CENTENAIRE DE LA SOCIÉTÉ GÉOLOGIQUE DE BELGIQUE
GÉOLOGIE DES DOMAINES CRISTALLINS, LIÈGE, 1974, 129-144

STRUCTURE AND METAMORPHISM IN THE SEVE-KÖLI NAPPE COMPLEX (SCANDINAVIAN CALEDONIDES) AND ITS IMPLICATIONS CONCERNING THE FORMATION OF METAMORPHIC NAPPES

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ABSTRACT

The stratigraphy and structure of the Seve-Köli nappe complex is described. Four units have been distinguished based on lithologic, metamorphic and structural criteria. They are usually separated by mylonite zones. Structurally from top to bottom an increase in metamorphic grade from greenschist facies to upper amphibolite facies, and then a decrease to green schist facies is found in the Seve nappe. This inversion of metamorphic zonation is due to thrusting. Based on microstructural evidence it can be shown that the acme of metamorphism predates the formation of the nappes, which is related to a second folding phase.

The mechanism of nappe formation is considered to be inhomogeneous shear with maximum strain in the mylonite zones.

The cause of the relatively high pressure metamorphism is thought to be burial in a first folding phase, possibly in a subduction zone, whereas metamorphism ceased when the rocks were upthrusted to the surface during the formation of the nappes.

INTRODUCTION

It is a well-known fact that the Caledonian mountain chain is for a large part built up of large nappes. This was for the first time realized by Törnebohn (1888) and has been confirmed by a.o. Kvale (1948), Kulling (1930), Strand (1961), Zachrisson (1969), just to mention a few authors. Following these authors it is customary to distinguish several nappes, which are called the lower thrust rocks, the middle thrust rocks and the upper thrust rocks. Below the lower thrust rocks a parautochtonous minor nappe complex, mainly consisting of lower Paleozoic sediments, occurs. This complex lies on the autochtonous foreland, which consists

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of Precambrian gneisses and granites, unconformably overlain by Eocambrian and lower Paleozoic unmetamorphosed sediments.

The lower thrust nappe is made of Eocambrian sparagmites and Cambro-Silurian sediments with a very low grade of metamorphism, corresponding to the quartz-albite-muscovite-chlorite subfacies (Winkler, 1967). Locally phengite has been observed, which may be indicative of fairly high pressures.

The middle thrust complex consists of a lower unit, the granite mylonite nappe and an upper unit, the Särv nappe. The granite-mylonite nappe is made of strongly deformed Precambrian basement, whereas the Särv nappe is mainly composed of quartzites and arkoses of presumably Eocambrian age. The grade of metamorphism is higher than the lower complex. Biotite may be present, besides muscovite and albite.

The next higher unit is the so-called Seve (or Seve-Köli) nappe complex, a major unit which can be followed from the northernmost tip to central Sweden, and stretches over a distance of at least 900 km. This large nappe consists of several units separated by thrust zones, so that it has a complicated structure. It is customary to divide this nappe into an upper unit, called Köli sequence which consists of dated sedimentary and volcanic Ordovician-Silurian rocks metamorphosed in the greenschist facies, and a lower unit, the Seve sequence, consisting of a metasedimentary and meta-igneous rocks of unknown age and generally metamorphosed in the amphibolite facies. It is possible that this unit is deposited in the late Precambrian or lower Paleozoic as it is strongly different from the Precambrian of the Baltic shield.

STRATIGRAPHY

A detailed stratigraphy of this nappe complex can be drawn up. The different units are however not stratigraphic units in the usual sense in which a chronological sequence is implicated, but rather they are tectono-metamorphic units, characterized by their structural style, by their grade and type of metamorphism, and by their lithologic character. These units display a certain succession in space which can be followed along the strike for at least 300 kilometres, or even more. Despite the fact that their superposition is usually consistent, this stratigraphy has no bearing whatsoever on the sequence of deposition of the original rocks nor on a general younging direction upwards, Hence it is a purely structural sequence. However, this does probably not apply to the uppermost Köli sequence, where a more or less normal stratigraphy has been mapped (Zachrisson, 1969).

Four major units can be recognized; these are from top to bottom: (1) the phyllite belt, consisting of Köli rocks, (2) the western schist and amphibolite belt, (3) the central gneiss belt, (4) the eastern schist and amphibolite belt (Table I).

1. The phyllite belt has recently been studied by Zachrisson (1969). It is divided from top to bottom in the Remdalen group, consisting of greenschists and phyllites, the Lasterfjäll group, made of quartz-keratophyres and calcareous phyllites, and the Tjopasi group which contains black phyllites and felsic and mafic metavolcanics. Conglomerates may occur between the three formations.

According to paleontological evidence the two last mentioned groups are of Ordovician age; the first group is Silurian. It is possible that in the Trondheim area, which presumably belongs to the Köli sequence, Cambrian is present, but the

TABLE 1

Tectonis unit		Rock type	Metamorphic zone
Köli		Keratophyre greenschist calcareous phyllite limestone, conglomerate quartz-keratophyre greenschist black phyllite	1, Chlorite 2, Biotite
Seve	Western belt	Garnet-micaschist quartzitic garnet-micaschist with amphibolites	3, Garnet 4, Staurolite-kyanite
	Central belt	Migmatitic ky-k-feldspar gneiss (with eclogites) quartzo-feldspathic gneiss amphibolite (hbl, cpx, gar) ky-k-feldspat gneiss (+ sill)	5, Kyanite-potassium feldspar
	Eastern belt	Meta-arkose and quartzite garnet-micaschist, marble amphibolite garnet-micaschist	4, Staurolite-kyanite 3, Garnet
Särv		Meta-arkose, quartzite, muscovite-schist	2, Biotite
Granite-mylonite		Augengneisses, mylonites	1, Chlorite
Lower nappes		Quartzite, arkose greywacke, shale	1, Chlorite
Parautochthonous Autochthonous			Unmetamorphosed

correlation between this area and the Seve nappe is still uncertain. The metamorphism of the phyllite belt falls in general in the greenschist facies, and only locally amphibolite facies conditions are reached.

2. The western schist and amphibolite belt underlies the Tjopasi group of the phyllite belt. The main rock type, called Svartsjöbäcken schists, consists of strongly planar, often platy, quartz-micaschists with large garnet porphyroblasts. In addition kyanite and staurolite have been found. The schists are generally fairly homogeneous, and may contain a mineral lineation with a west-northwestern direction.

Smaller and larger amphibolite bodies occur as layers or lenses in the schists. They may be up to a few hundred metres thick.

The contact between the Köli sequence and the Svartsjöbäcken schists is tectonic. This was first described by Zachrisson (1969) and based on a mappable disconformity. Further work has confirmed that the contact is faulted, as shown by cartography and a jump in metamorphism between the two units (Trouw, 1973). Metamorphism of the western schist and amphibolite belt falls in the amphibolite facies.

3. The central gneiss zone, underlying the western belt, consists of more or less strongly migmatized gneisses of medium grain size. Besides feldspar, quartz, muscovite and biotite, garnet and kyanite are often present. Quartzo-feldspathic layers of about 1/2-1 cm thickness cause the migmatitic aspect of the rocks. Locally these develop into large patches and small masses, but mostly there is still a distinct schistosity. This unit has a characteristic appearance in the field and can be mapped over very large distances along the strike of the Caledonian chain. Within this gneiss unit amphibolites occur, sometimes as thin, fairly continuous layers, but also as very thick bodies which may wedge out quite rapidly. These amphibolites may be up to 2 km thick. In one area, east of Blåsjön, abundant eclogites occur as small bodies and boudins up to some tens of metres size in a matrix of migmatitic gneiss. The whole central gneiss zone may be up to 5 km thick; elsewhere it wedges out completely. The contact between the western and central belt is often badly exposed; thus far it is considered to be gradational.

4. The eastern schist and amphibolite belt. This unit consists mainly of meta-arkoses to feldspar bearing quartzites, and garnet-micaschists with occasional marble layers and amphibolites. Kyanite and staurolite occur sporadically in this unit. Garnet and micas are abundant. The contact between the central gneiss belt and the eastern belt is usually a mylonite zone. The contact between the eastern belt and the Särv nappe is also tectonic.

These four units always have the same superposition, but each unit, and also individual formations within one unit may vary considerably in thickness and sometimes may disappear completely, to reappear again in the same position in another area.

STRUCTURE

The major structures in the thrust units are the nappes themselves. These nappes consist of thrust slices of varying thickness, bounded on the lower and upper side by mylonites. No large recumbent fold nappes have been found and the major folds which do occur, postdate the formation of the nappes. Thus the whole Seve-Köli nappe complex consists of several superposed smaller nappe units. For the Köli sequence this has been demonstrated by Zachrisson (1969), where a repetition of the stratigraphy indicates the presence of several small nappes.

However, the contact of the Köli with the underlying Seve unit is in many cases a thrust contact as well, whereas another major mylonite occurs between the central gneiss zone and the eastern belt, and the contact with the underlying Särv nappe is also a thrust. Furthermore mylonite zones may occur elsewhere in the Seve sequence.

The whole Seve sequence wedges out towards the west, so that on the Norwegian side the Köli nappe lies directly on the reactivated Precambrian

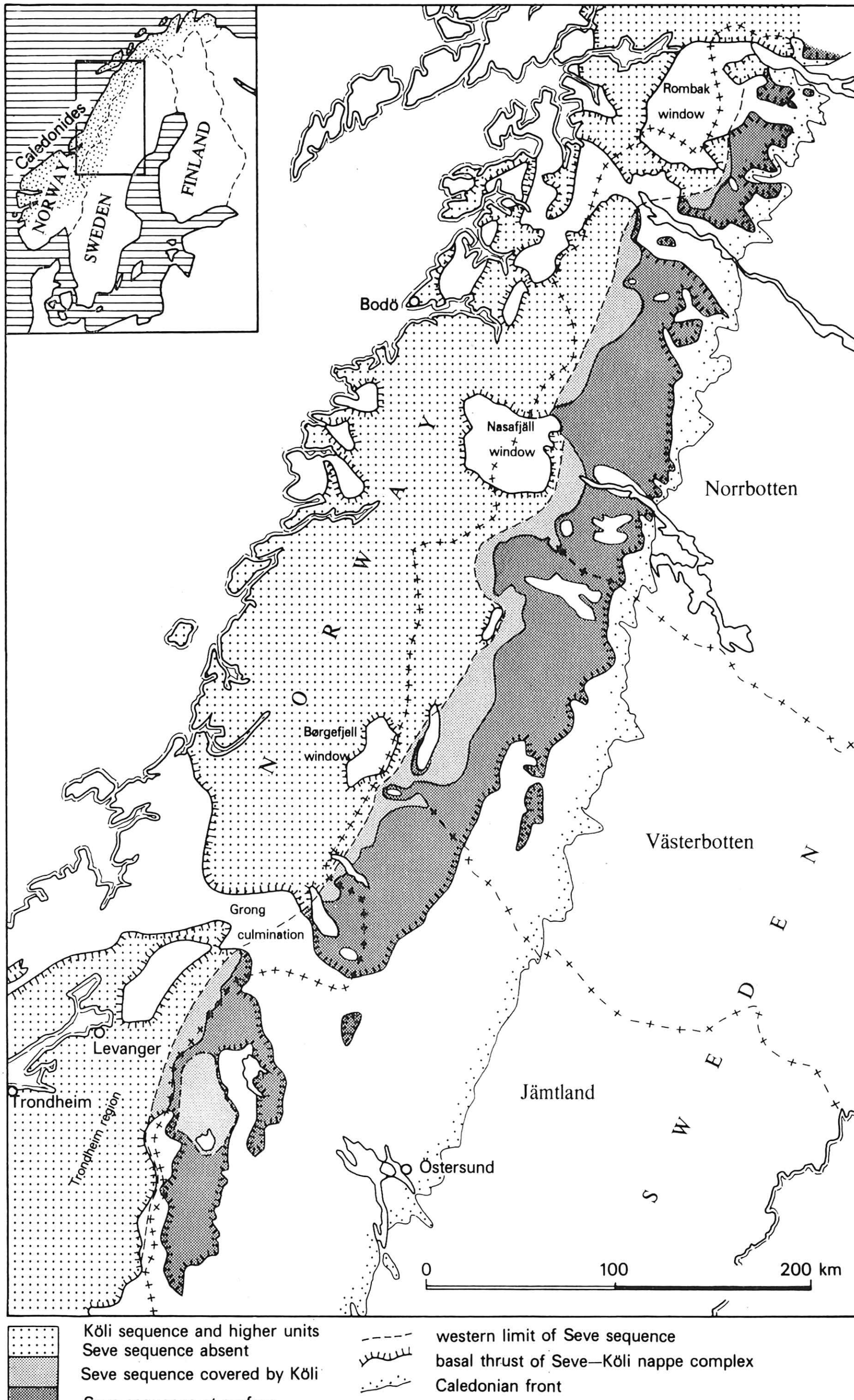

FIG. 1. — *Extension of the Seve nappe (after Zachrisson, 1973).*

basement. The total width of the Seve nappe is therefore not more than 80-100 kilometres. The extension of the Seve nappe is shown on figure 1, after Zachrisson (1973).

Small scale structures are abundant in all rock units. Like usual several generations of structures are present, some of which seem to be correlatable over a large region.

In the Köli phyllite belt three foldsets are readily distinguished. A first set is characterized by isoclinal folds with an axial plane slaty cleavage. The attitude of the axial planes and the foldaxes vary, which in part is due to later folding phases.

A second folding phase refolds the F_1 folds and often causes the development of a crenulation cleavage. The axial planes have a variable, usually shallow westward dip; the foldaxes may have a north-north-eastern direction, but they vary considerably. Besides folds on a microscopic scale, larger folds up to several hundreds of metres are attributed to this folding phase (fig. 2.)

A third set of folds is responsible for the formation of open folds, folding the S_2 crenulation cleavage. These folds have steep to vertical axial planes and a north-north-eastern direction parallel to the Caledonian trend (fig. 2).

In the Seve rocks the situation is to a certain extent similar, but S_2 may be a crenulation cleavage, a new transposed schistosity or a rotated S_1 schistosity (S_{1+2}). F_1 folds have been found in a few localities in the schists, but seem to be more abundant in amphibolites. Most F_1 folds are isoclinal, like F_2 folds. Their age can only be established with certainty with overprinting relationships. In some outcrops these relationships indicate the existence of more than one fold generation before F_2, but thus far the dates are too scanty to make a more definite statement. Another indication of the existence of a deformation phase before F_2 are internal inclusions in porphyroblasts like garnet and biotite, which are not continuous with the external schistosity. In the western schist belt the S_2 schistosity consists usually of unstrained crystals of quartz and mica. In the central gneiss zone and the eastern belt only quartz is strainfree; the other minerals often show strong postcrystalline deformation due to F_2. F_3 finally folds the S_2 schistosity in open folds, sometimes with a crenulation cleavage. All minerals

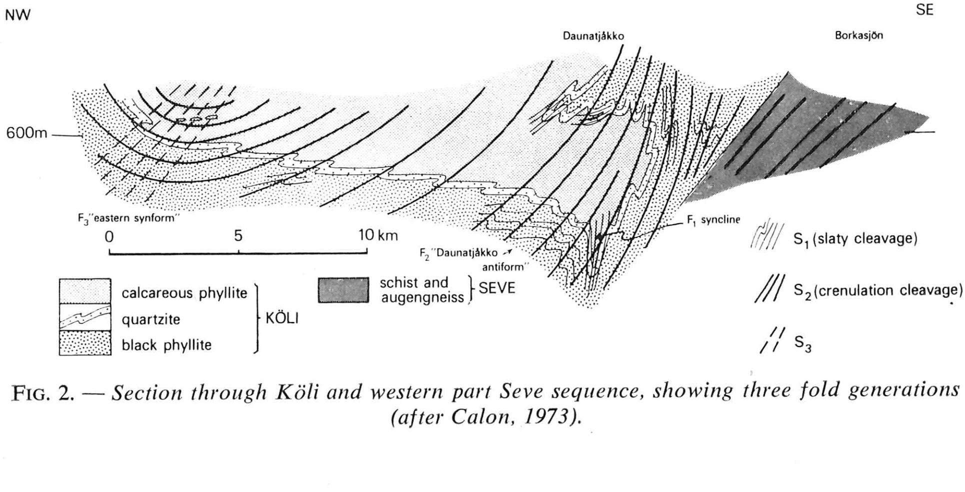

FIG. 2. — *Section through Köli and western part Seve sequence, showing three fold generations (after Calon, 1973).*

are usually deformed by this phase. F_1 folds are too scarce to tell anything about their axial direction. F_2 folds, however, usually have a west-north-western direction perpendicular to the Caledonian trend, and differ in this respect from F_2 folds in the phyllite belt. Lineations parallel to these foldaxes are common throughout the Seve. They are due to fabric habit of minerals, to preferred orientation of hornblende crystals or to quartz rods. This lineation is the same as the well-known transverse lineation of the Caledonides, which has been described by several authors (Kvale, 1953; Olesen and Sörensen, 1972).

Of great interest are the structures in the mylonite zones separating various thrust slices above, within and below the Seve nappe. These mylonites are usually finegrained, strongly laminated rocks in which porphyroclasts of garnet, kyanite and feldspar often can be recognized. The gradual change from the S_2 schistosity in the gneisses and schists into the mylonitic foliation makes it probable that the formation of the mylonites took place during the second folding phase. This interpretation is further corroborated by time relations with metamorphism. Consequently the thrusting and nappe formation belong to this folding phase.

METAMORPHISM

The most prominent feature of the regional metamorphism in the nappe sequence is that from top to bottom first an increase, and further downward a decrease of metamorphic grade occurs, or in other words, the lower part of the nappe complex shows inverted metamorphic zoning. This has been described already by several authors (Kulling, 1972; van der Harst, 1956). Although on preliminary field investigation a gradual increase and decrease in grade seems to prevail, detailed microscopic work has revealed that breaks or jumps in metamorphism do occur, and that these are especially located near mylonite zones. However, the jumps in grade are seldom very large.

The following zones have been recognized from top to bottom: chlorite zone, biotite zone, almandine zone, staurolite-kyanite zone, kyanite-potassium-feldspar zone, staurolite-kyanite zone, garnet zone, biotite zone, chlorite zone.

In table I the distribution of the metamorphic zones in the structural units is shown. The zones are numbered from 1 to 5 and the symmetric arrangement is quite evident.

The rocks of zone 1 are finegrained slates containing only quartz, muscovite and chlorite, in zone 2 porphyroblasts of biotite and ilmenite develop in this slaty matrix; plagioclase in these rocks is albite. Porphyroblastic garnet occurs in similar rocks of the garnet zone. In basic rocks bluish green hornblende, albite and epidote form a typical assemblage.

In the staurolite-kyanite zone, garnet, muscovite and biotite occur together with plagioclase up to 40 % An. Amphibolites contain green hornblende, oligoclase-andesine, epidote, biotite, quartz, carbonate.

Zone 5 is characterized by the coexistence of kyanite and potassium feldspar in pelitic rocks, together with quartz, plagioclase, biotite, garnet. Usually muscovite is also present, but locally (Marsfjällen) this mineral is absent. Sillimanite has been found in a few localities. Basic rocks contain plagioclase (An 40-80 %), hornblende, garnet, and at various localities clinopyroxene. In the Marsfjällen area orthopyroxene has been found, indicating conditions in or close to the granulite facies.

It is evident that the inversion of the metamorphic sequence is in part due to thrusting, as several zone boundaries coincide with mylonite zones. However, there is evidence that even within one zone the metamorphic sequence is inverted. This indicates that, assuming that normally metamorphism increases with depth, a whole sequence must lie upside down.

It is of some interest to investigate the time relationships of metamorphism with the successive folding phases. Like in many regional metamorphic areas, metamorphism is plurifacial, that means more than one mineral assemblage has been formed during a certain time interval — this is clearly to be seen in the Köli phyllites. The matrix consists of a finegrained aggregate of quartz, muscovite and chlorite. In this matrix large porphyroblasts of biotite and ilmenite have grown. As the biotite contains a planar internal schistosity inherited from the schistosity of the matrix, these porphyroblasts are indicative of a second stage of metamorphism of a somewhat higher grade, viz. chlorite vs. biotite-zone (fig. 3). In all rocks where a F_2 crenulation is present, the crenulation postdates the porphyroblasts, so that the highest grade metamorphism falls between F_1 and F_2. However, the micas in F_2 folds are clearly recrystallized and essentially strain free, indicating that the rocks were still hot enough to allow recrystallization. F_3 folds are, however entirely postcrystalline. In the western schist belt the relations are in principle the same, but porphyroblastesis of garnet may start already during F_1, as indicated by snowball garnets, and may continue into F_2. However, in most cases porphyroblasts of biotite and garnet contain a planar, finegrained F_1 internal schistosity, while the F_2 schistosity is curved around the porphyroblasts. Moreover

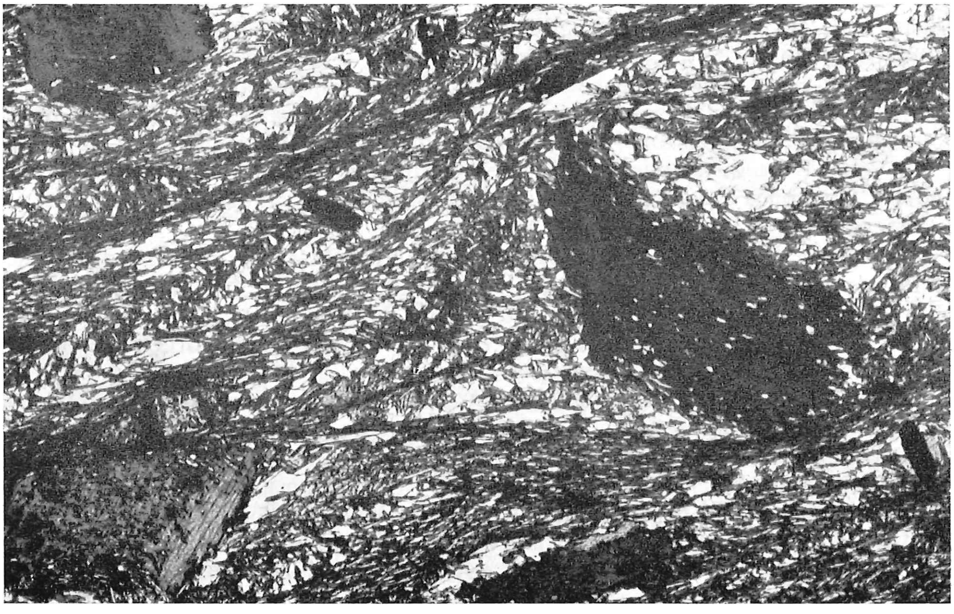

FIG. 3. — *Phyllite with biotite porphyroblast (Köli). S_1 crenulated by S_2 ; biotite has a planar S_i and postdates S_1, predates S_2.*

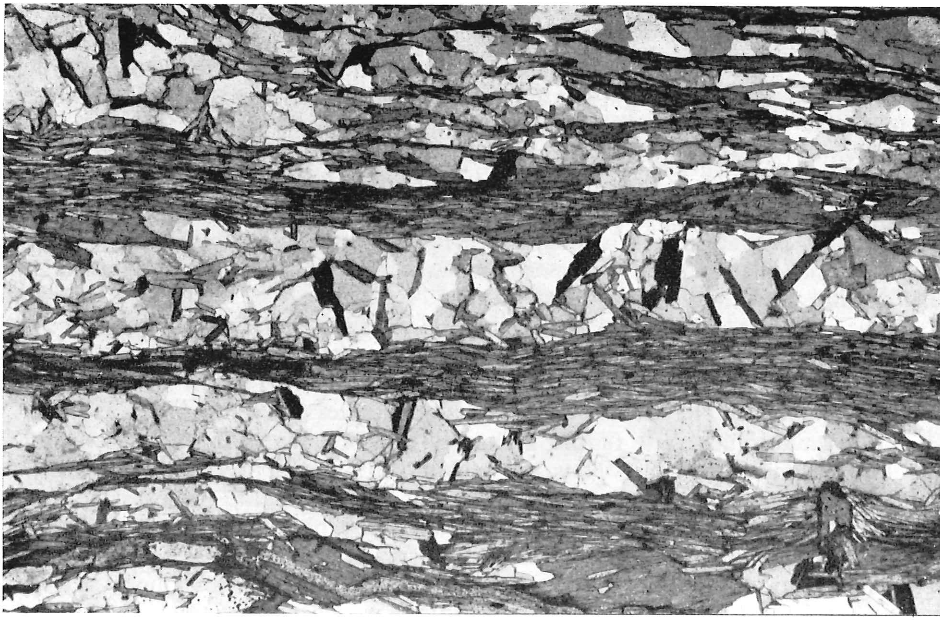

FIG. 4. — *Micaschist from western belt. Differentiated layering developed from crenulation cleavage S_2. Remnants of S_1 between micalayers.*

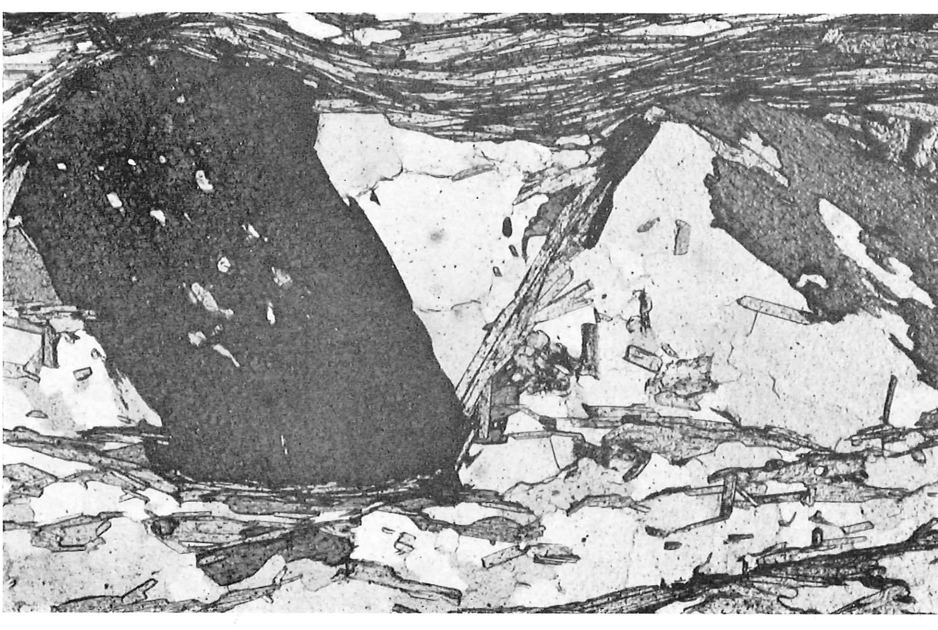

FIG. 5. — *As fig. 4; biotite porphyroblast between micalayers, bowing out S_2; biotite earlier than S_2.*

these biotites are deformed by the second folding phase. Again the acme of metamorphism falls between F_1 and F_2 (figs. 4, 5).

The central gneiss belt is characterized by unusually strong deformation textures. Mica, plagioclase and kyanite crystals show intense postcrystalline strain, the feldspars being augenshaped with a strongly curved matrix around them. Also the quartzo-feldspathic layers are strongly folded. The only mineral which has recrystallized and is unstrained, is quartz (figs. 6, 7). The folds referred to here belong to the F_2 generation, that means minerals like micas, garnet, kyanite and feldspar predate F_2. Also the migmatization predates this folding phase, indicating that the peak of metamorphism was past at that time, just as in the Köli phyllites and the western schist belt.

In the mylonite zone separating the central gneiss zone from the eastern schist belt, similar relations are found. Feldspar, kyanite and garnet occur as rounded porphyroclasts in a finegrained, laminated quartz-rich matrix which has completely recrystallized, and in fact these rocks are blastomylonites (fig. 8).

The metamorphic grade of the mylonites is the same as in the rocks above or below the mylonite zone. Thus the mylonitization in the zone separating the central from the eastern belt, took place under amphibolite facies conditions, as is shown by the absence of any retrogressive replacement of minerals like feldspar, kyanite and garnet. Mylonites in lower grade rocks belong to the greenschist facies. This indicates that mylonitization was a synmetamorphic process, although temperatures were already decreasing at that time, as the peak of metamorphism was earlier.

Summarizing it can be stated that the mylonites show a similar structural and metamorphic history as the gneisses and schists, and therefore mylonitization took

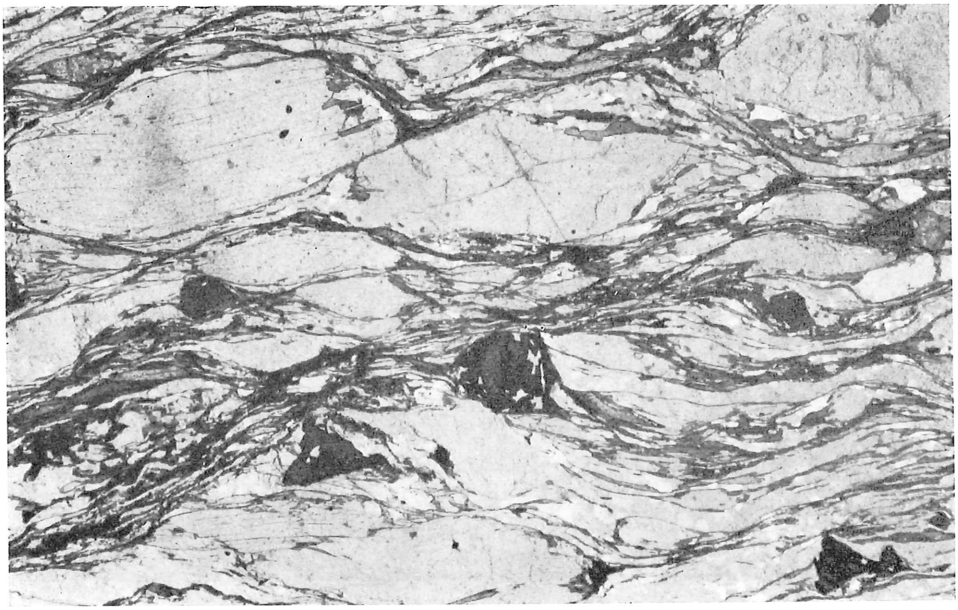

FIG. 6. — *Garnet-gneiss, central belt. Note strong deformation structure; foliation is* S_2.

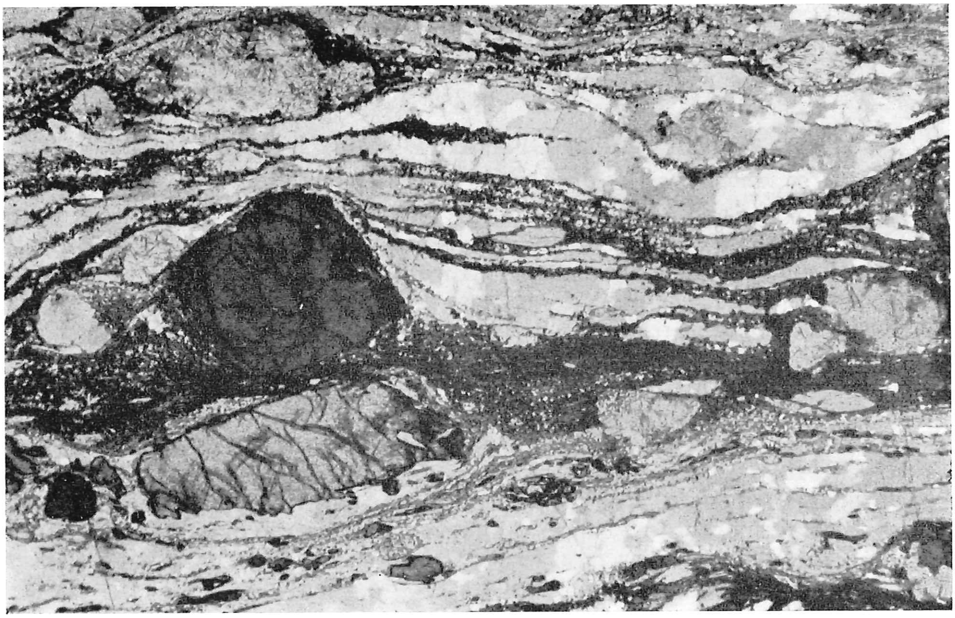

FIG. 7. — *Kyanite-garnet gneiss, central belt.*

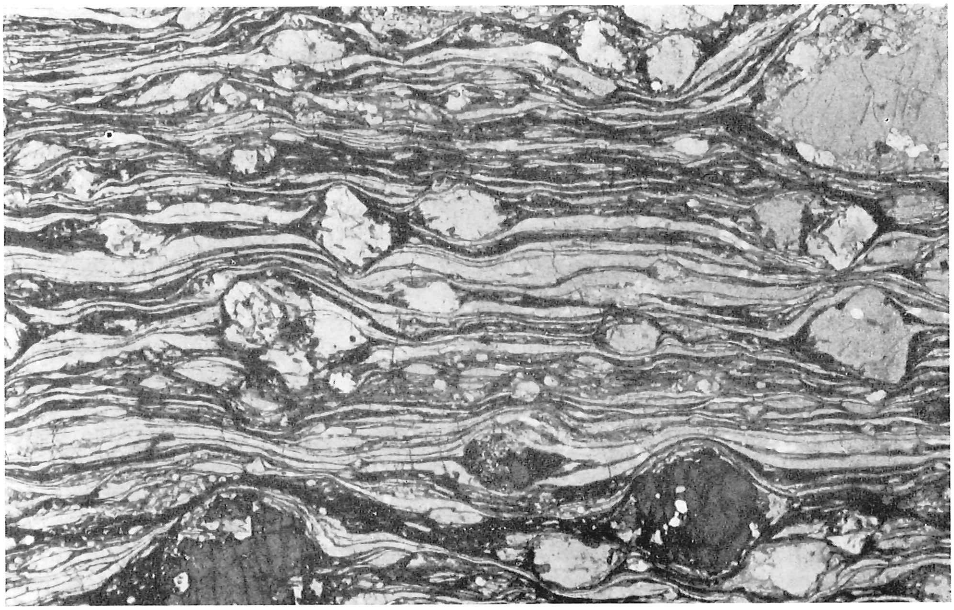

FIG. 8. — *Mylonite between central and eastern belt. Note similarity in structure with gneisses of figs. 6 and 7.*

place during F_2. Consequently the nappes were formed during F_2, by which the metamorphic zones became inverted.

MECHANISM OF NAPPE FORMATION

The description and interpretation of the Köli-Seve nappe complex, leads us to a more general problem, that of the mechanism of the formation of nappes. It is generally admitted that two types of nappes exist, recumbent fold nappes and thrust nappes. Large recumbent folds of several kilometres amplitude have been described from various regions, for example in the Alps. However, with a few exceptions (Morcles nappe), all Alpine nappes are overthrust plates with a thrust plane at the base. This applies to the Helvetic and Penninic as well as to the Austroalpine nappes. It is true that recumbent folds are quite common in the Alps, but most of these postdate the nappe movements, as the thrust contacts are also folded. Also in other mountain chains with large nappes, like the Caledonides, Appalachians, American Cordillera, Himalaya, thrust nappes are far more common than recumbent fold nappes. Moreover recumbent folds with an amplitude of more than 10 km are very rare, whereas many nappes have travelled distances of tens or even hundreds of kilometres.

Thrust nappes can be divided in two types, one type consists of unmetamorphosed, mostly sedimentary, but als crystalline rocks, the other type consists of metamorphic rocks in which metamorphism is contemporaneous with thrusting. The main difference between the two types is that rocks of the first group are not internally deformed during thrusting, and all movement is located on the basal thrust plane, whereas in the second type internal deformation takes place throughout the whole thrust mass, but with a maximum strain in a zone at the base of the slice.

Typical examples of the first type are the Helvetic nappes, part of the Austroalpine nappes, the thrusts in the Canadian Cordillera and in the Appalachians. These nappes were formed at shallow depths of probably not much more than 5 km. Many are typical sedimentary cover nappes sheared off their basement. It is in these nappes that one encounters the difficulty of transmitting a compressive stress through a relatively thin sheet of rocks, and the problem of the friction at the thrust plane which has to be overcome. Several solutions to these problems have been proposed, for instance by Hubbert and Rubey (1959) using high fluid pore pressures at the thrust plane to reduce friction, or by assuming gravitational sliding downhill, or possibly uphill as proposed by Price (1972) for the nappes in the Canadian Cordillera. All of these possibilities may apply to these kinds of nappes. Essential is that they are plates moving on a basal thrust plane under more or less brittle conditions, at shallow depth and at low temperatures.

Greatly different in their behaviour are nappes formed under metamorphic conditions that is under higher temperature and pressure. Here the rocks are much more ductile, so that strain is no longer restricted to a basal fault plane, but distributed throughout the whole thrust pile. As a type example the described section of the Caledonian mountain chain can be used. It was shown that all rocks were strongly deformed during F_2, but with an exceptionally large strain in the mylonite zones. There can be little doubt that the deformation has a large shear component, as indicated for example by the occurrence of abundant rotated garnets in all units. However, it has to be a highly inhomogeneous shear with a general movement of West-North-West to East-South-East. In this manner the isograds become deformed, and higher grade rocks may come to rest on lower grade ones. In figure 9 this mechanism is shown, starting from a set of isograds with an original more or less horizontal position. Future mylonite zones are indicated and become strongly sheared, leading to overturning of the metamorphic sequence. Seen as a whole we are dealing with a huge fold, folding the isograds. The mechanism is similar to that of Gleitbrett folds, as described by Schmidt (1932).

It will be evident that besides the isograds also the rock sequences are folded. However, the rocks were already folded during a first period predating the main metamorphism. The geometry of these early folds cannot be reconstructed, but it is unlikely that the isograds would be parallel to original stratigraphic boundaries. This explains why there is a regular metamorphic sequence first increasing and than decreasing in grade with structural depth and thus showing an almost perfect symmetry, whereas the lithologic rock types in similar metamorphic zones are very different and lack such symmetric arrangement.

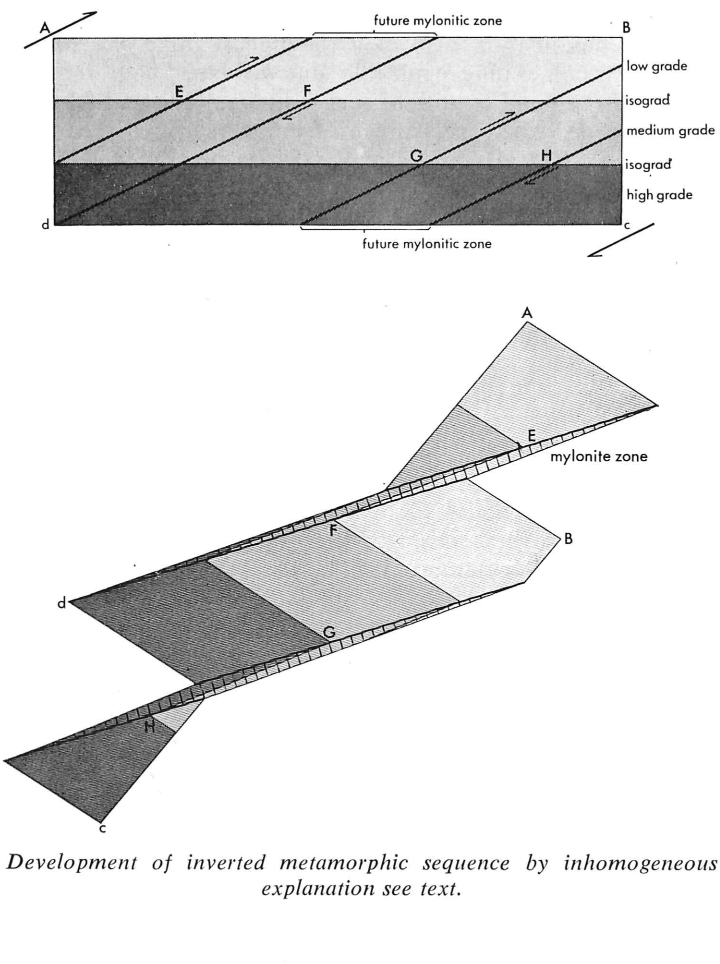

FIG. 9. — *Development of inverted metamorphic sequence by inhomogeneous shear; for explanation see text.*

This interpretation has several advantages above traditional views in which all nappes are considered as blocks moving on thrust planes. One argument in favour of the interpretation as proposed here is, that it is no longer necessary to transmit the stress through a sheet of rocks which is being pushed from the rear. Furthermore the problem of friction on the thrust plane ceases to exist, as a whole pile of rocks is deformed and not all movement is restricted to a single plane.

The relationships in the Caledonides are in sofar favourable as in this case the thrusting and nappe formation postdate the establishment of the metamorphic zonation, resulting in their inversion. As top and bottom criteria in metasediments are nonexistent or at least ambiguous, no large scale inversion of rock units can be proved, and on this base only the mechanism of nappe formation cannot be solved.

It is the author's opinion that many, if not all nappes in a metamorphic environment, that means nappes formed during metamorphism, have the same mode of formation. However, in many cases the evidence is not conclusive, as for example in the Penninic nappes of the Alps, which were certainly formed under metamorphic conditions. Here the highest grade of metamorphism postdates the formation of the nappes, that means no inversion of metamorphic zones is present, and the isograds have such a position that the deepest exposed rocks, those in the Tessin culmination, also show the highest grade. Furthermore mylonite zones may have become unrecognizable due to later high temperature metamorphism. As again top and bottom of rock units are indistinguishable, there is no way of proving the described mechanism of inhomogeneous shear.

A similar case to the Caledonides may exist in the Himalayas where inversion of metamorphic isograds occurs on a large scale. Several interpretations have been given for this feature, like the intrusion of a hot migmatite sheet with decreasing grade on both sides, or a more intense retrogressive metamorphism downward. It seems likely that in this case similar mechanism to the one described for the Caledonides was also responsible for the inversion.

CAUSE OF METAMORPHISM

It is evident that for regional metamorphism introduction of heat is necessary. In the case of the Caledonides with its Saxonian and Barrovian facies series, metamorphism took place under high pressure and relatively high temperatures. In other cases elsewhere heat is introduced high into the earth crust and may give rise to high T, low P metamorphism, as has been described from many parts of the world. This type of metamorphism is characterized by high geothermal gradients from 40-60 °C/km or even more. Other types of metamorphism, like the one described here, require geothermal gradients of about 20-30 °C/km, which are approximately the same as those existing today. In contrast to low pressure metamorphism where active heat introduction is required, for kyanite metamorphism it is sufficient to bury the rocks deeply enough, resulting in a rise in temperature due to the normal heat flow. That means the beginning of metamorphism in this case is caused by burial, which certainly must be due to orogenic forces and provides the high pressures, whereas metamorphism can cease only when the rocks cool off again, which must be due to uplift so that the rocks approach the surface. In the case of the section of the Caledonides described here, metamorphism reaches its peak after the first and before the second folding phase; this indicates that during F_1 the rocks were folded and at the same time carried to depth, whereas during F_2 the rocks were thrust from the depth towards the surface. The highest grade metamorphism took place in the interval between F_1 and F_2 when the rocks were deep in the earth's crust.

If one tries to relate this process to plate tectonics, then the burial during F_1 could be explained as taking place in a subduction zone in a similar way as the blueschist belts around the Pacific and in the Alps. It is more difficult, however, to imagine what happened during F_2 when the nappes were formed, bringing the rocks back towards the surface. Obvioulsy this is not merely an isostatic uplift, as the strain and total displacement during the formation of the nappes are extremely large.

A possible explanation is that in first instance the early Atlantic ocean was not yet closed, and subduction zone existed, thrusting the oceanic plate under the Precambrian of the north European continent. Sediments and ophiolites were carried along with the descending plate and were strongly deformed and metamorphosed during this tectonic phase. Due to continued burial, temperature and metamorphic grade increased. When finally the ocean was closed, the American plate collided with the European plate, leading to underthrusting of the latter plate, stripping off the metasedimentary sequence and upthrusting it towards the east.

ACKNOWLEDGMENT

The author wishes to thank Carlsberg Fondet, Copenhagen for financial support of the fieldwork.

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