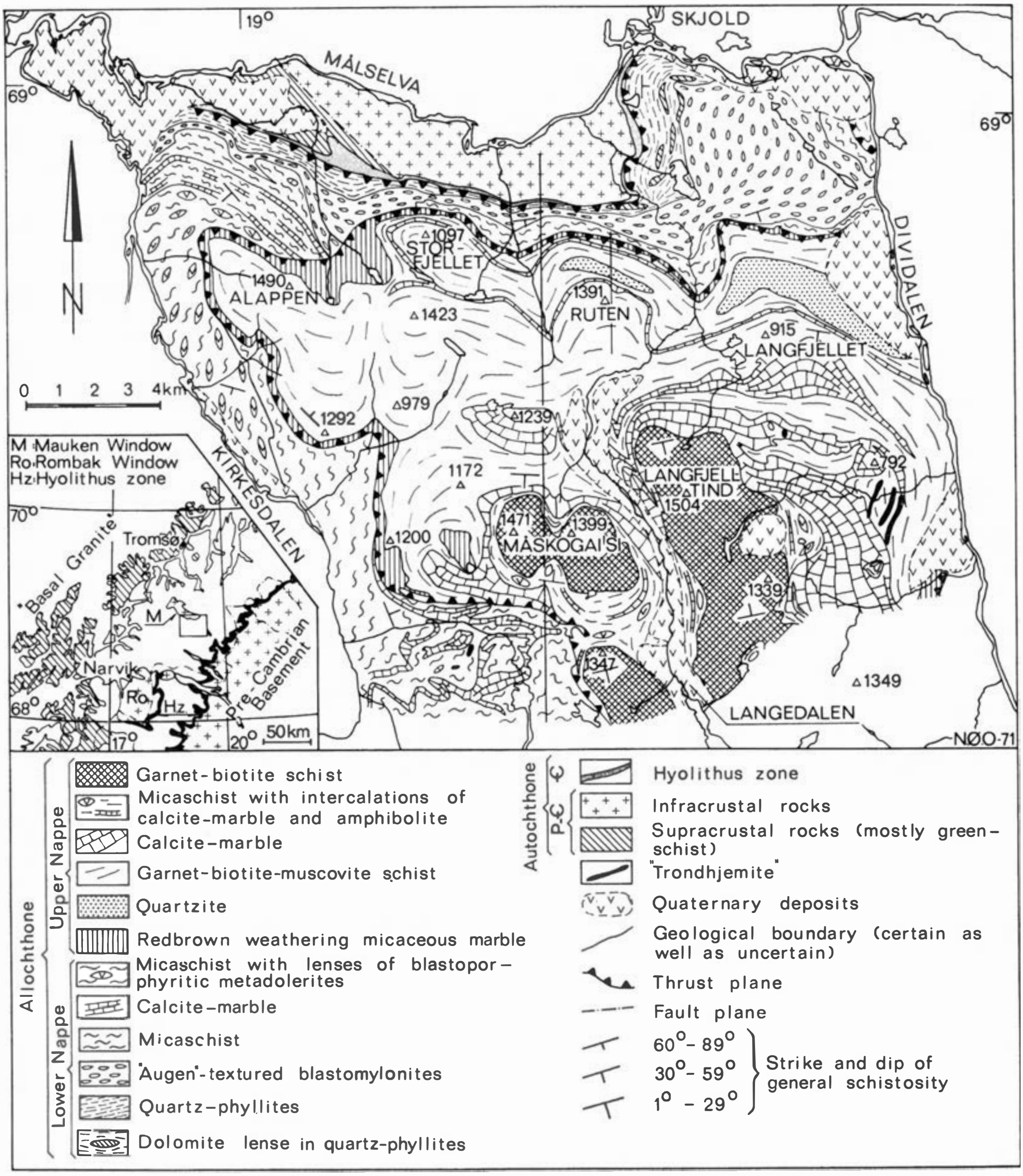

Fig. 1. Simplified geological map of the Langedalen area. Profile lines refer to Fig. 2. Geology of index map compiled from Holtedahl & Dons (1960), Kulling (1960), Berthelsen (1967), Landmark (1967), and Kalsbeek & Olesen (1967).

Below this thrust plane Precambrian infracrustal and supracrustal rocks are unconformably overlain by sediments of possible Cambrian age. The sediments are mostly slates and quartzitic sandstones and are interpreted as equivalent to the fossiliferous Hyolithus zone sediments along the eastern margin of the Caledonides (Vogt 1918, 1967).

The allochthonous Caledonides lie above the basal thrust plane and are separated into two, the Upper and the Lower Nappes. The Upper Nappe may correspond to the Røddingsfjell Nappe and the Lower Nappe to the Seve-Kjøli Nappe (Strand 1961).

Simplified stratigraphic sequences of the two nappes from top to bottom are as follows:

Upper Nappe
Biotite schists.
Muscovite-biotite schists alternating with calcite marbles.
Quartzite.
Reddish brown weathering micaceous marble (this unit may be a separate tectonic unit below the Upper Nappe).

Lower Nappe
Different types of micaschists with intercalation of calcite marble.
Micaschists with numerous discordant and concordant bodies of blastoporphyritic metadolerites.
Augen-textured blastomylonites (partly gneissic, partly schistose).
Quartz phyllites (probably phyllonites, i.e. of mylonitic origin) with lenses of dolomite marble.

No blastomylonites are found at the base of the Upper Nappe, but the micaceous marble is strongly tectonized.

Fig. 2 shows that in the area of the mountains of Storfjell and Ruten, part of the stratigraphic sequence of the Upper Nappe is repeated by large scale folding.

At several localities in the Upper Nappe, graded bedding has been observed in porphyroblastic micaschists (Fig. 3) indicating that they are the 'right-side-up'.

Only on the lower flanks of the major isoclinal folds is the sequence inverted.

Structural geology

The rocks of the two nappes apparently possess identical structural patterns, and are accordingly treated as one rock unit in this section.

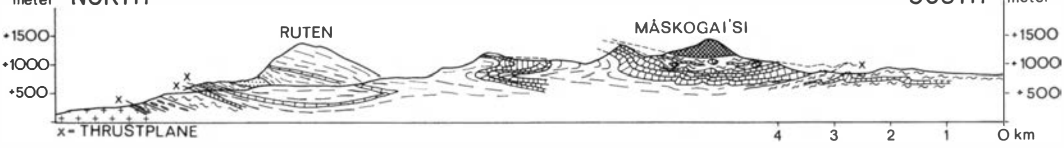

Fig. 2. N-S profile through the Langedalen area. For location see Fig. 1.

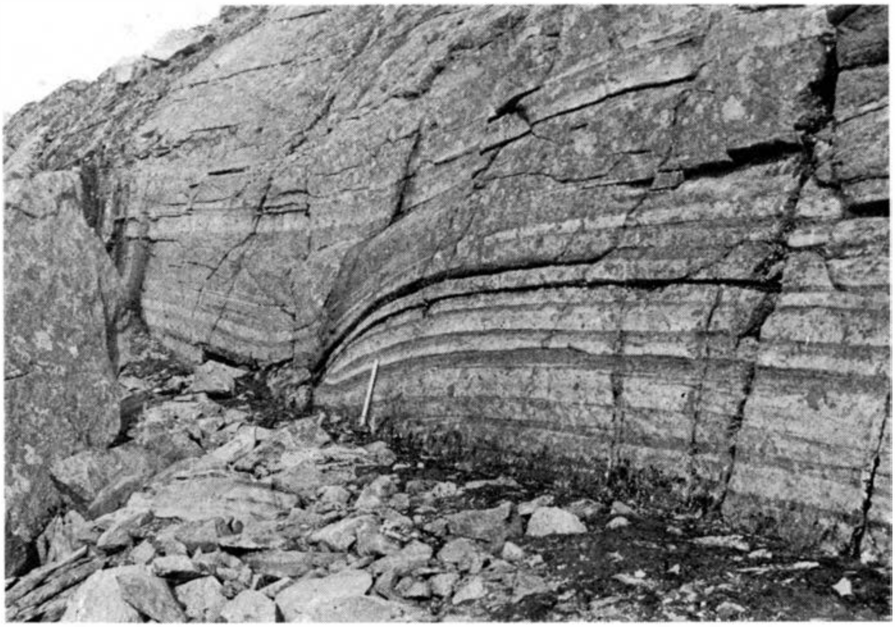

Fig. 3. Relict graded bedding in garnet micaschist of the Upper Nappe from a locality west of Måskogai'si. At the top of the hammer shaft a clearly graded bed is seen. The light-coloured micaschist corresponds chemically to a graywacke, while the darker micaschist corresponds to a pelite. The lower boundary of the metagraywacke is sharp, while there is a transitional change upwards from the metagraywacke to the metapelite.

STRUCTURAL SEQUENCE

Five fold phases have been established in the Langedalen area. They are divided into a set of 'early fold phases' (F_1 and F_2) and a set of 'late fold phases' (F_3, F_4, and F_5), the distinction between 'early' and 'late' is based on the following main criterion:

Folds belonging to the early phases possess, as an important feature, an axial plane schistosity.

Folds belonging to the late phases deform the schistosity created during the early fold phases, and locally a crenulation cleavage is formed.

The second of the 'early fold phases' (F_2) is accompanied by a characteristic lineation, which will be described in detail below, and F_2 is responsible for the most penetrative deformation of the rocks involved and is a useful fixed reference when attempting to work out the structural history of the area. Table 1 shows schematically the main features of the five fold phases.

In Fig. 4 some examples of the fold styles of the five fold phases are shown.

A comparison between this structural sequence and similar sequences in the literature on North-Scandinavian Caledonian tectonics reveals a difference in that the kind of structures which in this paper are termed F_2 structures are termed F_1 structures in the following literature: Ramsay & Sturt (1963), Sturt & Ramsay (1965), Skjerlie & Tan Tek Hong (1961), Padget (1955), Lindström (1955, 1956, 1957, 1958), Ash (1967), Hooper & Gronow (1970). Only Roberts (1968) has identified two early fold phases. The chance of miscorrelation is slight as the so-called 'transverse lineation' forms the basis of the above correlation. The 'transverse lineation' is a very conspicuous type of lineation of widespread occurrence in the Caledonides. It is equivalent to the so-called 'tverr-folding' of Landmark (1951) and the 'transverse lineation' of Lindström (1958), and in the present area it corresponds to the lineation of the second fold phase.

In the Langedalen area there is one conclusive indication for the establishment of F_1, namely the existence of double fold patterns, of which two examples are known (the localities are indicated with thin arrows in Fig. 7). In both examples isoclinal and intrafolial folds are affected by F_2 deformation. The example from the locality of Langedalen is shown in Fig. 4 (A).

The following observations also support the view of the existence of a pre-F_2 fold phase:

In several rock samples, collected from closures of F_2-folds, the relations between internal schistosities of porphyroblasts and the external schistosity of the matrix have been observed (Figs. 5 and 6). The internal schistosity (s_i) of the porphyroblasts lies parallel to the bedding, which again is oblique to the F_2 axial plane schistosity. As s_i consists of elongate quartz grains, a schistosity must have existed before the formation of the F_2-folds and it seems reasonable to attribute the formation of this early schistosity to the formation of the F_1-folds.

Table 1. Main features of fold phases.

		Axial direction	General vergence	Fold characteristics
F_1	'early fold phases'	?	?	isoclinal, congruent, intrafolial
F_2		N100–120°E	towards south	subisoclinal, congruent
F_3	'late fold phases'	N20°W–N20°E	both towards east and west	locally conjugate folds, concentric to congruent
F_4		N130–150°E	towards north-east	asymmetric, open, concentric to congruent
F_5		N20–80°E	towards south-east	asymmetric, open, concentric to congruent

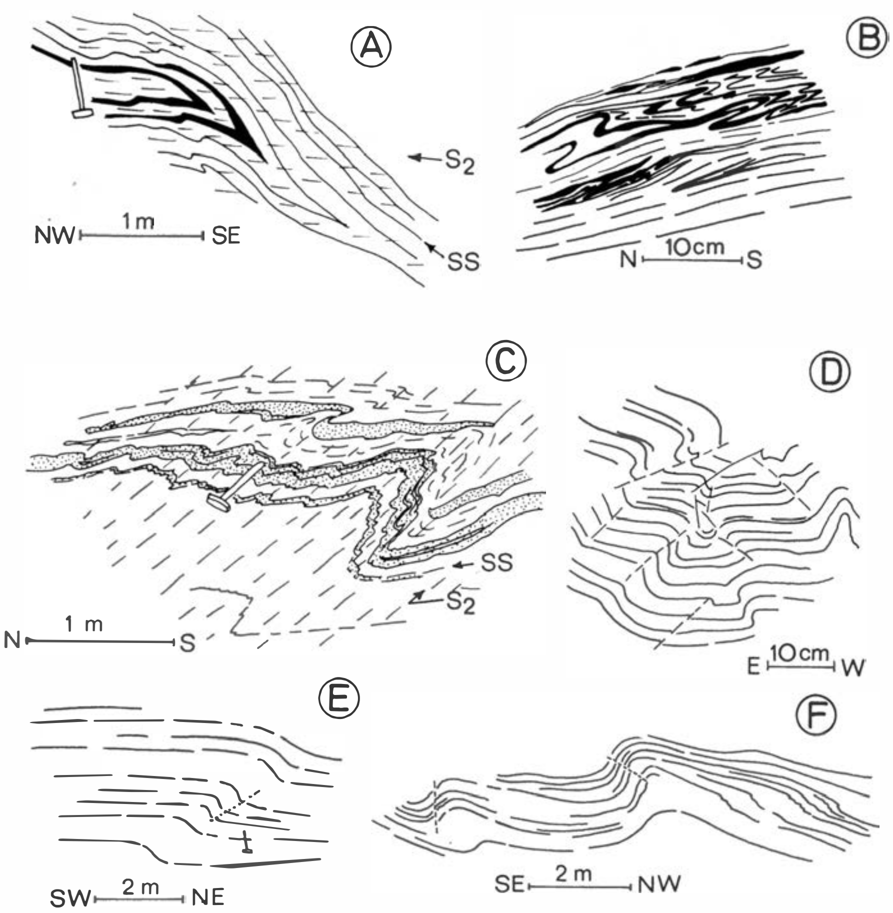

Fig. 4. Examples of fold style.
(A) F_1-fold. Lithology: Black = micaceous marble, white = calcareous micaschist.
(B) F_2-fold. Lithology: Quartz phyllite.
(C) F_2-fold. Lithology: Dotted = micaceous marble, white = calcareous micaschist.
(D) F_3-fold. Lithology: Thin-bedded quartzite.
(E) F_4-fold. Lithology: Micaschist.
(F) F_5-fold. Lithology: Calcareous micaschist.

As already mentioned, the Caledonian rocks were strongly deformed during F_2. In addition to the mesoscopic and the large macroscopic folds (Fig. 2) the regional schistosity and the distinct 'transverse lineation' are results of the second fold phase, and the 'transverse lineation' is well developed throughout the whole sequence of allochthonous Caledonian rocks.

The late fold phases are divided into three generations on the basis of superposed fold patterns (Olesen 1968).

The folds generally have amplitudes ranging from about one meter to around 50 metres. In Fig. 2 some of the largest F_5-folds occur in the southern part of the profile.

Only a few examples of F_3-folds are known.

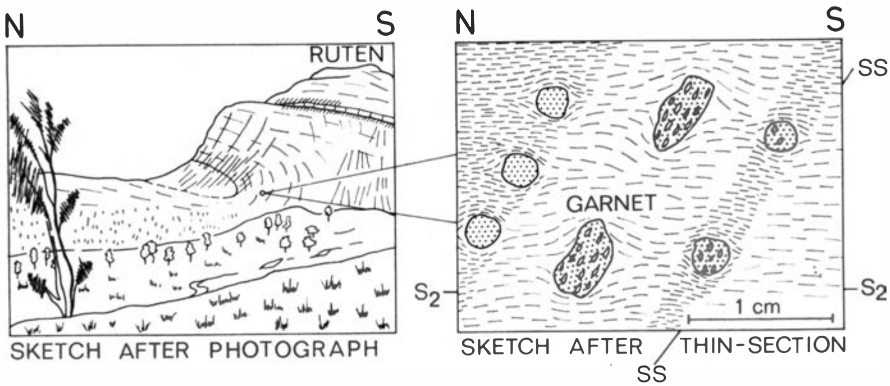

Fig. 5. For explanation see text.

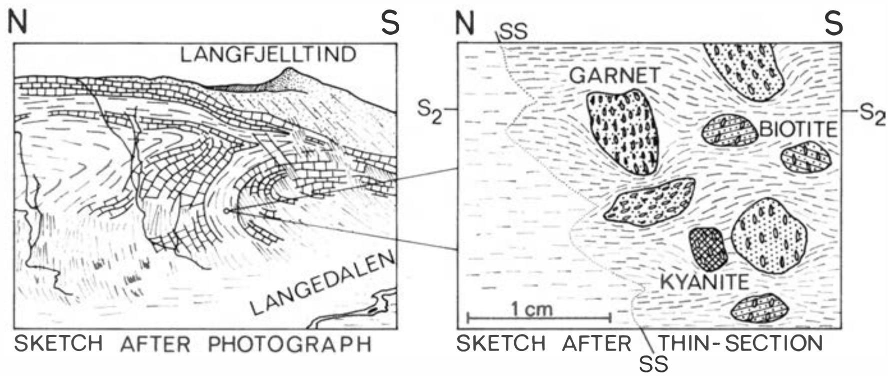

Fig. 6. For explanation see text.

Folds belonging to F_4 and F_5 are common, but do not occur everywhere. F_4-folds for example are most frequently observed in the southwest, while the F_5-folds are more abundant in the east and south. The folds of F_5 are non-cylindrical which results in variable axial directions. This feature is common to all late folds.

Fig. 7 is a trend-line map showing the general axial directions of the fold phases. It indicates, subjectively, the regional distribution of the folds of the different fold phases. The non-cylindrical nature of the F_5-folds is shown by the curving trend-lines.

THE 'TRANSVERSE LINEATION'

Description on the mesoscopic scale

In many rocks there is a mineral lineation, i.e. the minerals show a more or less perfect preferred form orientation. In micaschists the micas are elongate and show a fabric habit due to their parallel orientation. Elongate porphyro-

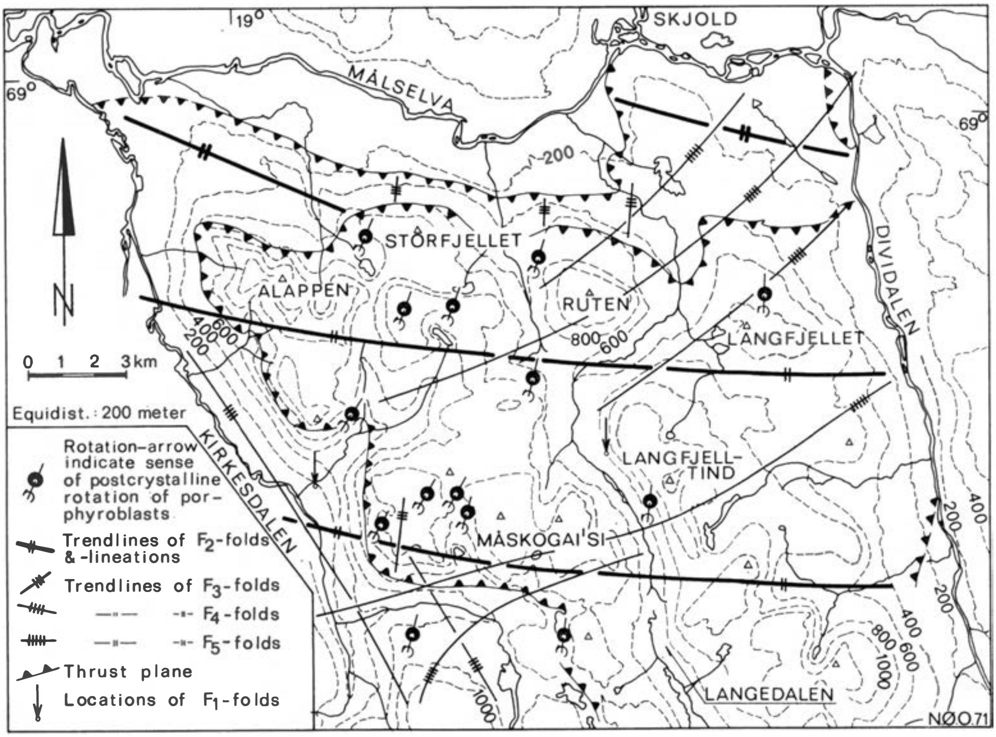

Fig. 7. Structural map of the Langedalen area.

blasts, e.g. hornblende, staurolite, epidote, and kyanite also have a parallel orientation. Moreover ellipsoidal biotite porphyroblasts have a linear arrangement. In amphibolites the hornblendes are aligned, and in marbles the same applies to tremolite, epidote, and zoisite porphyroblasts.

Other types of lineation are also frequently encountered.

Table 2. Proposed subdivision of second fold phase.

	Subdivision	Deformation type	Hypothetical orientation of principal stress axes σ_1	σ_2	σ_3	Relative direction of main tectonic transport
F_2	early-F_2	simple bending of bedding	horiz. NNE–SSW	horiz. WNW–ESE	vertical	from NNE to SSW
	late-F_2	flattening, axial stretching and laminar flow	vertical	horiz. NNE–SSW	horiz. WNW-ESE	from ESE to WNW

Fig. 8. Quartzite conglomerate observed parallel to the longest axis of deformed pebbles.

In F_2-folds the intersection between bedding and axial plane schistosity forms a lineation. Another type of lineation is quartz rods (Wilson 1953, 1961) which are frequently observed in micaschists and in marbles. On the southern slope of Storfjell, bedding and schistosity are oblique to each other and thus form structures which may be termed 'cleavage mullions' (Wilson 1953). To the south not very far from this locality a deformed conglomerate is found, in which almost all pebbles consist of quartzite. The pebbles are deformed to tri-axial ellipsoids (Fig. 8) of which the approximate axial ratio is A:B:C=10:3:1. The longest axis (A) is parallel to the 'transverse lineation', while the shortest axis (C) is perpendicular to the regional schistosity.

Description on the microscopic scale

A microscopic study of the lineation in a garnet micaschist, for example, first of all shows the same general form orientation of matrix minerals and elongate porphyroblasts as already observed on a mesoscopic scale.

Secondly it is observed that the micaceous matrix always shows a deflection around the porphyroblasts and cone-shaped pressure shadows are parallel to the lineation.

In the third place the same porphyroblasts often show post-crystalline rotation (with regard to the growth of the porphyroblasts) as the matrix shows an asymmetric configuration around the porphyroblasts when observed in thin sections cut parallel to the lineation (Fig. 9). In thin sections cut perpendicular to the lineation the matrix is symmetrical about the porphyroblasts (Fig. 10).

24 oriented rock samples have been examined with the purpose of determining the axis of rotation of porphyroblasts and the direction of this rotation. In 10 of these samples no post-crystalline rotation was observed, but in the remaining 14 rock specimens a rotation was visible and the sense of rotation could be established. The results of this examination are shown in Fig. 7. The rotation in all 14 samples is anti-clockwise when the axis is observed from the south.

Interpretation

It is believed that the 'transverse lineation' and the mesoscopic and macroscopic F_2-folds are connected genetically.

This assumption is based on the observations that the intersections between bedding and axial plane schistosity of the F_2-folds coincide almost exactly with the mineral lineation and with the rodding of the 'transverse lineation' on a *mesoscopic* scale. The same parallelism is observed on a *macroscopic,* regional scale.

Fig. 11 shows the spatial distribution of 48 measurements of the 'transverse lineation' in the Langedalen area. In the same diagram, 5 fold axes are plotted. Two of these are constructed on the basis of the geological map (one axis from the fold hinge of the quartzite of Ruten and Langfjellet, and

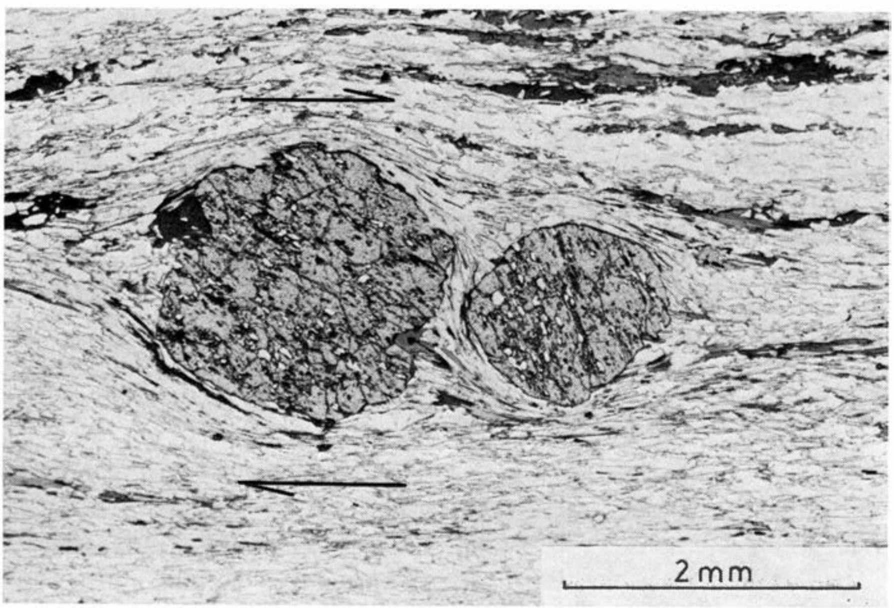

Fig. 9. Thin-section parellel to 'transverse lineation' and perpendicular to schistosity showing late-F_2 laminar flow causing rotation of porphyroblasts (Garnet). The section is observed from the north. One nicol.

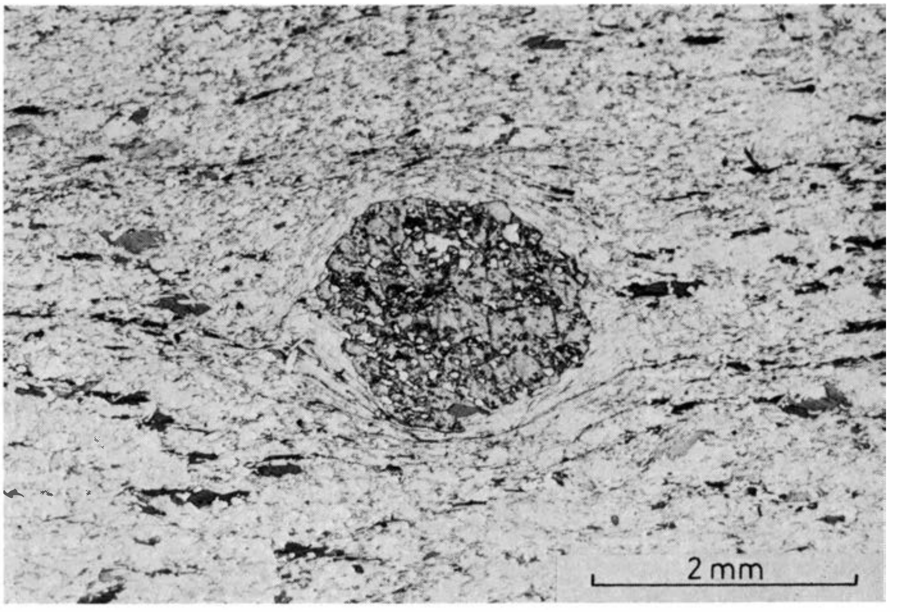

Fig. 10. Thin section perpendicular to 'transverse lineation' and schistosity showing flattening of matrix schistosity and no laminar flow. One nicol.

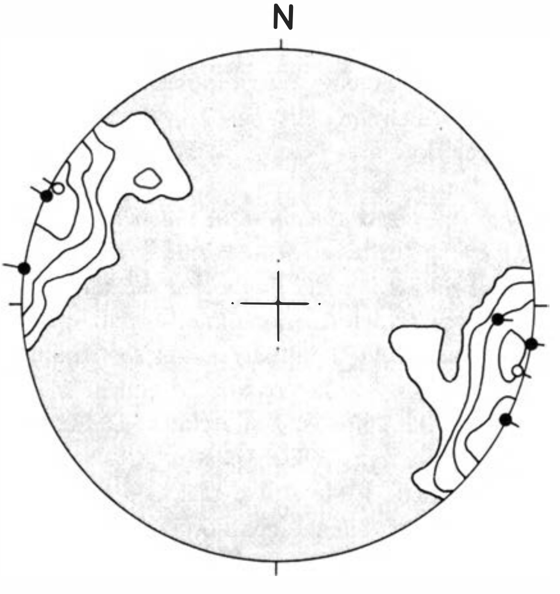

Fig. 11. 48 'transverse lineations' from the Langedalen area. Contours: 1%, 3%, 7%, and 13% per 1% area. Schmidt Net, lower hemisphere. Two axes with open head are constructed from the geological map. For further explanation see the text.

the other from the fold hinge of the marble of Måskogai'si and Langfjelltind (Fig. 1)) and three axes are measured on mesoscopic folds of the same hinge zones. The five fold axes coincide fairly closely with the maximum of the diagram.

Considering the pebbles of the deformed conglomerate to be strain ellipsoids, they indicate which kind of deformation the surrounding rocks – micaschists, marbles, etc. – were exposed to during the formation of the 'transverse lineation'.

It is found that the Caledonian rocks were exposed to a process of flattening across the schistosity and a corresponding process of stretching parallel to the lineation.

A microscopic examination of rock samples leads to the same main conclusions:

The deflection of matrix round the porphyroblasts is interpreted as the result of a flattening of the matrix round preexisting porphyroblasts (Zwart 1962). Synchronous with this flattening, the rocks have to yield along the plane of schistosity, giving way to the formation of pressure shadows around the porphyroblasts. The orientation of these pressure shadows thus indicates the direction of the yielding. In the present case the pressure shadows are always observed in thin sections cut parallel to the 'transverse lineation', while no pressure shadows are observable in thin sections cut perpendicular to this lineation (very small pressure shadows in the form of cone-shaped granoblastic, unoriented mineral aggregates of quartz and micas are visible in Fig. 9).

Finally the post-crystalline rotation of porphyroblasts, as described above, is interpreted as the result of laminar flow along the schistosity planes.

The laminar flow and the process of flattening have presumably taken place more or less synchronously since the rotated porphyroblasts are only observed in sections which are cut parallel to the 'transverse lineation'. Therefore the laminar flow also belongs to F_2.

The position of the 'transverse lineation' in the structural sequence

As described above, the 'transverse lineation' is believed to be genetically connected with the F_2-folds, i.e. the folds and the lineation were formed in one and the same phase of deformation. The formation of major recumbent folds probably demands at least initially a simple bending of bedding. On the contrary the formation of the 'transverse lineation' took place during plastic conditions with flattening and stretching. These two types of deformation are essentially different, which is why a subdivision of the second fold phase seems indicated. Table 2 is a proposal to such a subdivision. It seems reasonable to believe that the condition of plastic deformation during which the 'transverse lineation' was formed was attained relatively late during F_2, while it likewise seems reasonable to believe that the initial F_2 deformation was mostly a simple bending of bedding.

The subdivision is of a hypothetical nature, but is used in the following discussion. It must be emphasized that it is believed that the transition from the bending of bedding to the flattening etc. is gradual.

Also the shift in orientation of the principal stress axes are tentative and only the orientation of σ_3 during late F_2 is well defined.

Metamorphism

The following is a description of the regional distribution of metamorphic facies followed by an attempt to establish the metamorphic history. The metamorphism is of the Barrovian type all over the area. The nomenclature of the metamorphic facies is from Winkler (1967).

Minerals written in italics are porphyroblasts (or -clasts) while matrix minerals are written in roman letters.

THE AUTOCHTHONOUS CALEDONIDES

The sediments of the 'Hyolithus zone' are only slightly metamorphosed. Generally the clastic grains of the quartzites and slates are easily recognized. A subhorizontal slaty cleavage, defined by the parallel orientation of muscovite and chlorite, is normally visible. In most cases the formation of this slaty cleavage seems to have taken place during flattening and extension in all directions in the horizontal plane since a very weak lineation is only sporadically developed. The sedimentary grains in the quartzites are often flattened and show strong undulatory extinction besides an incipient recrystallization in the margins of the grains. Frequently the quartzites are cut by minute crush zones, and the slates are crossed by cracks which are filled by quartz, calcite, and chlorite. Biotite has not been detected, and the metamorphic changes of the rocks of the 'Hyolithus zone' must therefore have taken place under the conditions of the lowest greenschist facies (quartz-albite-muscovite-chlorite subfacies). In the Langedalen area it looks as if there has been a gradual increase in tectonic deformation and metamorphic reconstitution of the sediments of the 'Hyolithus zone' from east to west.

THE ALLOCHTHONOUS CALEDONIDES

The Lower Nappe

The lowest unit in the Lower Nappe is the quartz phyllites, which are probably blastomylonites.

Common mineral parageneses are:

(1) quartz-microcline-albite-muscovite-chlorite-epidote-acc.
(2) quartz-dolomite±chlorite
(3) *Albite*-quartz-albite-biotite(green)-chlorite-epidote-acc.
(4) *Hornblende*(green cores and blue-green rims)–
Albite-quartz-albite-biotite(green)-chlorite-epidote-acc.

The 'augen-textured blastomylonites' (Fig. 1) are found above the quartz phyllites.

A common mineral paragenesis is:

(5) *Garnet-Hornblende*(blue-green and green)–
Albite-quartz-microcline-albite-biotite(green and brown)-chlorite-epidote-acc.

This paragenesis indicates that the rocks are metamorphosed in the highest subfacies of the greenschist facies (quartz-albite-epidote-almandine subfacies). Rocks of the same metamorphic grade are found in still higher stratigraphic levels. The transition from rocks of greenschist facies to rocks of almandine-amphibolite facies takes place at the stratigraphic level of 'micaschists with numerous discordant and concordant bodies of blastoporphyritic metadolerites' (Fig. 1). Above this level the rocks locally contain kyanite, and staurolite has been detected in one rock sample. Typical mineral parageneses are (6) and (8). These rocks belong to the almandine-amphibolite facies. As no sillimanite has been found and muscovite is widespread in the rocks of the Lower Nappe, the grade is probably lower and/or intermediate subfacies of the almandine-amphibolite facies (staurolite-almandine subfacies and/or kyanite-almandine-muscovite subfacies).

The Upper Nappe
A typical mineral paragenesis of the marbles of the Upper Nappe is:

(6) quartz-calcite ± *Tremolite*

Mineral parageneses of the micaschists are:

(7) *Garnet-Staurolite-Kyanite-Biotite*(brown)-quartz-plagioclase-muscovite-biotite(brown)-chlorite-acc.
(8) *Garnet-Hornblende*(green)-quartz-plagioclase-biotite(brown)-chlorite-epidote-acc.

According to Winkler (1967) the mineral paragenesis (6) indicates metamorphism in the intermediate and/or highest subfacies of the greenschist facies (quartz-albite-epidote-biotite subfacies and/or quartz-albite-epidote-almandine subfacies) but in the Alps, (6) has been demonstrated to be stable in the lower part of the almandine-amphibolite facies also (Trommsdorff 1966). The mineral parageneses, (7) and (8), both indicate metamorphism of almandine-amphibolite facies (except for the presence of chlorite). As sillimanite is not found in the rocks of the Upper Nappe, and muscovite is a mineral widespread in the rocks of the Upper Nappe, the grade probably corresponds to the lower and/or intermediate subfacies of the almandine-amphibolite facies (staurolite-almandine subfacies and/or kyanite-almandine-muscovite subfacies).

To summarize: The entire Upper Nappe and the upper part of the Lower Nappe show mineral parageneses indicating metamorphism in the lower and middle almandine-amphibolite facies, while most of the remaining part of the sequence shows mineral parageneses indicating metamorphism in the upper and middle greenschist facies. Only locally in the lowest part of the Lower Nappe are mineral parageneses found which may indicate metamorphism in the lower part of the greenschist facies. The sediments of the 'Hyolithus zone' are metamorphosed in the lowest part of the greenschist facies.

TEXTURAL RELATIONSHIPS

A microscopic examination of the rocks of the Langedalen area has demonstrated the existence of two groups of minerals: one group of 'older minerals', i.e. the porphyroblasts, and another group of 'younger minerals', i.e. the matrix minerals.

The porphyroblasts

As described above the matrix schistosity always deflects around the porphyroblasts, indicating that the matrix was flattened synchronous with and/or later than the growth of the porphyroblasts (Zwart 1962). Only rarely has post-flattening growth of the edges of porphyroblasts been observed on *Zoisite, Garnet,* and *Kyanite.*

When the porphyroblasts have an internal schistosity (s_i), there is usually a clear discontinuity between this and the external schistosity (s_e), both as regards the orientation and the grain size, and s_i is always more fine-grained than s_e.

The following shapes of s_i have been observed:

(a) s_i is planar
(b) s_i is planar in the centre and S-shaped at the margin of the porphyroblast
(c) s_i is S-shaped

According to Zwart (1962) the tectonic conditions during the growth of the porphyroblasts are reflected to some extent by the shape of s_i. From this it follows that the porphyroblasts with s_i:

(a) grew under static conditions
(b) grew initially under static conditions and later under rotation
(c) grew under rotation

The para-crystalline rotation of porphyroblasts mentioned under (b) and (c) should not be confused with the post-crystalline rotation of porphyroblasts, which has been mentioned above in connection with the 'transverse lineation'.

The axis of the para-crystalline rotation is not constant. Several directions have been observed, among which an approximate E-W axis with a clockwise rotation when viewed from the west is frequent. Fig. 12 illustrates the two types of rotation. It should be noted that the prominent E-W axis of para-crystalline rotation is consistent with the direction of transport during early F_2.

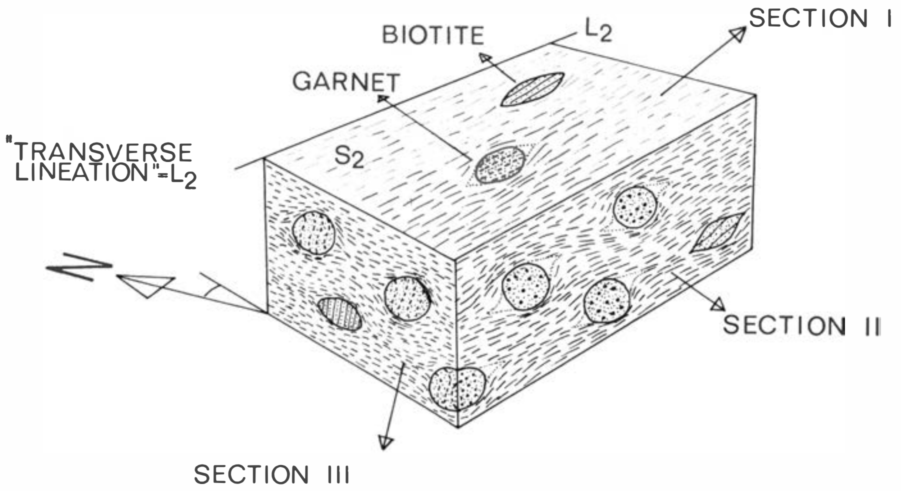

Fig. 12. Block sketch demonstrating fabric of typical garnet-biotite micaschist.
Section I: Sub-horizontal section parallel to F_2 axial plane schistosity (S_2). The section shows an elongate biotite porphyroblast and a garnet porphyroblast with pressure shadows in the direction of the 'transverse lineation'.
Section II: Sub-vertical section perpendicular to S_2 and parallel to L_2. The section shows an elongate biotite porphyroblast and garnet porphyroblasts with pressure shadows in the direction of the 'transverse lineation'. The section also shows the post-crystalline rotation of the porphyroblasts.
Section III: Sub-vertical section perpendicular to S_2 and perpendicular to L_2. In this section the biotite porphyroblast is sub-circular, the micas of the matrix are short and none or very faint pressure shadows are visible. The s_i of the garnet porphyroblasts are S-shaped, which is the result of para-crystalline rotation.

The matrix

The matrix of some specimens has a typical 'dynamic' schistosity, shown by the perfect planar and linear orientation of the minerals. With this directional fabric as starting point all transitional stages towards a *mimetically* recrystallized matrix have been observed.

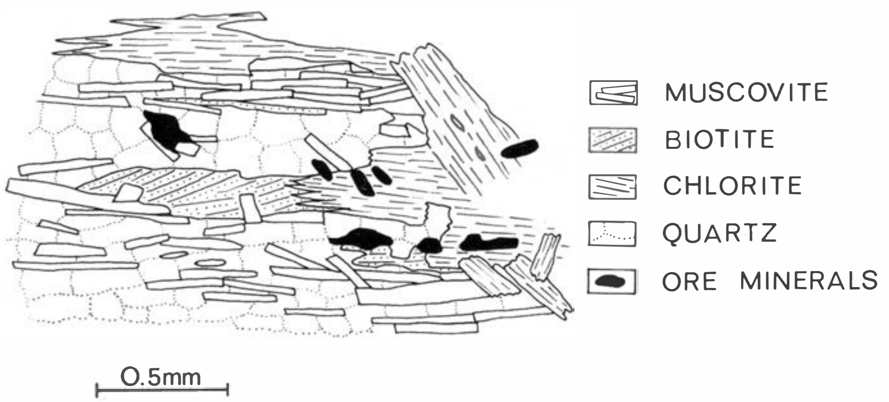

Fig. 13. The relations between matrix minerals. For further explanation see the text.

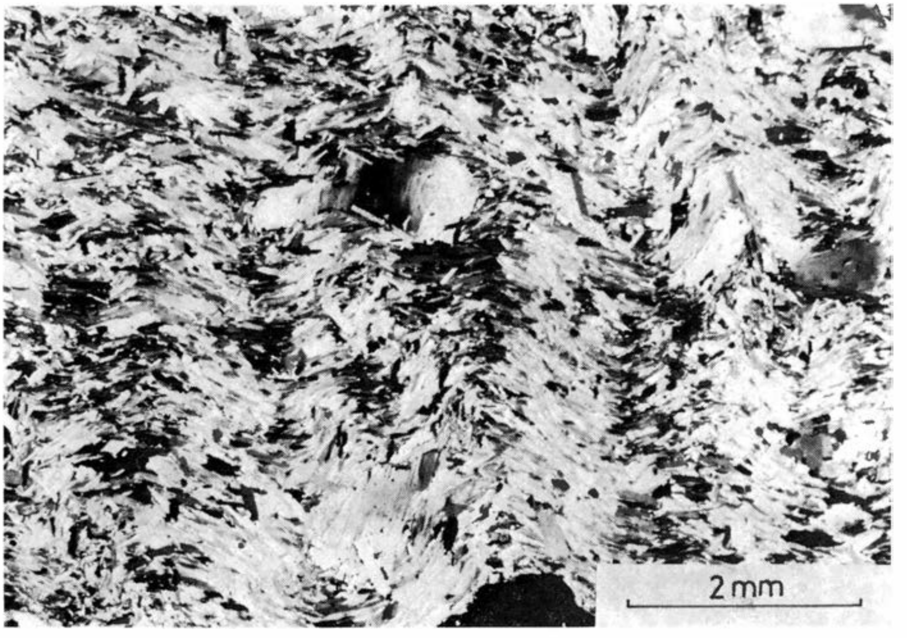

Fig. 14. Recrystallized F_4-crenulation (polygonal arcs). Crossed nicols. Porphyroblasts are *Biotite,* showing undulose extinction. Matrix consists almost exclusively of muscovite.

The platy minerals, i.e. biotite, muscovite, and chlorite mostly show the mutual relationship which is illustrated in Fig. 13. When biotite and muscovite are present together the latter mostly grows through the former, and when chlorite is present together with biotite and/or muscovite, the chlorite always replaces or grows through both the biotite and the muscovite.

When the schistosity is deformed by late folds, F_3 and F_4-crenulations show polygonal arcs, i.e. the crenulation is recrystallized (Fig. 14), while in F_5-crenulations the schistosity is only slightly, or not at all, recrystallized (Fig. 15).

Relations between porphyroblasts and matrix minerals

Generally an unstable relationship between porphyroblasts and matrix minerals is apparent. *Staurolite* and *Kyanite* are replaced by muscovite. *Garnet* is replaced by chlorite, *Biotite* by muscovite and chlorite, and *Plagioclase* and *Hornblende* by epidote and zoisite. This is interpreted as the effect of retrogressive metamorphism.

The replacement of *Staurolite* by muscovite and *Garnet* by chlorite is apparently related to the topographic level and to the position in the stratigraphic column of the rock specimens.

Staurolite visible in a hand specimen has only been observed on the top of the mountains of Middagsfjellet, Stålegai'si, and Måskogai'si. Correspondingly the *Staurolite* from these localities shows only slight replacement by

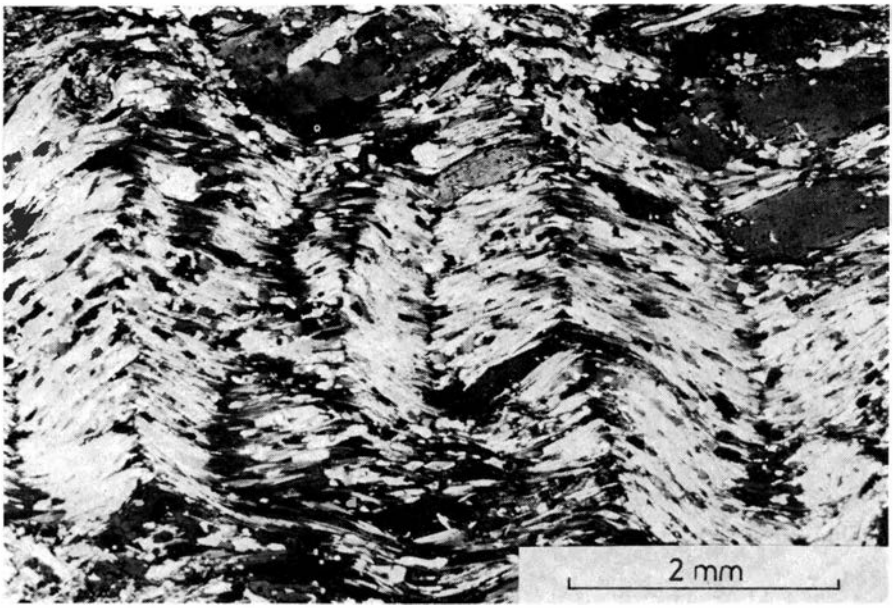

Fig. 15. Not or only weakly recrystallized F_5-crenulation. Crossed nicols. Porphyroblasts are *Biotite*. Matrix consists of muscovite, quartz, and some biotite.

muscovite. At other localities in the Upper Nappe, and one locality at a high stratigraphic position in the Lower Nappe, *Staurolite* is usually replaced by muscovite, indicating an increasing replacement from the highest topographic levels of the area towards lower levels.

Garnet replaced by chlorite is found in most specimens from the area, but the replacement seems to be most pronounced in specimens collected from the lowest stratigraphic levels, i.e. in the vicinity of the basal Caledonian thrust plane. Similar observations on garnet are made by Gustavson (1966).

Interpretation

If one accepts the interpretation that the internal schistosity (s_i) of the porphyroblasts is a relic of S_1 and that the para-crystalline rotation of the porphyroblasts was the result of an early F_2 deformation, we find that practically all porphyroblasts had finished their growth before the termination of F_2, and that most of the porphyroblasts began their growth between F_1 and F_2 or during early F_2.

Among the porphyroblasts *(Garnet, Staurolite, Kyanite, Biotite, Hornblende, Tremolite, Epidote, Zoisite,* and *Plagioclase)* the minerals are found which are indicative of almandine-amphibolite facies metamorphism, namely *Staurolite* and *Kyanite*. Moreover these index minerals are found exclusively in this group of 'older minerals'.

The observations on the matrix minerals suggest that they were partly formed after F_2 and are partly preserved original minerals of the late F_2 deformational schistosity. Moreover the observations suggest that the mimetic recrystallization ceased during F_5.

The minerals of the matrix (muscovite, biotite, chlorite, epidote, zoisite, quartz, plagioclase, calcite, and accessories) are stable in the greenschist facies, and chlorite is even indicative of greenschist facies metamorphism.

To summarize: The peak of metamorphism coincided roughly with the most penetrative tectonic phase (F_2), and the rocks recrystallized subsequently during static and probably retrogressive conditions.

The recrystallization did not obliterate the F_2 axial plane schistosity, but merely modified it, and it was increasingly effective towards the basal Caledonian thrust plane.

The grain size of s_i (i.e. S_1) suggests that the rocks during F_1 were rather fine-grained and the micaschists for example were probably phyllites.

Whether the thermal front during F_2, which resulted in the almandine-amphibolite facies metamorphism, was followed by a fall in the front and a subsequent rise to a lower level than originally (curve I in Fig. 16), or the thermal front fell continuously and slowly during the structural evolution (curve II in Fig. 16) is debatable.

The author believes that curve I is the most probable, because the growth of the porphyroblasts in most cases terminated during F_2, whether the porphyroblasts were *Staurolite,* indicative of almandine-amphibolite facies

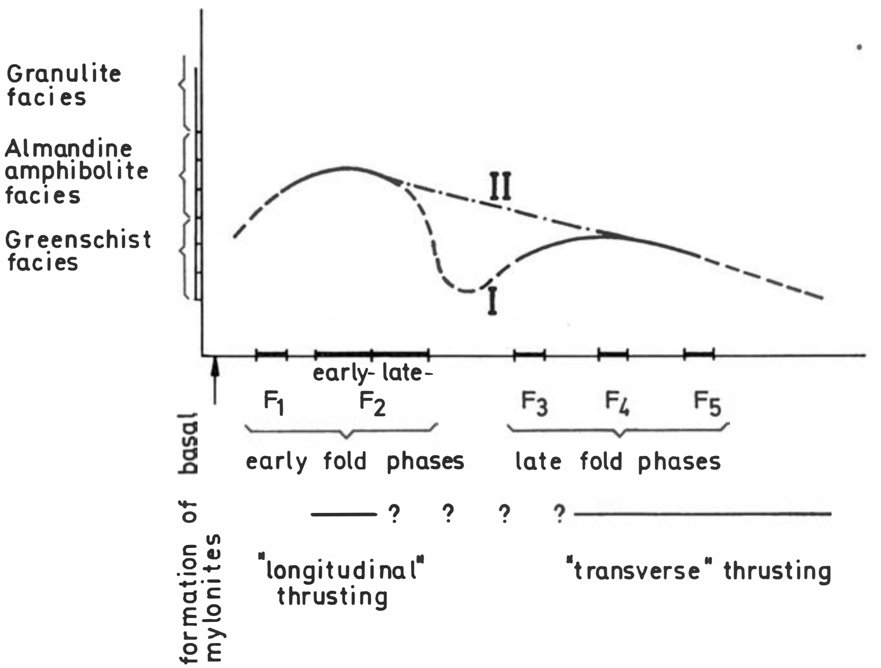

Fig. 16. Schematic correlation between deformation and metamorphism. For further explanation see the text.

metamorphism, or e.g. *Garnet, Hornblende, Zoisite,* and *Biotite,* which also are stable under the metamorphic conditions of greenschist facies, though the author realizes that these features may have been controlled by the rock chemistry.

The author finds it interesting to note the apparent direct relationship between the onset of high-grade metamorphism and the deformation of F_2, and suggests the possibility that the high-grade metamorphism was a direct result of the thickening of the strata during the folding of F_2.

Discussion

The distribution of metamorphic facies seems to indicate a reverse gradient of metamorphism.

It might be possible to explain the reverse gradient by an overlying hot mass, such as a large sheet of granite. Such an intrusion can produce a reverse gradient as demonstrated from the Caledonides of East Greenland (Haller 1962). But granites of large dimensions are absent from the present part of the Caledonides. The reverse metamorphic gradient is found all over the Caledonides of inner Troms (Kalsbeek & Olesen 1967), i.e. over a distance of more than 60 km. If an intrusion of granitic rocks caused the reverse metamorphic gradient of inner Troms, the 'mushroom' must have been more than three times as extensive as the examples known at present from Greenland.

A reversal of gradient due to large scale inversion of the rock sequence seems excluded by the sedimentary structures showing right side up.

The explanation that every zone of equal metamorphic grade corresponds to an individual nappe is favoured by e.g. Gustavson (1966). It may be that the fairly low-grade quartz phyllites form an individual nappe, as the author has found locally a possible thrust boundary between the quartz phyllites and the overlying rocks, yet it is difficult to explain the gradual metamorphic and lithologic transition which has been observed at several localities, both in the Langedalen area and in other parts of inner Troms (Kalsbeek & Olesen 1967 and Kalsbeek 1968). Moreover a thrust plane between the rocks of higher greenschist facies and those of the almandine-amphibolite facies has not been observed in the present area.

Finally the reverse gradient might be explained as being the result of retrogressive metamorphism. This is supported to some degree by the microscopic observations which suggest a polymetamorphic evolution of the rocks in question, but relics of high-grade minerals have not been observed in the low-grade rocks. The author finds a combination of overthrusting and retrogressive metamorphism as the most reasonable explanation.

It is mostly accepted that the allochthonous Caledonides in general have thrust from the central of the Caledonian geosyncline, which is now situated along the western coast of Norway, towards SE into their present position. Convincing evidence for this was found by Berthelsen (1967, p. 61), who describes the sediments of the 'Hyolithus zone' along the southern and southeastern edge of the 'Mauken Window' as lying 'on the lee side of the window structure'.

It was demonstrated above that the peak of metamorphism in the allochthonous rocks roughly coincided with F_2 and that the progressive metamorphism of the autochthonous sediments only reached the lowest greenschist facies. This allows us to conclude that the *'transverse lineation' has no relation to the large scale thrusting of the allochthonous Caledonides from NW to SE.* If the 'transverse lineation' was formed during the thrusting it is to be expected that the sediments of the 'Hyolithus zone' would also have been transformed into higher-grade rocks.

The observation that the deformation which resulted in the formation of the 'transverse lineation' included an element of laminar flow from ESE to WNW seems to exclude the interpretation, advocated by Kvale (1953) and Lindström (1957, 1958), that the 'transverse lineation' is an a-lineation formed during the thrusting towards SE. On the contrary the direction of thrusting at the time of F_2 may have been from NNE to SSW (i.e. in the longitudinal direction of the geosyncline) as the major F_2-folds form large recumbent structures, all with a southern vergence (Fig. 2). This 'longitudinal thrusting' is especially obvious when considering the thrust plane between the Upper Nappe and the Lower Nappe, which in the northern part of the Langedalen area forms the lower boundary of the reversed flank of a major recumbent F_2-fold and therefore may have served as a plane of gliding during F_2.

Similar 'longitudinal thrusting' has been described from the Scottish Caledonides by Phillips (1937) and Christie (1956, 1963). An analogous early longitudinal compression of a geosyncline is also known from the Pyrenees (Zwart 1960).

It was also demonstrated above that the metamorphic conditions during the late fold phases were rather high, probably higher than the metamorphic conditions reached by the sediments of the 'Hyolithus zone'. Therefore we may conclude that *the final thrusting of the allochthonous Caledonides to their present position took place at a very late stage in the structural evolution.* Also a purely tectonic consideration supports this view of a very late time of thrusting, namely that the folds of the late fold phases deform the allochthonous rocks, but not the basal Caledonian thrust plane, as already mentioned by Kalsbeek (1968).

However the thrust plane between the Lower Nappe and the Upper Nappe is certainly deformed by F_5 (Fig. 2). The two nappes must therefore have acted as a single nappe unit during the final thrusting of the rocks.

Finally we may state that the mylonitization of the quartz phyllites and the 'augen-textured blastomylonites' took place at a very early stage in the structural evolution as the mylonitic banding, formed during the mylonitization, participates like sedimentary bedding in the deformation. Fig. 4 B shows mylonitic banding in quartz phyllites folded in F_2-folds. Even F_1-folds have been observed by F. Kalsbeek in a neighbouring area.

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