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TOMAS SJÖSTRAND

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STRATIGRAPHY, METAMORPHISM, DEFORMATION

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SUMMARY

Tomas Sjöstrand: Caledonian geology of the Kvarnbergsvattnet area, northern Jämtland, central Sweden. Manuscript received 1977-04-27.

The Kvarnbergsvattnet area in northwestern Jämtland is situated in the Seve-Köli Nappe Complex, a major tectonic unit in the metamorphic allochthon of the Scandinavian Caledonides.

The easternmost formations in the area belong to the Seve. The transition to the overlying Köli is marked by a pronounced zone of tectonic discontinuities. The Seve is mainly composed of amphibolites and micaceous to quartzo-feldspathic gneisses, while the Köli consists of various, often graphitic or calcareous, phyllites, garbenschiefers and mica schists together with intercalated metavolcanic units (quartz keratophyres, greenschists and amphibolites). Quartzite conglomerate occurs at three distinct levels, the most conspicuous being the Portfjället Conglomerate in the western part of the area. Carbonate rocks are present in both the upper and lower parts of the Köli, and one of these, a limestone overlying the Portfjället Conglomerate, contains crinoid stems and indeterminate echinodermata.

Intrusive metagabbros occur in three different zones in the central part of the area. Bodies and layers of probably intrusive quartz keratophyre are found in the transition between the thick Blåsjö Phyllite and the Haraön Phyllites. Ultrabasic rocks are restricted to the Seve and the lower part of the Köli.

36 samples of metabasite (greenschists, greenstones, and amphibolites), quartz keratophyre, as well as quartzo-feldspathic and other metasedimentary rocks have been analysed chemically. The metabasites of the Seve and Lillvattnet Formation display non-spilitic, subalkaline basalts and differ from the Köli metabasites which are spilitic and hence apparently more alkaline. The non-spilitic, uniform basaltic character as well as the frequent and close alternation with quartzo-feldspathic rocks (meta-arkoses) of the Seve amphibolites indicate quite a different environment of deposition as compared to the Köli metabasites, which often accompany quartz keratophyres in a sequence of marine metasedimentary rocks. It is suggested that the Seve amphibolites were formed in a non-marine or continental milieu during a period of Precambrian disruption of the Baltoscandian-Greenlandian shield, whereas the Köli volcanites appeared in an island arc or archipelago environment resulting from the closing of the proto-Atlantic ocean during the Ordovician. The metagabbros are compositionally similar to the Köli metabasites. They have been subjected to the same metamorphism and deformation as the volcanic greenstones. Some compositional differences between quartz keratophyres, trondhjemites and quartzo-feldspathic metasedimentary rocks are described.

The metamorphism is of high pressure or Barrovian type and increases from low grade (the chlorite zone) in the upper Köli to high grade (migmatitic gneisses with potassic feldspar and kyanite) in the Seve.

The following deformational sequence has been established for the rocks of the Kvarnbergsvattnet area:

1. Pre-metamorphic deformation (D_1): folding and development of a bedding foliation.
2. Interkinematic period (I_1) during which the metamorphism reached its peak with static crystallization of porphyroblastic biotite, garnet, and hornblende as well as migmatization in lower parts of the sequence.
3. Syn-metamorphic deformation (D_2): formation of the regional foliation (S_{reg}) as a result of strong, microscopically penetrative deformation (flattening and shear).

The regional foliation is parallel to either the lithological layering or the axial plane foliation of tight to isoclinal folds, many of which are probably strongly modified D_1 folds. In most outcrops there is a clear transverse or NW-oriented lineation (mineral lineation, surface intersection lineation, striation or rodding) parallel to the elongation of many conglomerate pebbles as well as to the axes of many D_2 and D_3 folds. This regional lineation is thought to define the direction of maximum D_2 elongation and extension, and also the direction of D_2 and D_3 shear movements. There is probably a close connection or continuity between D_2 and D_3, and it is thought that the main nappe translation was initiated during D_2 but continued during D_3.

4. Late-metamorphic deformation (D_3): formation of major and minor folds with a generally pronounced axial plane crenulation cleavage. The D_3 folds are to a large extent sideways-closing with axes parallel or subparallel to the regional lineation. The large folds in the western part of the area, the so-called Portfjället folds, were formed during D_3.
5. Post-metamorphic deformation (D_4 and D_5): folding and also faulting probably in response to basement instability after the main nappe translation. During D_4 major open antiforms, synforms, domes, and basins were developed, as well as congruent minor folds with variable orientations. In the western part of the area, both the D_2 and D_3 structures were deformed into a vertical orientation during D_4. The D_5 folds are open or kink-like, reclined to recumbent folds or flexures which are symmetric or show a down-dip vergence. They were possibly formed due to gravity-induced settling of the major, steep, D_4 structures.

A comparison is made between the deformational sequences of the Kvarnbergsvattnet area and four other areas in Västerbotten county (Zachrisson 1969, Trouw 1973, Stephens 1977), and the northern Trondheim region (Roberts 1967).

The applicability of the terms Seve and Köli is reviewed and discussed. It is suggested that Seve and Köli should be used in a broad sense for two major litho-tectonic units within the metamorphic allochthon of the Scandinavian Caledonides. The essential characteristics of the contrasting Seve and Köli lithologies are listed, and the tectonic delimitation of these units is discussed.

The rock units of the Kvarnbergsvattnet area are correlated with those in Västerbotten county and the northern Trondheim region. Judging from these correlations and the tectonic evolution of the area, it is argued that the western part of the Köli sequence is inverted and older than the central Blåsjö Phyllite, which is thought to be of Lower to Middle Silurian age.

An attempt has been made to insert the stratigraphy, deformation, and metamorphism of the investigated area in a large-scale tectonic model involving the following elements:

1. Precambrian division and separation of the Greenlandian-Baltoscandian continent; deposition of the Seve sequence in a largely non-marine milieu.
2. Development of a proto-Atlantic ocean.
3. Mixed Ordovician volcanic activity and sedimentation in an island arc environment.
4. Silurian approach of the Greenlandian plate to the Baltoscandian continent, collision and overthrusting of the Greenlandian plate. Deformation and metamorphism of the rocks of the Seve-Köli Nappe Complex, these rocks being simultaneously displaced from their original position in the eugeosynclinal basin west of the present Norwegian coast to their final position upon the eastern miogeosynclinal sedimentary rocks along the Caledonian Front.

INTRODUCTION

GENERAL REMARKS, METHODS AND NOMENCLATURE

The Kvarnbergsvattnet area is situated in northwestern Jämtland and extends from Lill- and Stor-Jorm in the north across western Kvarnbergsvattnet to Kvesjøen (Norway) in the south (Plate I). The Swedish part of the area lies within the topographic maps 22 D Portfjället and 22 E Frostviken, while the Norwegian part belongs to the map-sheets Nordli and Tunnsjø. The topography is rather even with tree-covered undulating hills and marshes between the larger lakes. To the west the ground is more broken and certain hills reach above the tree line, which here runs at a height of about 650 m. The bedrock is generally covered with till or other loose Quaternary glacial deposits and large parts of the area, especially in the east, are badly exposed.

The mapwork was carried out in connection with SGU's[1] base metal prospecting programme in the Swedish Caledonides. Most of the field work was undertaken during the summers 1969 to 1971. Complementary work has followed during the last few years in connection with continued mapping in adjacent areas. Aerial photographs at the scale of 1:20 000 were used as base maps in the field. The geology was transferred to and compiled on topographic maps at the same scale; these were then reduced to the present scale of 1:50 000. The outcrops examined are outlined in a simplified way on the main map. The alternation between various rock units is sometimes rapid and the contacts are often transitional. Since only the dominant rock type in such sequences is indicated on the map, this gives in some areas a misleading impression of well delimited, relatively thick and homogeneous units. Certain members, for example some limestone or marble units, have been exaggerated in order to be represented.

Magnetic and electromagnetic ground measurements have been carried out over a 9 km² area between Kvarnbergsvattnet and Björkvattnet (Plate I) and four slingram profiles have also been measured across the Haraön Phyllites between Viken and Långviken. The presence of conducting graphitic phyllites gives a good control of the rock distribution in these areas.

The inset map (Plate I) shows the main lithostratigraphic units (formations and groups) in the northwestern Jämtland and eastern Grong region. The geology of the Norwegian side has essentially been taken from the geological maps Nordli and Tunnsjø (Foslie 1958, 1959) and Namsvattnet (Foslie and Strand 1956), while the Swedish parts outside the Kvarnbergsvattnet area have been compiled from published geological maps (Nilsson 1964, Zachrisson 1969) and recent SGU mapping by G. Juve, I. van der Molen, M. Wilson, and the present author under the direction of E. Zachrisson.

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[1] SGU = Sveriges geologiska undersökning (Geological Survey of Sweden.)

All rocks of the Kvarnbergsvattnet area are metamorphic and deformed. As primary sedimentary or igneous microtextures are scarce the following grain size scale is employed for both metasediments and meta-igneous rocks: Coarse-grained > 2.0 mm, medium-grained between 0.2 and 2 mm and fine-grained < 0.2 mm.

The fine-grained pelitic to psammitic metasediments of the chlorite and biotite zones have been mapped as phyllites and four different types have been distinguished:

1. Graphitic phyllites containing sufficient organic matter to blacken the fingers when rubbed;
2. Calcareous phyllites giving a clear reaction to dilute HCl;
3. Quartz phyllites containing 50 to 90 vol. % quartz;
4. Ordinary grey phyllites.

Within the garnet-hornblende zone the quartz phyllites change gradually to somewhat coarser mica or quartz-mica schists, while the pelitic metasediments still have a phyllitic appearence. The term garbenschiefer is used for a phyllite or mica schist with rods, bundles or sheaves of hornblende more or less randomly oriented in the foliation plane (cf. p. 67). Fine- to medium-grained rocks with a marked planar fabric and a well developed fissility are called schists, while more coherent, medium- to coarse-grained rocks are called gneisses (split into plates or angular blocks a few centimetres or more in thickness).

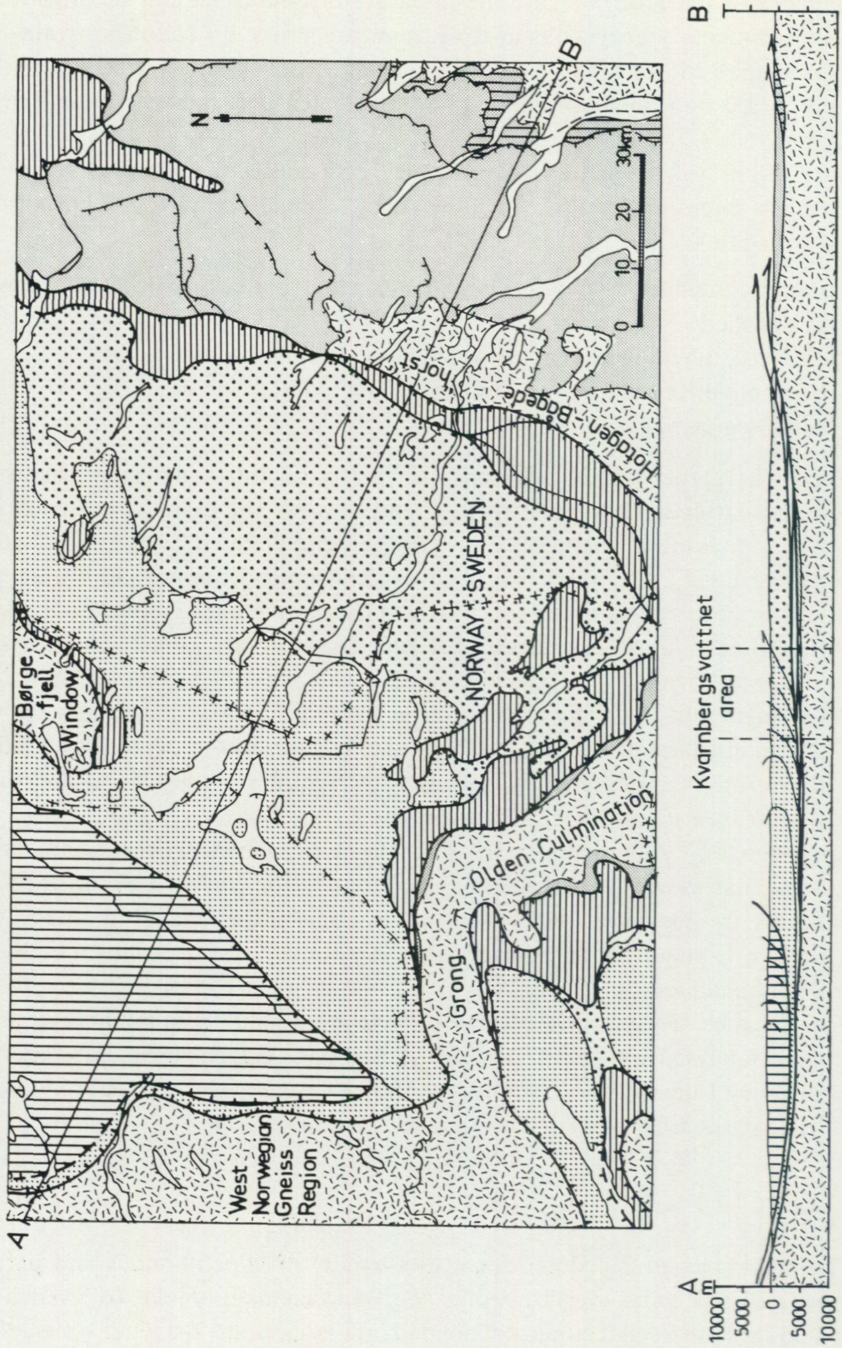
If the main foliation (cleavage, schistosity, gneissosity) is parallel to a lithological layering, its orientation is marked with continuous symbols on the maps; otherwise broken symbols are used.

Approximately 250 thin sections have been examined. The An-content of plagioclase has mostly been estimated according to the Michel-Levy method. In some cases the maximum extinction in the zone perpendicular to (010) was measured by U-stage and in 20 sections the An-content was determined by X-ray microprobe analysis.

Various rock associations from the Kvarnbergsvattnet and adjacent areas have been analysed for major elements at the SGU Geochemical Laboratories. The location of the analysed samples are shown on the map (A 1–A 36, Plate I), and the analyses are presented and discussed on p. 33.

REGIONAL GEOLOGY

The Scandinavian Caledonides consists mainly of allochthonous and parautochthonous rock units overthrust onto the Baltoscandian Shield. In Sweden the Caledonides have been tectonically divided into Uppermost – Upper – Middle – Lower – Lowermost thrust rocks and Autochthonous sedimentary rocks deposited directly on the basement (Kulling 1964, Strand and Kulling 1972).


A
B
N
0 10 20 30 km
Børgefjell Window
NORWAY
SWEDEN
Hotagen - Bågede horst
Olden Culmination
Grong
West Norwegian Gneiss Region
Kvarnbergsvattnet area
m
10000
5000
0
5000
10000

Present paper	Kulling 1972
Helgeland Nappe Complex	Uppermost thrust rocks
Köli — Seve: Seve-Köli Nappe Complex	Upper thrust rocks
Särv Nappe Offerdal Nappe, Stalon Nappe	Middle thrust rocks
Jämtlandian Nappes, Blaik Nappe Complex	Lower thrust rocks
East Jämtland Nappes	Lowermost thrust rocks
Cover	Autochthonous sedimentary rocks
Basement	Pre-Cambrian basement

Fig. 1. Major tectonic units in northern Jämtland, southern Västerbotten and the Grong district.

Along a traverse through the central Caledonides, the crystalline basement, composed of Precambrian granites, porphyries and gneisses, is exposed in the West Norwegian Gneiss Region, the Grong-Olden Culmination and in several tectonic windows (Fig. 1). Autochthonous Late Precambrian to Ordovician sediments occur unconformably as a thin cover on top of the basement along the Caledonian Front. The Lowermost and Lower thrust rocks are made up of a series of parautochthonous to allochthonous décollement nappes (Gee 1975), consisting of Late Precambrian arkoses (sparagmites) and quartzites, and fossiliferous Cambro-Silurian shales, greywackes and limestones.

The lower part of the major metamorphic allochthon, which belongs to Kulling's Middle thrust rocks, is in the southern part of the Swedish Caledonides divided into two units, the Offerdal Nappe (including the Granite-mylonite Nappe, the Fuda Nappe and the Tännäs augen gneiss) and the Särv Nappe (Strömberg 1955, 1961, Gee 1974, 1975). The Offerdal Nappe consists of usually schistose or mylonitic Precambrian crystalline rocks and Late Precambrian arkosic metasediments. It is traceable along the Grong-Olden Culmination (Oftedahl 1956) and also appears in the Tømmerås Antiform (Gee 1974). The Särv Nappe is essentially composed of schistose, feldspathic metasandstones intruded by an olivine-bearing tholeiitic dyke swarm referred to as the Ottfjället dolerite.

The Kvarnbergsvattnet area belongs to the Seve-Köli Nappe Complex (Zachrisson 1973), which is equivalent to Kulling's Upper thrust rocks. The Seve rocks consist mainly of alternating amphibolites and micaceous to quartzo-feldspathic or quartzitic schists or gneisses. They are unfossiliferous and probably older than the Köli, which contains several formations with fossils of Ordovician to Silurian age. In Jämtland there is a pronounced tectonic discontinuity separating the Seve from the overlying Köli rocks, which are characterized by phyllites to metagreywackes, often calcareous or graphitic, together with occasionally thick units of basic or alternating basic and acid metavolcanites (greenschists, greenstones and quartz keratophyres). Other typical Köli rocks are conglomerates, quartzites and limestones. Many ultrabasic bodies occur concentrated in the upper Seve and the lower Köli.

In the Grong district the Seve-Köli Nappe Complex, including in this paper the Rørvik Group, the Limingen Group (Foslie and Strand 1956) and the Gjersvik Nappe (Oftedahl 1956), is overlain by the Helgeland Nappe Complex (Gustavsson 1973), which very likely is tectonically equivalent to Kulling's Uppermost thrust rocks. The Helgeland Nappe Complex is compositionally quite different from the Köli, and consists mainly of porphyritic granites, various granodiorites, granitic gneisses, micaceous gneisses and mica schists.

Most units within the Seve-Köli Nappe Complex wedge out towards the base of the allochthon. A conspicuous feature is the absence of Seve rocks in the western part of the Grong-Olden Culmination and around the Børgefjell window

(Zachrisson 1973) where various Köli formations almost directly overlie the crystalline basement.

The metamorphism in the Lowermost and Lower thrust rocks is of very low to low grade, the rocks being almost unmetamorphosed or belonging to the chlorite zone. It then increases up the sequence towards the central or upper part of the Seve, which, amongst other units, contains kyanite + K-feldspar gneisses with eclogites and garnet + clino-pyroxene amphibolites (Zwart 1974). Further up or westwards the metamorphism decreases to the biotite and chlorite zones in the upper Köli. This major inversion of the metamorphic zonation is possibly due to inhomogeneous shear in connection with nappe formation (Zwart 1974). In the Grong district there is a sudden increase from low to medium or high metamorphic grade between the Köli and the Helgeland Nappe Complex.

PREVIOUS WORK

The first geological maps over the Kvarnbergsvattnet area were the county maps of Jämtland at the scale of 1:800 000 and 1:500 000 (Högbom 1894, 1920). Following Törnebohm (1872, 1888), the overthrust Caledonian mountain schists were divided on these maps into Seve and Köli schists, and the larger part of the Kvarnbergsvattnet area was assigned to the Northern Jämtland Köli Schist Area.

The adjacent Norwegian Grong and Liene districts were mapped by Foslie during the twenties and the geology was briefly described in work reports (Foslie 1923, 1924, 1926); the geological maps were published at the scale of 1:100 000 during the fifties.

A schematic map of the Kvarnbergsvattnet area was presented by Du Rietz (1935) and, in two articles (1935, 1936), he described in more detail a few sections across the Caledonides of northwestern Jämtland. In a later paper Du Rietz (1938) discussed the metamorphism of the Muruhatten (Lillfjället) area, which borders the Kvarnbergsvattnet area to the southeast (Plate I).

During SGU's ore-prospecting work in northern Jämtland and southern Västerbotten under the direction of G. Kautsky, large parts of the Seve-Köli Nappe Complex were mapped and considerable areas were geophysically surveyed by means of electromagnetic ground measurements (unpublished SGU-material); in this connection, the area west of Stor-Blåsjön was mapped in detail (Nilsson 1964). The rock units of the Blåsjö area continue without significant lithological changes southwards into the western part of the Kvarnbergsvattnet area (Plate I).

In his compilation of the Caledonian geology of northern Jämtland and southern Västerbotten, Zachrisson (1969) divided the Swedish Köli into three groups – the Tjopasi, Lasterfjäll and Remdalen Groups (Table 10) – and correlated them with the fossiliferous rocks of the Björkvattnet–Virisen area (Kulling 1933). Based on these correlations the lowest unit, the Tjopasi Group, is considered to be Cambrian(?) to Upper Ordovician in age, and the overlying Lasterfjäll and Remdalen Groups are thought to be uppermost Ordovician to Silurian. The upper part of the rock sequence in the Blåsjö area was treated as a separate Köli unit, the Leipik Nappe, containing rocks of uncertain age.

DESCRIPTION OF FORMATIONS

INTRODUCTION

The rocks of the Kvarnbergsvattnet area are folded and displaced due to shear and thrust movements. They form a structural rather than a stratigraphic sequence and the rock units on the main map (Plate I) make up formations of rather informal character. Continuation of the different formations within the Kvarnbergsvattnet area to the south towards the Grong Culmination and northwards into the Blåsjö area is evident from the inset map, which also shows the distribution of the underlying Seve and the overlying western Köli of the Grong district. The meaning of the terms Seve and Köli is reviewed and discussed on p. 91.

Besides the inset map a correlation table (Table 10) has been compiled to illustrate tectonic positions and correlations between various units north and south of the Grong Culmination.

Type and reference sections, some of which are situated outside the Kvarnbergsvattnet area, are marked with coarser lines on the inset map. The boundaries between the formations are often vague and difficult to define more precisely due to alternation of rock units in transition sequences. The thickness of the different units has been measured perpendicular to the most pronounced foliation, which is generally parallel to the bedding or the lithological layering but also to the axial surface of early, tight or isoclinal folds. The values are not always directly comparable since the amount of flattening and the intensity and style of folding vary in different parts of the area.

The formations are described from east to west i.e. from the structurally lowest to the highest. The metamorphism decreases up the sequence from high or medium grade (amphibolite facies) to low grade (lower greenschist facies). The legend to the main map gives a short summary of the rock sequence in the Kvarnbergsvattnet area.

SEVE UNITS

BLÅSJÖÄLVEN FORMATION

The easternmost rock units of the Kvarnbergsvattnet area belong to the Blåsjöälven Formation, which is composed of amphibolites alternating with micaceous,

Fig. 2. Alternating amphibolite and migmatitic gneiss, Blåsjöälven Formation, N. Digerhösen.

quartzo-feldspathic or quartzitic metasediments (schists or gneisses). In the type section along the river between Blåsjön and Stor-Jorm, the Blåsjöälven Formation is underlain by often migmatitic, micaceous gneisses – the Avardo Formation – containing more or less amphibolitized bodies of eclogite, and minor units of amphibolite. There is a gradual transition to the overlying Lillfjället Gneiss marked by a decrease in the proportion of amphibolite. The thickness of the Blåsjöälven Formation is approximately 900 m in the type section.

At Stor-Jorm rocks belonging to the upper part of the Blåsjöälven Formation are exposed. They are mainly composed of light, often brownish-weathered quartzitic to quartzo-feldspathic gneisses alternating with fine- to medium-grained, layered to flaggy foliated amphibolites (A 23–24, Plate I). The alternation is sometimes distinct with planar layers varying in thickness from a few millimetres to several metres, sometimes it is diffuse or more irregular; conformable layers or lenses of pegmatite are rather common. Below the Seve-Köli discontinuity strongly and irregularly folded chlorite-muscovite schists and blasto-mylonitic gneisses occur. It is uncertain whether these rocks belong to the Blåsjöälven Formation or to the overlying Lillfjället Gneiss.

Along the southern shore of Kvarnbergsvattnet, southeast of Digerhösen, amphibolites and gneisses belonging to the Blåsjöälven Formation occur. They

	Q.	Plag.[1)]	Hbl.	Ep/cl.	Bi.	Mu.	Chl.[2)]	Acc.[3)]
Amphibolite (A 22)	—16—	(An34)	69	15				
Amphibolite (A 23)		21(An21)	70	6			+	3
Amphibolite (A 24)	17	9(An28)	70	2				2
Quartzo-feldspathic gneiss	58	33(An22)				—9—		
Quartzo-feldspathic gneiss	61	33(An20)		—6—				
Migmatitic micaceous gneiss (A 28)	40	22(An28)			14	22	+	2
Quartzo-feldspathic gneiss (A 29)	61	30(An8)		+		+	8	1

1) The plagioclase consists of xenoblastic, generally non-twinned, clear or altered grains representing two generations.

2) The chlorite is a secondary mineral occuring in partly retrogressed garnets or in thin irregular crush zones (A 29).

3) Mainly sphene, garnet and ore minerals.

Table 1. Mineral composition (vol. %) of some typical amphibolites and quartzo-feldspathic gneisses from the Blåsjöälven Formation.

are compositionally very heterogeneous and intermediate rock types and transitional sequences are found in many outcrops. The amphibolites are fine- to medium-grained and occur either as massive, homogeneous to faintly layered bodies, or as more regular, foliated layers (A 22, Plate I) alternating with gneisses (Fig. 2). The leucocratic rocks consist mainly of fine- to coarse-grained, locally kyanite-bearing, micaceous to quartzo-feldspathic gneisses (A 28, Plate I). The rocks are often strongly migmatitic and soaked with plagioclase-rich pegmatitic neosome. The orientation of the main foliation changes rapidly, partly due to pronounced post-schistosity folding but also due to flattening around bodies of amphibolite.

At Digerhösen an ultrabasic body is enclosed in slightly migmatitic, micaceous schists or gneisses, which have been ascribed to the Blåsjöälven Formation on the inset map. However, it is possible that these rocks belong to the Lillfjället Gneiss. The mineral composition of some typical rocks from the Blåsjöälven Formation are shown in Table 1.

LILLFJÄLLET GNEISS

The Lillfjället Gneiss is a medium- to coarse-grained gneiss, often migmatitic with streaks, lenses or patches of pegmatitic neosome (Fig. 3), sometimes soaked with mobilized material. Essential minerals are quartz, acid oligoclase to ande-

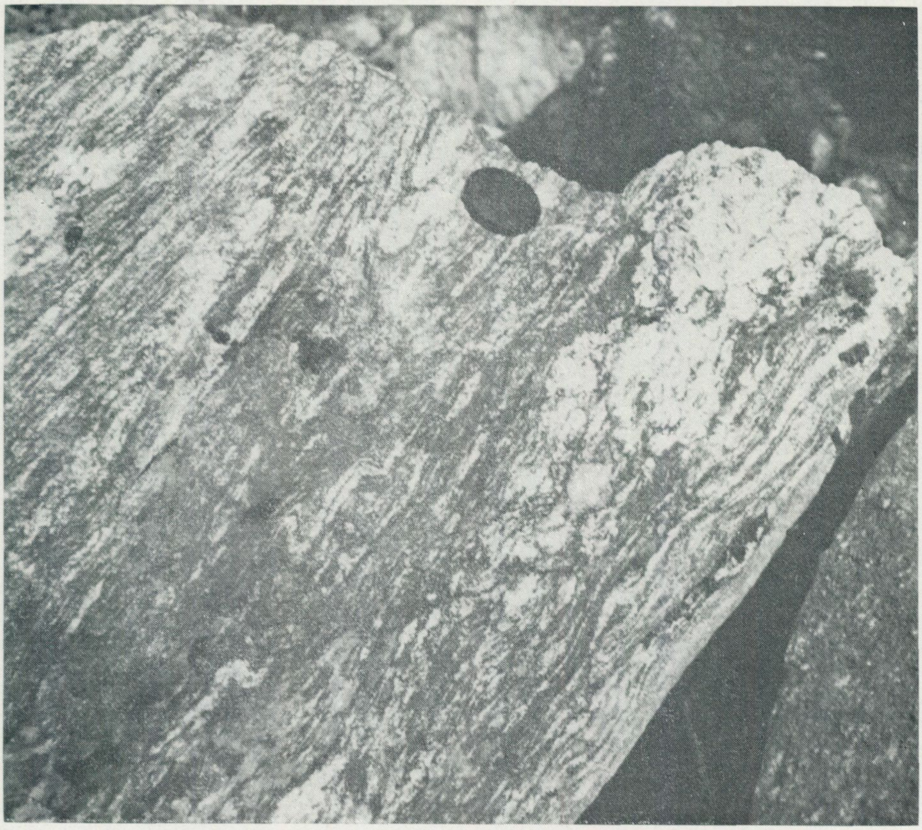


Fig. 3. Migmatitic Lillfjället Gneiss with tight early folds, Blåsjöälven.

sine, microcline, muscovite, biotite and garnet; kyanite and sillimanite (Du Rietz 1938) occur among the accessory minerals. The composition often varies strongly within a single outcrop, changing from lighter quartz-rich to darker, biotite-rich units. The main foliation is in most outcrops strongly folded or contorted. The pegmatitic neosome is composed of acid plagioclase, quartz and muscovite with minor amounts of K-feldspar and occasional garnet. In some areas, however, K-feldspar is the dominant mineral (Du Rietz 1938).

In the type area west of Gäddede the Lillfjället Gneiss is approximately 400 m thick. It is underlain by alternating amphibolites and gneisses belonging to the Blåsjöälven Formation, and overlain by schistose amphibolites and mica schists of the Lillvattnet Formation. Towards Kvarnbergsvattnet the gneiss wedges out, but reappears at Kvarntjärnen and east of Småvattsbränna, where it attains a thickness of about 300–400 m. Between Stor-Jorm and Blåsjön the Lillfjället Gneiss rapidly wedges out again towards the Seve-Köli discontinuity.

Ultrabasic bodies and layers of talc-serpentine-carbonate rock occur at serveral places around Kvarnbergsvattnet, particularly within the Lillfjället Gneiss and the overlying Lillvattnet Formation (Plate 1); they have been described in detail by Du Rietz (1935).

SEVE-KÖLI TRANSITION UNIT

LILLVATTNET FORMATION

The Lillvattnet Formation consists of amphibolites and schists with both Seve and Köli affinities, and is delimited by tectonic discontinuities on both its lower and upper boundaries; several minor thrust zones also occur within the formation. It is, therefore, classified as a Seve-Köli transition unit. East of Klumplidklumpen (Plate 1) there is a gradual transition from mica schists of Lillvattnet type to mica schists of Köli type. This lithology is termed the Tången Mica Schist and is also treated as a transition unit between the Seve and the Köli. From Stor-Jorm and northwards the Tången Mica Schist successively overlies the Lillfjället Gneiss, the Blåsjöälven Formation, the Avardo Formation, and the Lejaren Formation, the latter being an even lower Seve unit. There is, accordingly, a considerable tectonic gap between the Tången Mica Schist and the Seve, corresponding at Lejaren to the upper half of the Seve.

Type and reference sections for the Lillvattnet Formation are located along both the Björkvattnet – Gäddede road, the southern shore of Kvarnbergsvattnet and in the Småvattsbränna area. The formation attains a maximum thickness of approximately 400 m south of Kvarnbergsvattnet. To the north it wedges out but reappears as a tectonic lens at Småvattsbränna.

The Lillvattnet Formation is composed of alternating amphibolites and schists. The thickness of the different units varies from a few millimetres to several metres or more. The amphibolites are fine-grained and markedly schistose. They characteristically contain small needles of hornblende orientated in a random to weakly linear fashion in the foliation. These amphibolites resemble the amphibolites in the overlying Köli as far as the presence of a well defined schistosity and the small needles of amphibole are concerned; indeed it is generally easy to distinguish them from the less schistose and more granular Seve amphibolites. However, they are more related to the Seve by their chemistry and the nature of the interbedded rock types i.e. quartzo-feldspathic metasediments rather than quartz keratophyres. The mineral composition of some typical schistose amphibolites and quartzo-feldspathic schists are shown in Table 2.

The major part of the Lillvattnet Formation is composed of different fine- to medium-grained schists. The following types can be distinguished:

1. Light quartzo-feldspathic schists to mica schists (Table 2).
2. Greenish or brownish-weathered garnet-mica schists with numerous garnets (3–6 mm across).

	Q.	Plag.[1]	Hbl.	Ep/cl.	Bi.	Mu.	Acc.[2]
Amphibolite (A 19)	9	6	65	19			1
Amphibolite (A 20)	11	1	72	14			2
Amphibolite	11	10(An22)	69	10			+
Amphibolite (A 21)		21(An21)	66	12			1
Quartzo-feldspathic mica schist	42	32(An19)			12	13	1
Quartzo-feldspathic schist (A 27)	65	18			6	7	4

1) The plagioclase is generally clear, xenoblastic and non-twinned.

2) Sphene, chlorite, calcite, apatite, garnet and ore minerals.

Table 2. Mineral composition (vol. %) of some typical schistose amphibolites and quartzo-feldspathic schists from the Lillvattnet Formation.

3. Dark grey garnet-mica schists with scattered garnets (5–10 mm across); the dark colour is caused by small amounts of graphite.
4. Black, strongly graphitic schists.
5. Light feldspar-rich schists with coarse garnets and randomly oriented stumpy prisms of hornblende.
6. A relatively thick unit composed of light-coloured quartzite to quartz-mica schist alternating with greenish mica schist occurs west of N. Digerhösen. It wedges out both northwards and southwards but the same rock unit occurs again in the Småvattsbränna area.
7. West of Lillvattnet there is a lens-shaped unit of garbenschiefer (A 36, Plate 1), which is separated from the overlying Köli, i.e. the Kvemoen Mica Schist, by a pronounced thrust zone. Downwards it alternates with and gradually changes into mica schists of Lillvattnet type. The garbenschiefer is a calcareous metasediment made up of lighter quartz-rich and darker micaceous layers with garnets and numerous sheaves or rods of hornblende randomly oriented in the foliation. It is very similar to the Köli garben-schiefers, which occur higher up in the sequence.

KÖLI UNITS

KVARNBÄCKEN CONGLOMERATE

East of Kvemoen a quartzite conglomerate is exposed in a few outcrops in and around a small stream called Kvarnbäcken. It consists of pebbles of light quartzite in a greenish matrix of mica or quartz-mica schist (Fig. 4). Two small pebbles of a foliated biotite-epidote rock have also been found. The pebble/matrix ratio is generally greater than 1. The pebbles are strongly flat and elongate, the larger

Fig. 4. Flat pebbles of quartzite in a schistose, more micaceous matrix, Kvarnbäcken.

ones being up to 1.5 m long. The Kvarnbäcken Conglomerate forms a lens-shaped unit approximately 50 m thick. Neither the upper nor the lower contacts are exposed. Nevertheless, they have been marked as tectonic on the map, as the rapid wedging out of the conglomerate is probably a result of significant tectonic movement. This is substantiated by the presence of pronounced mylonites and phyllonites at the same level further north.

The Kvarnbäcken Conglomerate is considered to be stratigraphically equivalent to the Sannaren – Ro Conglomerate which occurs as a thick unit in the area just to the northeast of that indicated on the inset map; similar conglomerates are also found in the Klumplidklumpen area and north of Lejaren.

KVEMOEN MICA SCHIST

The Kvemoen Mica Schist is a plane-schistose, garnet- and biotite-porphyroblastic, semi-pelitic metasediment which occasionally displays clear alternation between quartz-rich and micaceous layers; in some outcrops to the north of Kvarnbergsvattnet it is graphitic. The average mineral composition of certain representative Kvemoen Mica Schists is as follows:

Quartz with some plagioclase	53 vol. %
Muscovite	23 vol. %
Biotite	14 vol. %
Garnet	8 vol. %
Calcite, chlorite, sphene etc.	2 vol. %

South of Kvarnbergsvattnet the schist attains a maximum thickness of approximately 250 m. It can be followed as a rather good marker unit throughout the area and continues into the Klumplidklumpen area to the north. The most suitable type section is situated along the Björkvattnet – Gäddede road but unfortunately there is no geographic name for this section. The mica schist is, however, typically developed further south at Kvemoen and the contact to the overlying Ankarede Volcanites is well exposed nearby in a small quarry in Fossdalälven. Wherever the contact towards the Lillvattnet Formation is exposed, it is tectonic with 10–20 m of phyllonites and mylonites marking the upper discontinuity of the Seve-Köli transition zone.

Along the road southwest of Stor-Jorm, there is an outcrop within the Kvemoen Mica Schist containing lens-shaped pebbles of quartz, light quartzite and greenish quartz-rich rocks in a phyllonitic matrix. Local boulders of conglomerate with pebbles of quartz keratophyre and strongly graphitic fragments have been found nearby. These rocks are probably related to similar polymict conglomerates in the Klumplidklumpen area and in Lejarälven. There they occur as intraformational zones in grey, sometimes graphitic, garnetiferous mica schists at a level close to the Sannaren – Ro – Kvarnbäcken Conglomerate. The conglomerate at Lejarälven is dominated by pebbles of light calcareous quartzite. In certain places there are numerous pebbles of trondhjemitic or keratophyric rocks together with pebbles of dioritic greenstone and fragments of dark metasediments; the matrix is schistose and rich in chlorite, biotite and muscovite. The igneous pebbles are different in appearance compared to the overlying Ankarede Volcanites and a direct derivation from these volcanites is unlikely.

ANKAREDE VOLCANITE FORMATION

The Kvemoen Mica Schist is overlain by an extensive volcanic unit, the Ankarede Volcanite Formation, which can be followed almost continuously northwards into southern Västerbotten. The best type sections are found along the shores of Stor-Blåsjön (Plate 1), where the volcanites are approximately 400 m thick. In the Kvarnbergsvattnet area they attain a maximum thickness of 250 m. The Ankarede Volcanites are mainly composed of alternating schistose or more massive amphibolites and quartz keratophyres together with various tuffitic rocks (i.e. mixed or intimately alternating epiclastic and volcanogenic material). The tuffitic rocks, in particular, are often developed as garbenschiefers. The alternation between basic and acid units is sometimes distinct and rapid (Fig. 5).

As discussed earlier, the schistose amphibolites resemble the Lillvattnet amphibolites as far as the presence of small, randomly oriented needles of hornblende is concerned. The more massive amphibolites are often associated with coarsely hornblende-porphyroblastic rocks of intermediate composition. The following mineral composition is typical for the schistose amphibolites:

Fig. 5. Alternating amphibolite and quartz keratophyre belonging to the Ankarede Volcanite Formation, south of Småvattsbränna.

Hornblende	60 vol. %
Oligoclase	30 vol. %
Calcite, chlorite, epidote-clinozoisite, sphene and ore minerals	10 vol. %

The quartz keratophyres are fine-grained, often layered plagioclase-rich rocks with scattered porphyroblasts of hornblende and garnet as well as occasional phenocrysts of plagioclase and quartz measuring several millimetres across. The average mineral composition of some representative quartz keratophyres is as follows:

Albite to acid plagioclase	62 vol. %
Quartz	33 vol. %
Hornblende, garnet and other accessory minerals	5 vol. %

East of Kveli and also in the type area there occur large, foliated to massive, lensoid bodies of white, homogeneous quartz keratophyres which are interpreted as flows or shallow intrusives closely related to the volcanicity; they are further described and discussed on p. 42.

On both sides of Kvarnbergsvattnet the volcanites are dominantly composed of quartz keratophyres together with garnet-bearing, keratophyric garbenschiefers with large spectacular rods or sheaves of hornblende.

South of Kvarnbergsvattnet there is a gradual transition into the overlying Björnhögen Formation as the upper part of the volcanic formation contains a significant proportion of epiclastic metasediment. This varied sequence of rocks has been marked as a tuffite/garbenschiefer member on the map. It includes, among other units, generally garnet- and hornblende-porphyroblastic, mica-rich, quartzitic, graphitic or very calcareous metasediments together with amphibolitic and feldspar-rich, keratophyric rocks. At Rauberget there is a large ultrabasic body in the upper part of the formation.

BJÖRNHÖGEN FORMATION

All rocks between the Ankarede Volcanites and the Kvemoruet Quartzite have been included in one formation with type section along the road and the shore north of Björnhögen. This formation is approximately 400 m thick south of Kvemoruet. North of Kvarnbergsvattnet it wedges out and does not reappear until the Klumplidklumpen area. The Björnhögen Formation is composed of various rock types. The lower part consists of alternating mica schist and quartz-mica schist, changing upwards to a calcareous garbenschiefer similar to the Lillvattnet garbenschiefer and to the garbenschiefers in the lower part of the Blåsjö Phyllite. The only difference in appearance between the mica schists and the garbenschiefer is that the latter contains hornblende porphyroblasts. The upper part of the formation is dominated by often graphitic phyllite to mica schist and includes units of light quartzite to quartz-mica schist and several layers (1–2 m thick) of marble and schistose, probably metavolcanic amphibolite (A 15, Plate 1).

Along the northern side of Kvarnbergsvattnet the Björnhögen Formation is represented by a sequence of mica schists and garbenschiefers with spectacular sheaves and rods of hornblende. The mica schists are partly altered to light sericite quartzites with finely disseminated pyrite. These rocks pass downwards into the keratophyric garbenschiefers of the Ankarede Volcanites. They are overlain by occasionally graphitic garbenschiefers of the Blåsjö Phyllite, the Kvemoruet Quartzite being apparently absent here.

In both the Björnhögen Formation and the Kvemoruet Quartzite there occur numerous bodies or layers of massive to weakly foliated, coarse-grained amphibolite which are interpreted as shallow intrusive metagabbros (A 4–A 5). They have been named the Fjällskaftet metagabbro zone after the largest body which is approximately 250 m thick (see p. 40).

KVEMORUET QUARTZITE

The Kvemoruet Quartzite is a light, fine-grained quartzite to quartz-mica schist with often greenish foliation planes. It can be followed as a 50–100 m thick unit throughout the southern part of the area. North of Kvarnbergsvattnet it is missing. In the type area and at Björnhögen the quartzite contains intraformational layers of quartzite conglomerate up to several metres thick. The conglomerate consists of elongate (10–20 cm long) to disc-shaped pebbles of light quartzite in a somewhat darker, more micaceous matrix. The pebble/matrix ratio is greater than 1.

HOLAND FORMATION

Schistose amphibolites occur east of Kveli between the Kvemoruet Quartzite and the Blåsjö Phyllite. They can be followed southwards into the Nordli area (Plate 1) where the type section is situated in a small stream close to the Holand farm. Here the formation is approximately 250 m thick and consists of usually calcareous, schistose amphibolites which locally pass over into subordinate keratophyric or tuffitic layers. In the lower part quartz keratophyres occur. A minor unit of quartz keratophyre has also been found east of Kveli. In the type area the Holand Formation passes downwards into a gabbro-intruded, mixed sedimentary and volcanic sequence corresponding to the Kvemoruet Quartzite, the Björnhögen Formation and the Ankarede Volcanite Formation.

BLÅSJÖ PHYLLITE

The Blåsjö Phyllite (Nilsson 1964) is a major unit of calcareous phyllite. The type section is situated in the Blåsjö area, but well exposed reference sections are found along the shores of Kvarnbergsvattnet. The thickness increases from 700 m east of Kveli to about 4000 m between Småvattsbränna and Långviken (cross-section A–B, Plate 1). The Blåsjö Phyllite represents a turbiditic, shale-

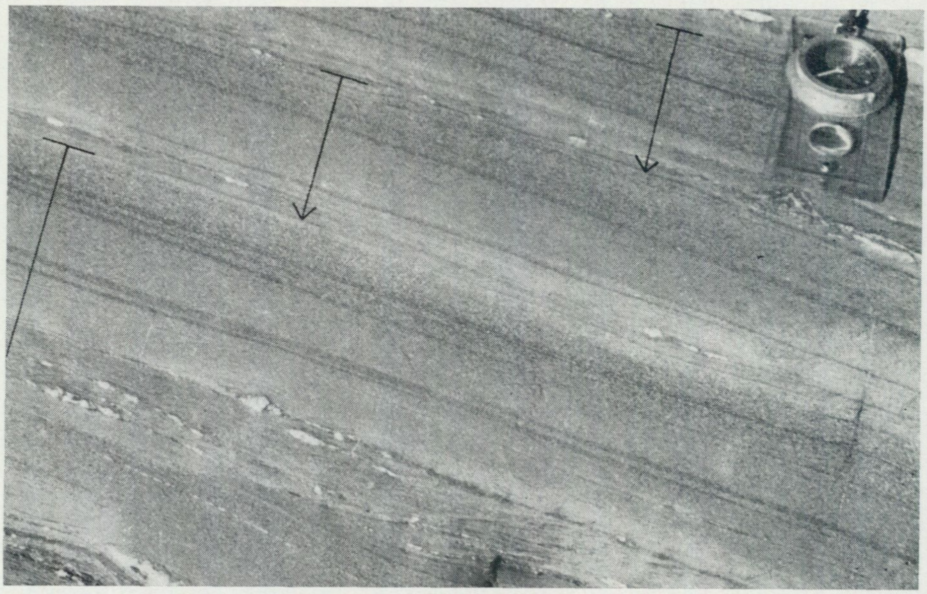


Fig. 6. Graded, quartz-rich to micaceous layers in Blåsjö Phyllite showing local inversion, west of Viken.

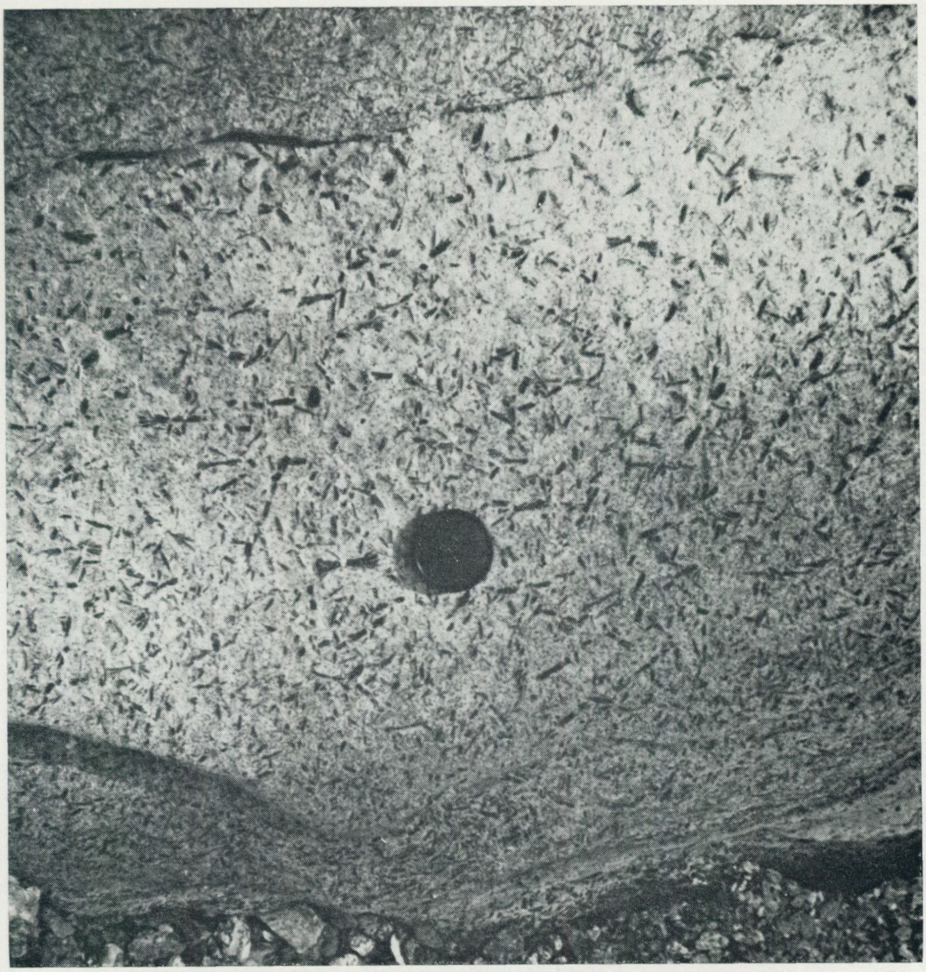


Fig. 7. Blåsjö Phyllite metamorphosed to garbenschiefer, southern shore of Kvarnbergsvattnet.

greywacke sequence composed of grey-greenish, calcareous, often layered pelitic to psammitic metasediments. Essential minerals are quartz, acid plagioclase, calcite, sericite-muscovite, chlorite and biotite (cf. Nilsson 1964). Graded beds, changing from quartz-calcite-rich basal units to more micaceous tops, are found in several outcrops (Fig. 6). However, the layering is generally non-systematic with either sharp contacts or unclear transitions between the micaceous and quartz-rich parts. As the metamorphic grade increases towards the east, the calcareous phyllite (A 33, Plate 1) passes downwards to biotite-porphyroblastic phyllite or schist (A 34, Plate 1) and subsequently to garnet-bearing garbenschiefer (A 35, Plate 1) with clearly developed sheaves and rods of hornblende (Fig. 7). The garnet-hornblende isograd is on a regional scale discordant, and

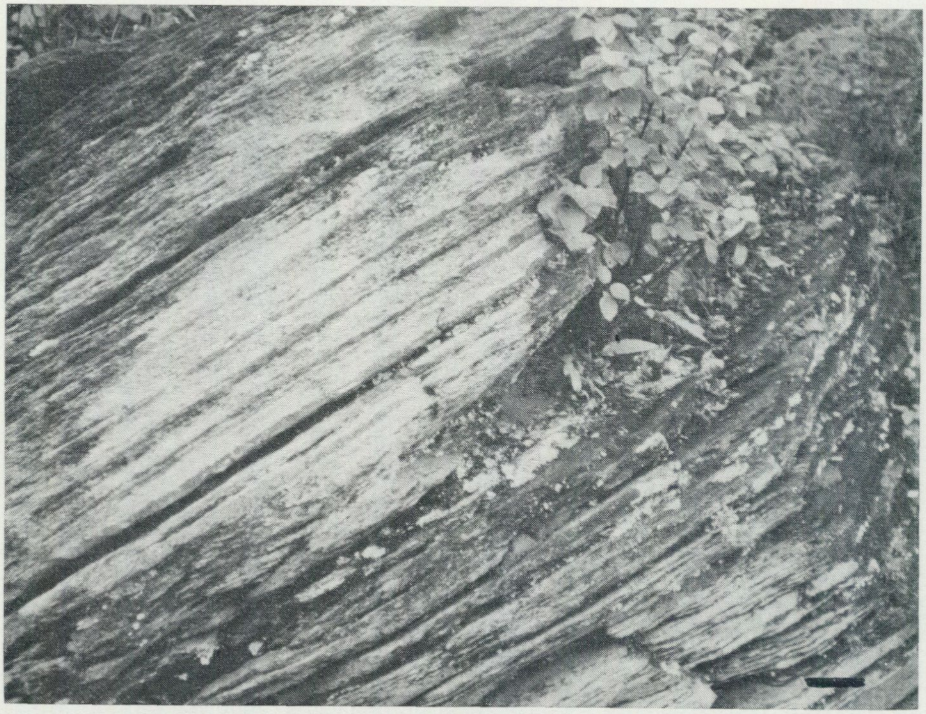


Fig. 8. Bedding marked by alternating quartz-rich and micaceous layers in a garbenschiefer belonging to the Blåsjö Phyllite, west of Björnhögen. Scale on photo = 1 dm.

passes from the base to the top of the Blåsjö Phyllite between Stor-Blåsjön and Kveli. Essential minerals within the garbenschiefers are quartz, calcite, plagioclase, muscovite, biotite, chlorite, hornblende and garnet. The alternation between micaceous and quartz-rich layers is often distinct (Fig. 8).

In the lowermost part of the Blåsjö Phyllite there are several graphitic zones. South of Kvarnbergsvattnet the basal unit of the formation is a less calcareous phyllite to mica schist with some layers of marble and amphibolitic, coarse-grained greenstone of probable intrusive origin.

North of Kvarnbergsvattnet the Blåsjö Phyllite passes transitionally upwards into the Skogsbäcken Volcanite Formation, the Haraön Phyllites being absent here. The boundary between the formations has been drawn where clear volcanogenic sediments, i.e. chlorite- or feldspar-rich tuffites, begin to dominate. Zones of greenish, chlorite-rich tuffites are intercalated further down in the Blåsjö Phyllite north of Långviken, and in one such zone keratophyric layers also occur.

Layers or lensoid bodies of greenstone to massive amphibolite (A 1–A 3, Plate 1) interpreted as metagabbro (Nilsson 1964, Zachrisson 1969) occur in the Blåsjö Phyllite from Svarttjärnen via Långviken to the western part of Kvarnbergsvattnet (the Långviken metagabbro zone, see p. 40).

HARAÖN PHYLLITES

The Haraön Phyllites are mainly composed of alternating graphitic, calcareous and ordinary grey phyllites. This unit is defined in a type section along the southern shore of Kvarnbergsvattnet. The geographic name is from a nearby island which is a well exposed reference area. In the southernmost part of the Kvarnbergsvattnet area the Haraön Phyllites are found as a rather thin unit between the Blåsjö Phyllite and the Skogsbäcken Volcanite Formation. They attain their maximum thickness northeast of Björkvattnet and can be followed from there towards Långviken in an attenuated fold structure. North of Bränna this formation is not present as a distinct and mappable unit. Phyllitic rocks occurring further north at this level are included in the Skogsbäcken Volcanite Formation, as they often are tuffitic or alternate with clear tuffites. It is likely that the rapid thinning out of the Haraön Phyllites at Bränna is partly due to strong shear and attenuation in connection with folding.

Layers and bodies of white, weakly foliated, probably intrusive quartz keratophyres (A 7–A 9, Plate 1) occur in the uppermost part of the Blåsjö Phyllite and in the Haraön Phyllites (see p. 42) and, furthermore, a minor intercalation of dark, porphyritic quartz keratophyre of effusive appearance occurs in the Haraön Phyllites north of Björkvattnet. At the transition to the Skogsbäcken Volcanites there is another zone of metagabbros (the Björkvattnet metagabbro zone).

SKOGSBÄCKEN VOLCANITE FORMATION

The Skogsbäcken Volcanite Formation is about 1500 m thick west of Björkvattnet. From there it thins down to only 300 or 400 m in the northern and southern parts of the area. The large thickness together with the presence of agglomerates and probably extrusive or shallow intrusive greenstones and quartz keratophyres indicate proximity to an old volcanic centre.

The boundary to the Blåsjö and Haraön Phyllites is transitional and composed of different kinds of tuffite, which generally are greenish, chlorite-epidote/clinozoisite-rich rocks of phyllitic appearance; occasionally they grade into greenschists. Units of graphitic phyllite or tuffite are also common in the transition unit. North of Björkvattnet the tuffites contain a sulphide mineralization which has been drilled by SGU. A compilation of the various rock types between the Haraön Phyllites and the volcanites based on drillcore information is shown in Fig. 9.

The major part of the Skogsbäcken Volcanite Formation is composed of regularly alternating greenschists or greenstones and quartz keratophyres which probably formed as water-lain tuffs during a period of recurrent, acid and basic volcanicity. The thickness of the different layers varies from a few millimetres to more than 30 m. The metabasites are typically composed of approximately equal

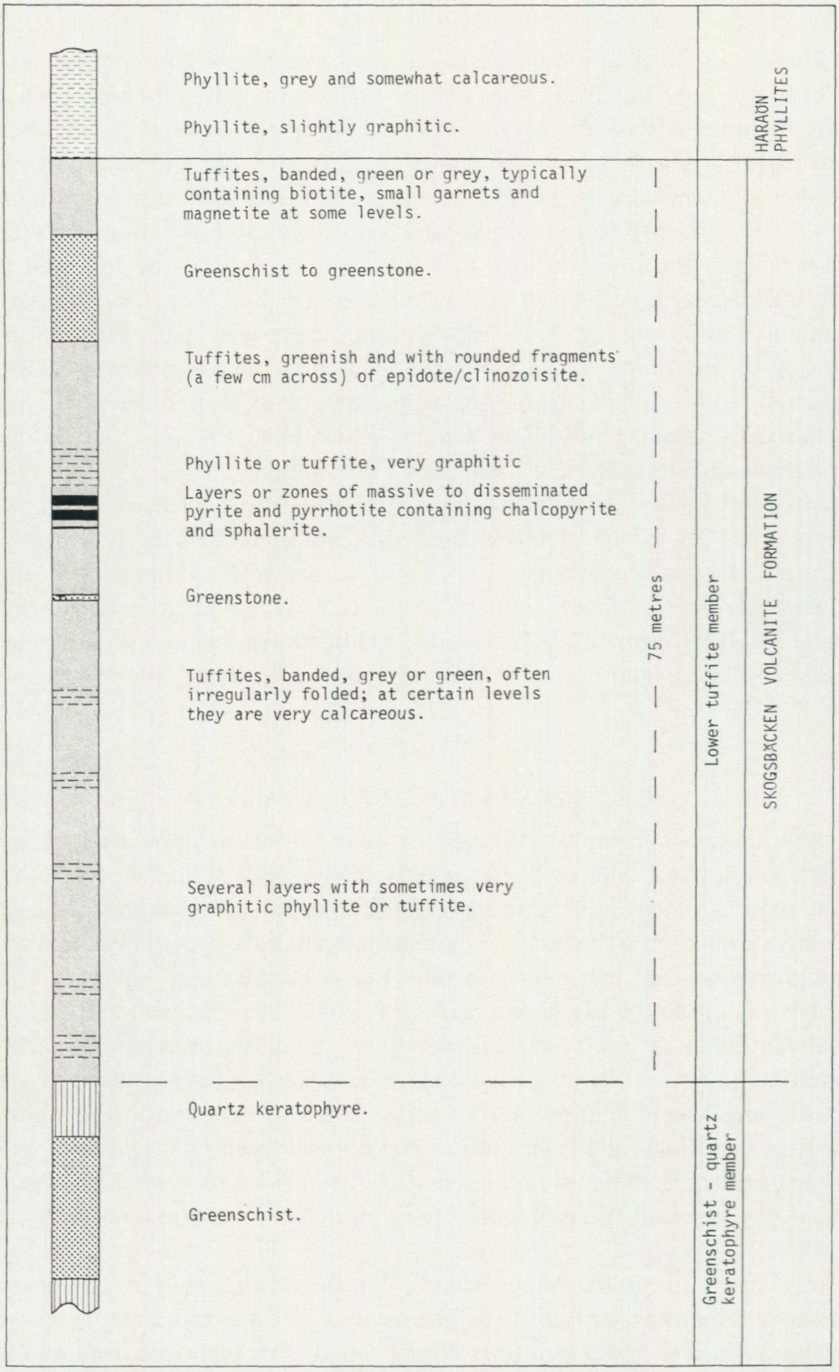


Fig. 9. Schematic compilation of different rock types within the tuffitic transition zone between the Haraön Phyllites and the Skogsbäcken Volcanite Formation north of Björkvattnet (based on drillcore information). Notice that the strata are structurally inverted on the overfolded limb of the major Portfjället fold (D_3).

amounts of albite, actinolite-hornblende and epidote/clinozoisite, chlorite, calcite and sphene (A 14, Plate 1). At several stratigraphic levels agglomeratic greenstones or greenschists occur which contain scattered, rounded or ellipsoidal fragments (up to 10 cm across) composed almost entirely of epidote/clinozoisite with only minor amounts of actinolite-hornblende, calcite and untwinned, fine-grained albite. Some fragments of leucocratic, keratophyric material have also been found. Northwest of Björkvattnet the most well-preserved agglomerates occur (Fig. 10) containing rounded fragments rich in epidote/clinozoisite with rectangular aggregates (1–2 mm across) of actinolite and calcite, which are thought to represent pseudomorphs after pyroxene. There are also spherical aggregates (1–2 mm across) similar in composition to the larger fragments. Such aggregates may well represent pyroclastic material (lapilli) rather than infillings of vesicular structures (Fig. 11).

The quartz keratophyres are generally white or greenish, layered, fine-grained rocks often containing phenocrysts of plagioclase and quartz (Fig. 12). A typical mineral composition is:

Albite	60 vol. %
Quartz	30 vol. %
Chlorite and accessory minerals	10 vol. %

In the upper part of the volcanites, west of Björkvattnet, a large lens-shaped body of weakly foliated to massive, medium-grained quartz keratophyre to keratophyre occur (Fig. 13) which is surrounded by usually agglomeratic greenstones (A 11–13, Plate 1). Epidote/clinozoisite-rich fragments have been found within the quartz keratophyres, indicating a possible extrusive origin for these rocks.

East of Portfjället the major greenschist – quartz keratophyre unit is overlain by basic metatuffs and tuffites, some hundred metres thick. They are marked as greenschists on the map but are, in fact, more often grey due to a dominance of biotite over chlorite. The texture is sometimes porphyritic with phenocrysts (1–3 mm across) of plagioclase and hornblende in a fine-grained matrix of saussurite. With increasing content of quartz, calcite and/or white mica the rocks become more tuffitic. It is, however, difficult to map these gradual variations and tuffites are marked on the map only where the content of epiclastic material is dominant. Essential minerals, which vary in proportion, are plagioclase, calcite, quartz, biotite, chlorite, epidote/clinozoisite and actinolitic hornblende. In this unit there also occur agglomeratic zones, which contain lenses (up to 10 cm long) conspicuously lighter or darker than the matrix. The lenses contain the same minerals as the matrix, only the mineral proportions differ.

As the metamorphic grade increases towards Kveli (Fig. 23), biotite and porphyroblasts of garnet and hornblende appear in the acid units, while the basic rocks are metamorphosed to amphibolite.

As at the base of the formation the boundary towards the overlying metasedi-

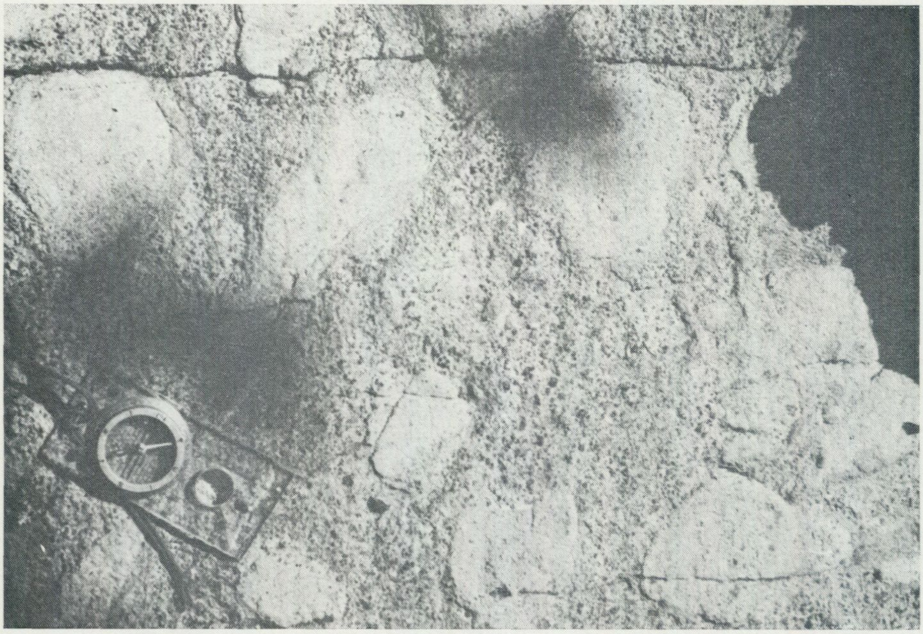


Fig. 10. Agglomeratic greenstone, Skogsbäcken Volcanite Formation, northwest of Björkvattnet.

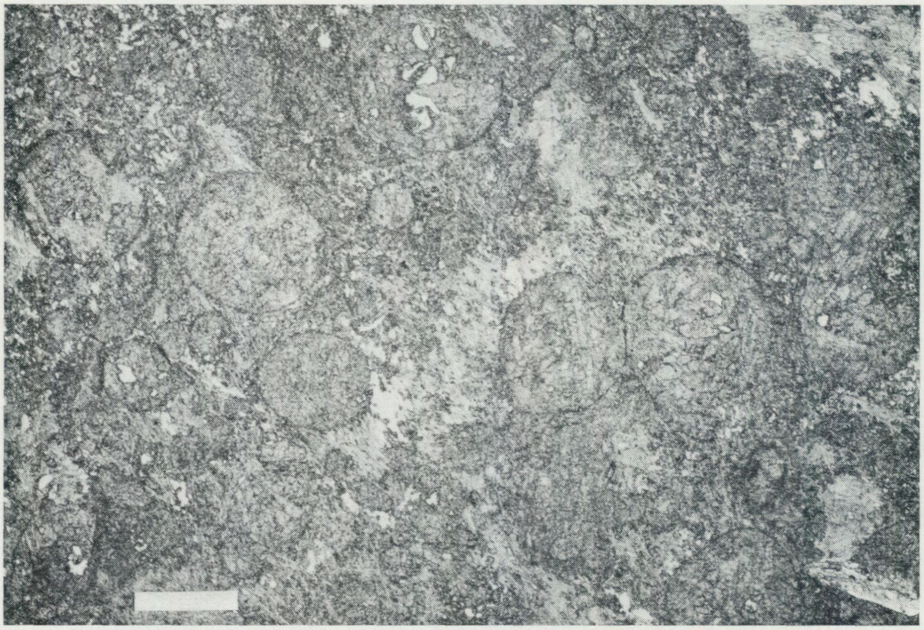


Fig. 11. Saussuritic greenstone with spherical aggregates of epidote/clinozoisite, Skogsbäcken Volcanite Formation, northwest of Björkvattnet (thin section, scale on photo = 1 mm, parallel nicols).

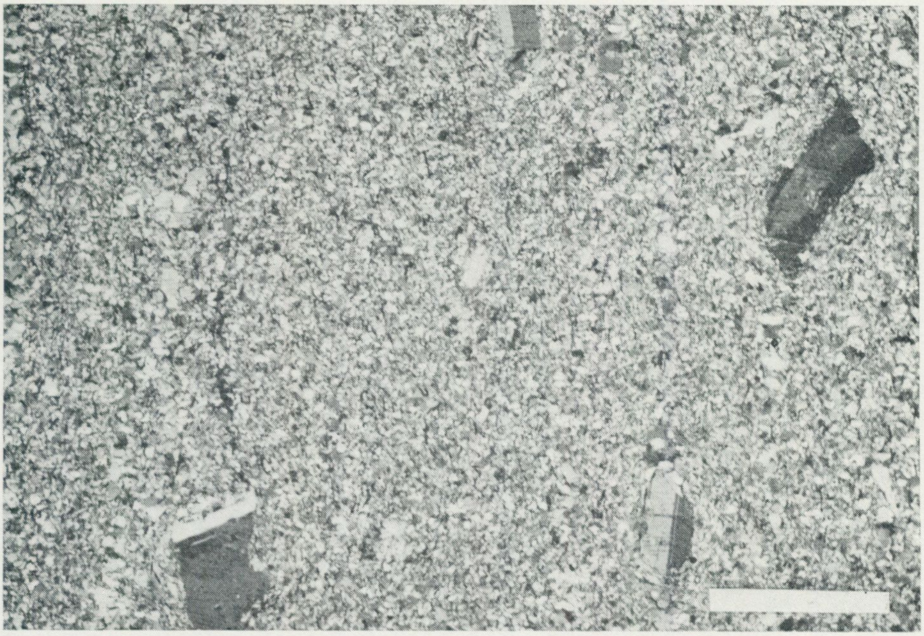


Fig. 12. Porphyritic quartz keratophyre with phenocrysts of albite in a very fine-grained quartz-albite matrix, Skogsbäcken Volcanite Formation, Skogsbäcken (thin section, scale on photo = 1 mm, crossed nicols).

Fig. 13. Medium-grained, massive to foliated quartz keratophyre, Skogsbäcken Volcanite Formation, west of Björkvattnet (thin section, scale on photo = 1 mm, crossed nicols).

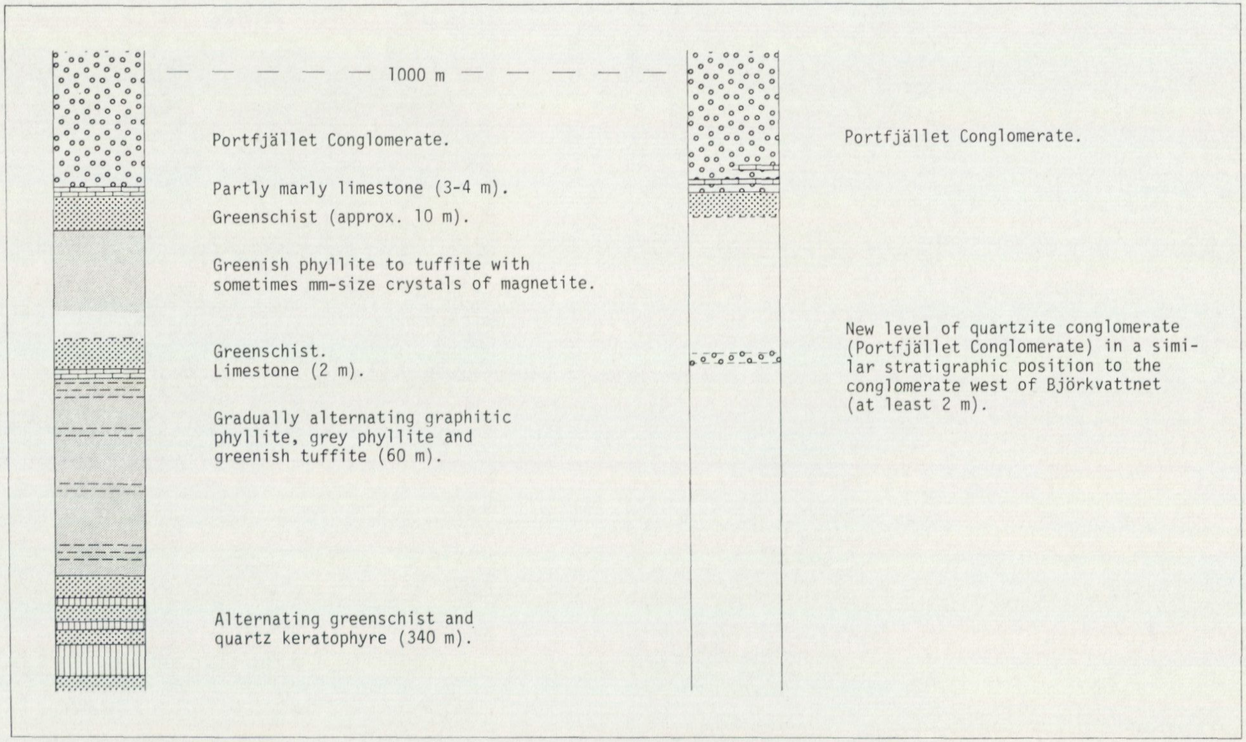


Fig. 14. Schematic illustration of the transition between the upper tuffite member of the Skogsbäcken Volcanite Formation and the Portfjället Conglomerate, western end of Kvarnbergsvattnet.

ments is gradual due to alternation and mixing of sedimentary and volcanic material. West of Björkvattnet the transitional rocks are very heterogeneous in composition and consist of various tuffites together with graphitic phyllite, marble, greenstone and greenschist, and also quartzite conglomerate of Portfjället type. A schematic section from the Skogsbäcken Volcanites to the Portfjället Conglomerate at the western end of Kvarnbergsvattnet is shown in Fig. 14. The occurrence of two levels of quartzite conglomerate is considered to be a primary feature rather than a tectonic repetition.

PORTFJÄLLET CONGLOMERATE

Portfjället, which is the type area for this formation, is completely built up of quartzite conglomerate. A good reference section is found at the western end of Kvarnbergsvattnet. The maximum thickness of the conglomerate is 250–300 m. To the north it wedges out but reappears a few kilometres outside the Kvarnbergsvattnet area. As mentioned above lenses of similar conglomerate occur in the upper part of the Skogsbäcken Volcanites. The Portfjället Conglomerate consists of more than 95 % light, flat and elongate quartzite pebbles in a somewhat darker quartzitic to quartz phyllitic matrix (Fig. 15); scattered pebbles of dark quartzite and marble also occur. At Bränna there are several pebbles of

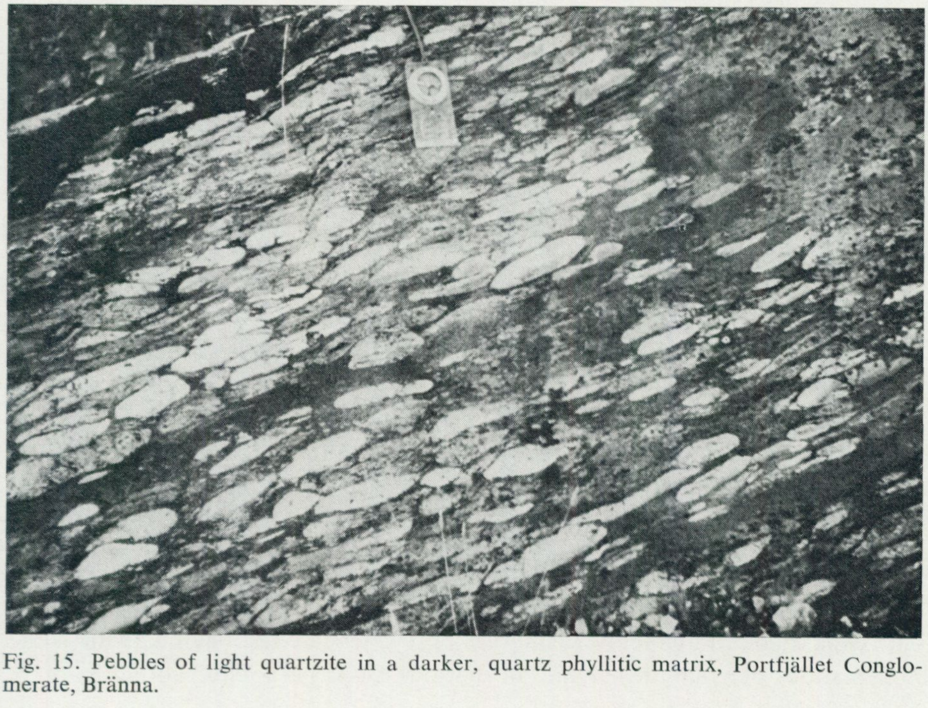


Fig. 15. Pebbles of light quartzite in a darker, quartz phyllitic matrix, Portfjället Conglomerate, Bränna.

light-coloured, layered, feldspathic quartzite with up to 15 % albite and a little microcline. Some of these pebbles contain bluish grains of quartz (1–2 mm across) and similar quartz grains have also been found in the matrix.

BRÄNNÄLVEN FORMATION

All rock units between the Portfjället Conglomerate and the Brakkfjället Phyllite are included in the Brännälven Formation which is almost 1500 m thick. The rocks are almost continuously exposed in Brännälven and all essential members are found there. If the joint sole thrust plane of the Gellvernokko and Leipik Nappes (Zachrisson 1969) continues southwards from the Blåsjö area (Plate 1), it is possible that there is an important tectonic break within the formation. At present, however, there is neither lithological nor tectonic evidence in the Kvarnbergsvattnet area to divide the Brännälven Formation into two tectonic units.

Along Havdalsälven the Portfjället Conglomerate and the directly overlying rocks are well exposed. Immediately above the conglomerate follows 2 m of phyllite with some pebbles of quartzite, and these units are overlain by graphitic phyllite with intercalations of calcareous phyllite and quartzite. At one locality there is a 20 m long and 0.5 m thick lens of fossiliferous marble containing numerous crinoid stems and some indeterminable echinodermata (Karis, pers.comm.); no microfossils have been found.

The lower and upper parts of the formation are dominated by graphitic phyllite, while more prominent units of light quartz phyllite and greenschist to greenstone occur in the central part. The alternation between various phyllites is often rapid and the transitions gradual. Essential minerals are quartz, albite, chlorite and sericite while graphite generally occurs as an accessory mineral. In the Kveli area and in some localities in Havdalsälven and west of Portfjället biotite is present (Fig. 23).

Along Brännälven and in nearby outcrops polymict conglomerates are found in the lower part of the formation. They consist of scattered small (1–3 cm across) pebbles of quartz, light quartzite and occasionally small fragments of dark metasediments in a phyllitic to quartz phyllitic matrix.

Greenschists to greenstones representing basic tuffs or lavas occur at different stratigraphic levels in the Brännälven Formation. They are at most 150 m thick. Transitions to adjacent phyllites are often gradual or tuffitic and in some outcrops intercalations of graphitic phyllite are found. The different units are very extensive and in the Blåsjö area are associated with agglomerate. Essential minerals are actinolite, albite, chlorite, epidote/clinozoisite and sphene.

BRAKKFJÄLLET PHYLLITE

The Brakkfjället Phyllite is a uniform, grey, calcareous phyllite with some intercalations of graphitic phyllite in the lowermost part. The bedding is often marked by alternating quartz-rich and micaceous layers or by layers with varying content of carbonate. Essential minerals are quartz, albite, calcite, sericite and chlorite. The type area is situated west of Stor-Blåsjön (Nilsson 1964). From here the Brakkfjället Phyllite can be followed along the national border southwards to the Kvarnbergsvattnet area where the thickness is roughly estimated to be 750 m. West of the phyllite follows the Rørvik Group which is compositionally similar to the Brännälven Formation. In the northern part of the Blåsjö area the Rørvik Group and the Brännälven Formation meet in a major synformal structure. West of Portfjället the Rørvik Group wedges out and further south, towards the Grong Culmination, the Brakkfjället Phyllite is found in juxtaposition with conglomeratic, greenish calcareous phyllites of the Limingen Group.

DESCRIPTION AND DISCUSSION OF CHEMICALLY ANALYSED ROCKS

INTRODUCTION

In order to classify and compare rocks of different metamorphic grade from the Kvarnbergsvattnet and adjacent areas, several groups of rocks have been chemically analysed (Table 3). The locations of the analysed samples (A 1–A 36) are shown on the maps (Plate 1). No corrections for possible alteration effects have been made. The only constituents in non-spilitic rocks for which realistic adjustments can be made are the volatiles O_2, CO_2 and H_2O (Irvine and Baragar 1971). The ratio Fe_2O_3/FeO can appreciably affect the normative classification but this is of no importance for the conclusions drawn in the present paper. CO_2 occurs only in subordinate amounts (generally <0.1 %)while H_2O is generally lower than 2.0 %. There is, thus, no significant dilution effects on the other elements. In order to illustrate various compositional characteristics the analyses have been plotted together with background analyses in several different diagrams. The CM-AF-R diagram (Fig. 16) of Brotzen (1972) provides a quick survey of the compositions and separates the various groups from each other.

GREENSCHISTS AND AMPHIBOLITES

In the Kvarnbergsvattnet area greenschists and amphibolites, interpreted as basic metavolcanites, are found at the following levels in the rock sequence (from top to bottom; cf. Plate 1):

The Brännälven Formation
The Skogsbäcken Volcanite Formation (A 13–A 14)
The Holand Formation
The Björnhögen Formation (A 15)

Fig. 16. CM-AF-R diagram for metabasites, quartz keratophyres, trondhjemites and metasediments from the Kvarnbergsvattnet area compared to various background analyses.

Symbols:

AF Nominal alkali feldspar (K, Na) Si_3O_8.

CM (Ca, Mg) SiO_3 plus (Ca, Mg) CO_3.

R The rest, mainly excess silica, excess alumina, the Fe, Ti-oxides and water.

1 – 5 Metagabbros (A 1 – A 5).

6 – 12 Quartz keratophyres and keratophyres (A 6 – A 12).

13 – 26 Greenschists and amphibolites (A 13 – A 26).

27 – 36 Various metasediments (A 27 – A 36, cf. Table 3).

Analysis	Sample	Rock type	Formation	Location
A 1	T 69:11	Greenstone (meta-gabbro)	Blåsjö Phyllite	S of Bränna
A 2	T 70:19	Amphibolite (meta-gabbro)	"-	N of Svarttjärnen
A 3	T 69:5	"-	"-	E of Björkvattnet
A 4	T 70:36	"-	Björnhögen Formation	Fjällskaftet
A 5	T 69:84	"-	"-	"-
A 6	T 71:13	Quartz keratophyre	Ankarede Volcanite Formation	SSE of Nordli
A 7	T 71:15	"-	Blåsjö Phyllite	ESE of Nordli
A 8	T 70:4	Keratophyre	Haraön Phyllites	NE of Kveli
A 9	T 71:165	Quartz keratophyre	Blåsjö Phyllites	S of Långviken
A 10	J 71:11	"-	Ankarede Volcanite Formation	Stor-Blåsjön
A 11	T 70:35	"-	Skogsbäcken Volcanite Formation	W of Björkvattnet
A 12	T 70:110	Keratophyre	"-	"-
A 13	T 70:106	Greenstone	"-	"-
A 14	T 70:80	Greenschist	"-	"-
A 15	T 69:77	Schistose amphibolite	Björnhögen Formation	N of Björnhögen
A 16	T 70:61	"-	Ankarede Volcanite Formation	Fossdalsälven
A 17	T 70:69	"-	"-	S of Småvattsbränna
A 18	T 71:176	"-	"-	"-
A 19	T 69:65	"-	Lillvattnet Formation	E of Lillvattnet
A 20	T 71:110	"-	"-	SE of Lillvattnet
A 21	T 71:174	"-	"-	S of Småvattsbränna
A 22	T 71:114	Amphibolite	Blåsjöälven Formation	S of Digerhösen
A 23	T 71:169	"-	"-	S of Småvattsbränna
A 24	T 71:156	"-	"-	"-
A 25	T 72:149	"-	"-	N of Gäddede
A 26	T 72:111	"-	"-	SE of Gäddede
A 27	T 70:57	Quartzo-feldspathic schist	Lillvattnet Formation	E of Lillvattnet
A 28	T 71:113	Migmatitic micaceous gneiss	Blåsjöälven Formation	S of Digerhösen
A 29	T 71:157	Quartzo-feldspathic gneiss	"-	S of Småvattsbränna
A 30	T 72:112	"-	"-	S of Gäddede
A 31	T 72:148	"-	"-	N of Gäddede
A 32	T 70:77	Mica schist	Kvemoen Mica Schist	N of Björnhögen
A 33	T 71:179	Calcareous phyllite	Blåsjö Phyllite	E of Långviken
A 34	T 71:178	Calcareous schist	"-	"-
A 35	T 71:145	Calcareous garbenschiefer	"-	S of Småvattsbränna
A 36	T 69:58	"-	Lillvattnet Formation	N of Lillvattnet

Table 3. Chemically analysed rocks from the Kvarnbergsvattnet and adjacent areas. Locations of samples, see Plate 1.

T Trondhjemites (Goldschmidt 1916, Gale 1974).
o Quartz keratophyres and keratophyres (Beskow 1929, Kulling 1933, Turner and Verhoogen 1960, Nilsson 1964, Svensson 1966, Zachrisson, unpublished SGU-material).
X Albite granites and trondhjemites (Beskow 1929, Kulling 1933, Svensson 1965).
S Quartz keratophyres from Stekenjokk (Juve 1974).
● Arkoses, sub-arkoses and sparagmites (Pettijohn et al. 1972, Bjørlykke 1966).
⊗ Quartzo-feldspathic schists or gneisses from the Seve and the Särv Nappe (Strömberg, unpublished SGU-material).
• Greenschists and often pillowed greenstones from the Köli including the Grong and Trondheim regions (Nilsson 1964, Juve 1974, Gale 1974, Zachrisson, unpublished SGU-material, et al.).
+ Seve amphibolites from southern Jämtland (Strömberg, unpublished SGU-material).
▲ Spilites (Turner and Verhoogen 1960).
B Metagabbros from the Blåsjö area (Nilsson 1964).
St Metagabbros from the Stekenjokk area (Juve 1974).
The shaded areas cover the plots of quartz keratophyres and Seve amphibolites.

The Ankarede Volcanite Formation (A 16–A 18)
The Lillvattnet Formation (A 19–A 21)
The Blåsjöälven Formation (A 22–A 26)

The amphibolites of the Blåsjöälven and Lillvattnet Formations often alternate with quartzitic to quartzo-feldspathic schists or gneisses, which very likely represent arkosic to sub-arkosic metasandstones. Acid volcanites have not been found in these units nor in the Seve as a whole. As already discussed, the Lillvattnet amphibolites are structurally very similar to those in the Köli and contrast with the less fissile and more granular Seve amphibolites. In the Ankarede and Skogsbäcken Volcanite Formations the basic rocks are interbedded with quartz keratophyres and volcanic rocks of more intermediate composition, while in the Björnhögen and Brännälven Formations they occur together with various, often graphitic, phyllites. In the Nordli area (Plate 1) quartz keratophyres are also found at different levels in a mixed volcanic-sedimentary sequence equivalent to the Björnhögen Formation and the lowermost part of the Holand Formation; the latter is, however, clearly dominated by amphibolitic metabasite. It cannot be excluded that some of the upper units of the Långviken metagabbro zone, between Kveli and Viken, are effusive greenschists rather than schistose metagabbros. Indeed, volcanic greenschists and greenstones occur in the eastern Trondheim region (the Vektarhaug Formation, Wolff 1973) and in the Stekenjokk–Remdalen area (the Lasterfjäll Greenschist, Zachrisson, 1964, 1969) at a tectonic level probably corresponding to the transition between the Blåsjö and Haraön Phyllites.

The chemical, normative and modal compositions of the analysed metabasites are shown in Table 4. All, except A 18 (Plate 1), have a basaltic composition with 44.0–53.5 % SiO_2. A 18, containing 55.7 % SiO_2, may be classified as a basaltic andesite even though the Q-value is somewhat too low. In the CM-AF-R diagram (Fig. 16) they show a marked linear spread due to varying AF/CM ratio, which, amongst other things, reflects the spilitic character of the Köli rocks.

The amphibolites from the Blåsjöälven and Lillvattnet Formations plot together with the Seve background values entirely within the subalkaline field of the total alkali-silica diagram (Fig. 17). The Köli metabasites from the Kvarnbergsvattnet area are consistently more alkaline, and A 16 and A 17 (Plate 1) plot within the alkaline field. The Köli background values show a great spread over both fields. In the alkali and alkali-lime diagrams (Figs. 18 and 19), which both are used to define spilites, the Seve and the Lillvattnet amphibolites plot outside the spilite field, in contrast to the Köli metabasites from the Kvarnbergsvattnet area which are clearly spilitic. The Köli background values again show a great spread.

Based on the data discussed above, it is concluded that the Seve and Lillvattnet amphibolites represent non-spilitic, subalkaline basalts frequently poor in

Chemical composition (wt %)	A 13	A 14	A 15	A 16	A 17	A 18	A 19	A 20	A 21	A 22	A 23	A 24	A 25	A 26
SiO_2	51.6	48.9	50.6	46.2	45.6	55.7	47.1	48.5	47.2	48.2	48.9	48.7	50.1	50.1
TiO_2	0.72	0,69	2.2	1.1	1.4	1.7	0.91	1.1	1.7	1.1	1.6	1.1	1.8	1.6
Al_2O_3	16.0	14.8	17.0	17.4	16.2	13.8	15.9	14.5	14.4	14.9	14.1	17.4	15.1	15.1
Fe_2O_3	3.9	2.4	1.1	2.0	2.4	2.3	2.7	2.9	3.0	2.8	2.3	1.4	1.0	1.5
FeO	6.1	6.7	8.6	6.7	8.5	9.2	6.4	7.8	9.8	6.0	9.6	8.5	10.8	9.7
MnO	0.16	0.15	0.15	0.16	0.18	0.19	0.17	0.21	0.27	0.17	0.21	0.21	0.23	0.23
CaO	6.6	7.4	8.2	10.3	9.3	4.9	13.6	11.3	11.7	12.3	10.6	10.3	9.7	9.9
MgO	6.5	10.1	5.7	8.2	6.7	4.9	8.8	9.0	7.3	9.5	7.4	7.1	6.5	6.7
Na_2O	4.4	3.8	4.2	4.0	4.5	5.9	1.3	1.4	2.7	1.9	2.8	2.9	2.1	3.2
K_2O	0.2	0.2	0.4	0.3	0.2	0.2	0.2	0.3	0.4	0.3	0.3	0.3	0.5	0.3
H_2O^+	3.1	3.6	1.4	1.8	1.6	1.2	1.9	1.9	2.0	1.9	1.7	1.7	1.6	1.4
H_2O^-	0.3	0.3	0.2	0.3	0.3	0.1	0.2	0.1	0.1	0.1	0.2	0.1	0.1	0.1
P_2O_5	0.05	0.08	0.32	0.08	0.15	0.14	0.07	0.13	0.14	0.13	0.11	0.09	0.22	0.19
CO_2	0.07	<0.01	0.30	2.05	3.26	0.03	0.05	0.06	0.01	0.03	0.02	0.11	0.04	0.04
F	0.02	0.02	0.06	0.03	0.05	0.07	0.04	0.04	0.04	0.02	0.02	0.03	0.05	0.07
S	<0.02	<0.02	0.29	0.02	0.03	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.21	<0.02
BaO	0.01	0.01	0.01	0.03	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.05	0.01	0.01
Sum	99.73	99.15	100.73	100.67	100.39	100.35	99.35	99.26	100.78	99.37	99.88	100.00	100.10	100.10
CIPW norm														
Q	0.4	-	-	Ne1.9	-	0.4	-	2.2	-	-	-	-	2.5	-
Or	1.2	1.2	2.4	1.8	1.2	1.2	1.2	1.8	2.3	1.8	1.8	1.8	3.0	1.8
Ab	37.4	32.5	35.4	30.3	38.0	49.8	11.1	11.9	22.7	16.2	23.8	24.6	17.8	27.1
An	23.4	23.0	26.2	28.5	23.4	10.6	37.2	32.7	25.8	31.5	25.1	33.6	30.3	25.9
Di	6.9	10.8	8.3	7.1	0.7	10.1	23.9	18.1	25.1	23.1	21.9	13.3	13.2	17.5
Hy	20.0	8.0	12.0	-	2.3	19.6	17.3	24.4	1.0	16.0	12.8	10.0	25.7	14.9
Ol	-	15.7	6.5	18.8	18.7	-	1.2	-	13.0	2.9	6.2	10.4	-	5.5
Mt	5.7	3.5	1.6	2.9	3.5	3.3	3.9	4.2	4.3	4.1	3.3	2.0	1.5	2.2
Il	1.4	1.3	4.2	2.1	2.7	3.2	1.7	2.1	3.2	2.1	3.0	2.1	3.4	3.0
Ap	0.1	0.2	0.7	0.2	0.4	0.3	0.2	0.3	0.3	0.3	0.3	0.2	0.5	-
Pr	-	-	0,5	-	0.1	-	-	-	-	-	-	-	0.4	-
Cc	0.2	-	0.7	4.6	7.4	0.1	0.1	0.1	-	0.1	-	0.3	0.1	0.1
SAL/FEM	62/34	57/40	64/35	62/36	63/36	62/37	50/49	49/49	51/47	49/49	51/48	60/38	54/45	55/44
Modal composition (vol %)														
Quartz	39		47			45	15	12		16		17	5	1
Plag.	| (Ab)	31(Ab)	| (01)	28(01)	33(01)	| (01)	| (01)	| (01)	21(01)	| (01)	21(01)	9(01)	17(01)	30(01)
Amph.	21	39	45	66	56	51	65	72	66	69	70	70	75	69
Chl.	17	17			3			1						
Ep/Cl.	21	11		2			19	14	12	15	6	2		
Sphene	2	1		1			1		1		2	1		
Ore					2	3								
Garnet												1	3	
Acc.		1	4			1		1			1			
Calcite			4	3	6									

Table 4. Chemical, normative and modal compositions of metabasites (greenstone, greenschist and amphibolites) from the Kvarnbergsvattnet and adjacent areas. Locations of samples, see Plate 1.

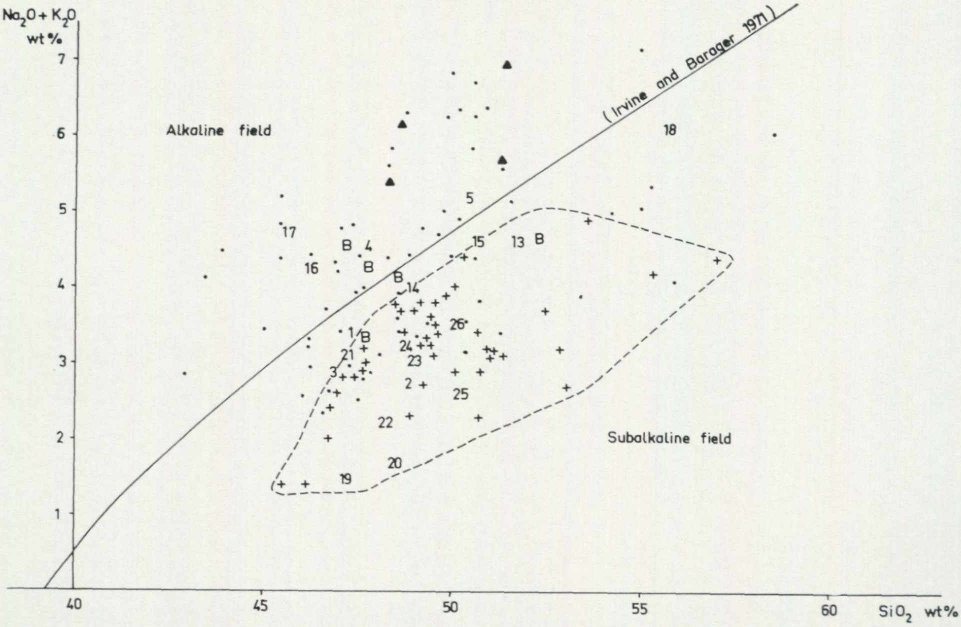


Fig. 17. Total alkali-silica diagram (wt %) for Seve and Köli metabasites from the Kvarn-bergsvattnet area compared to various background analyses. The continuous curve is the dividing line between the alkaline and subalkaline fields after Irvine and Barager (1971). The Seve amphibolites plot within the field enclosed by the dashed line. Symbols:

1 – 5 Metagabbros (A 1 – A 5).
13 – 18 Köli metabasites (A 13 – A 18).
19 – 21 Amphibolites from the Lillvattnet Formation (Seve-Köli transition unit) (A 19 – A 21).
22 – 26 Seve amphibolites (A 22 – A 26).

For explanation of the other symbols see Fig. 16.

potassium which formed during a period of uniform basic volcanicity as thick and extensive sheets interbedded with arkosic sediments. One possible explanation for their non-spilitic character is that they originated in a non-marine environment.

It is also probable that the intercalated arkosic sediments are related in time to the arkoses and feldspathic quartzites of the Särv Nappe and the Risbäck Group, which are all thought to be largely continental (Gee 1975). In a model for the tectonic evolution of this part of the Caledonides (see p. 102), it is suggested that the Seve amphibolites formed as flood basalts, during a period of continental disruption of the Baltoscandian – Greenlandian shield during the Late Precambrian. This event may well be related to the growth of a spreading ridge system beneath the continent.

The analysed Köli metabasites from the Kvarnbergsvattnet area are classified as spilitic, subalkaline metabasalts generally poor in potassium. The Köli suc-

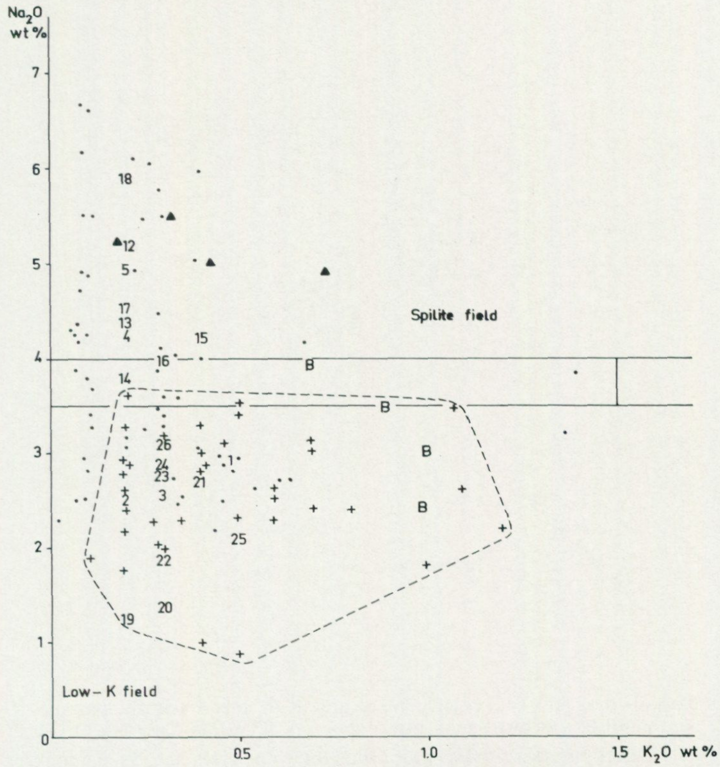


Fig. 18. Alkali diagram (wt %) for Seve and Köli metabasites from the Kvarnbergsvattnet area compared to various background analyses. A dividing zone between 3.5 and 4 percent Na_2O is used to delimit a spilite field (Fiala 1974). The dashed line encircles the Seve amphibolites. The symbols are the same as in Figs. 16 and 17.

cession was deposited in a marine environment which probably is one reason for the spilitic and keratophyric character of the volcanic rocks (Vallance 1960, 1969, Levi 1969, Carmichael et al. 1974). The major part of acid volcanites in modern tectonic environments are found within active continental margins and it is, therefore, thought most likely that the mixed acid and basic Köli volcanite formations originated in a similar tectonic environment, which developed within the Ordovician during the closing of the proto-Atlantic ocean.

Most of the Köli background analyses are from units in the Grong, Løkken and Støren areas of central Norway which are composed predominantly of often pillowed greenstones (Gale 1974). On the basis of trace element evidence Gale and Roberts (1974) demonstrated the presence of ocean floor tholeiites in all these areas, while potassium-poor tholeiites with island arc affinities were thought to occur in the Grong region and in the upper part of the Løkken greenstone sequence.

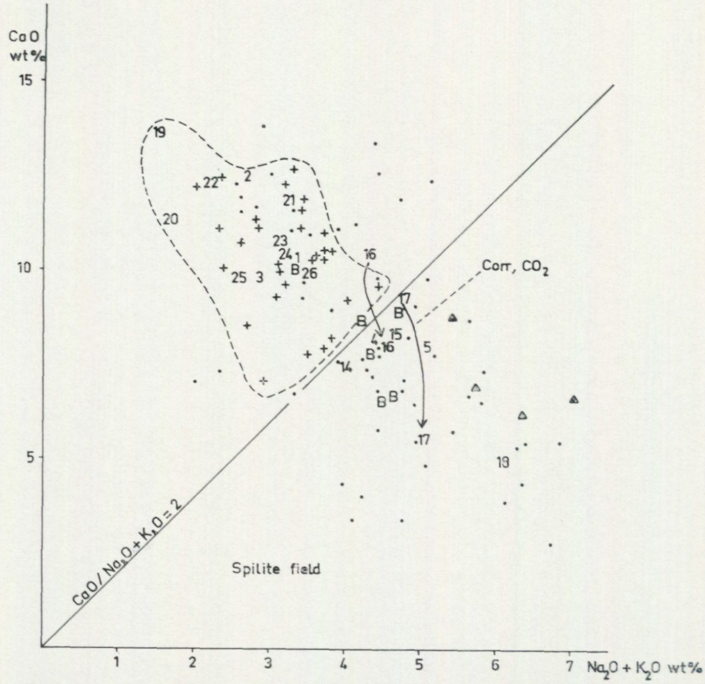


Fig. 19. Lime-alkali diagram (wt %) for Seve and Köli metabasites from the Kvarnbergsvattnet area compared to various background analyses. The line $CaO/Na_2O+K_2O = 2$ delimits the spilite field (Papezik 1968). The dashed line encircles the Seve amphibolites. The symbols are the same as in Figs. 16 and 17.

METAGABBROS

Layers and lensoid bodies of medium- to coarse-grained greenstones and massive amphibolites, interpreted as metagabbros, occur at three different levels in the Kvarnbergsvattnet area:

1. The Björkvattnet metagabbro zone at the transition between the Haraön Phyllites and the Skogsbäcken Volcanites.
2. The Långviken metagabbro zone in the Blåsjö Phyllite (A 1–A 3, Plate 1).
3. The Fjällskaftet metagabbro zone in the Björnhögen Formation, the Kvemoruet Quartzite and the lowermost part of the Blåsjö Phyllite (A4–A5).

In addition one body of metagabbro has been found in the volcanites south of Björkvattnet.

The Långviken zone passes northwards from the lowermost to the upper part of the Blåsjö Phyllite, while the others are stratabound. The contacts to the host rocks are sometimes diffuse with transitions from coarse-grained, massive greenstone, via greenschist to fine-grained phyllites rich in chlorite and epidote/clinozoisite. In the eastern parts of the area, where the metamorphic grade is higher,

Chemical composition (wt%)	A 1	A 2	A 3	A 4	A 5	(A 22)	(A 23)	(A 24)	(A 25)	(A 26)
SiO_2	47.3	48.9	46.9	47.7	50.4	47.72	47.66	48.4	47.08	52.1
TiO_2	2.2	1.6	2.5	4.0	2.0	2.30	1.56	2.04	2.16	1.89
Al_2O_3	14.4	14.7	13.5	14.2	19.4	16.95	15.60	15.5	17.05	15.5
Fe_2O_3	3.6	2.5	2.7	2.1	1.6	3.35	2.69	2.91	2.26	2.44
FeO	7.5	7.2	10.5	12.3	6.8	7.28	7.50	7.21	8.37	6.17
MnO	0.18	0.19	0.24	0.25	0.16	0.18	0.17	0.18	0.19	0.16
CaO	10.3	12.5	9.7	8.1	8.0	7.85	10.10	8.60	6.66	8.90
MgO	7.9	7.7	7.7	5.8	5.5	5.56	7.85	7.12	7.44	5.50
Na_2O	2.9	2.5	2.6	4.3	5.0	3.45	2.40	2.96	2.96	3.96
K_2O	0.5	0.2	0.3	0.2	0.2	0.89	1.01	1.11	1.53	0.70
H_2O^+	3.2	1.8	2.5	1.4	1.4	3.55	3.43	3.24	3.88	2.26
H_2O^-	0.3	0.2	0.3	0.2	0.2	0.06	0.06	0.22	0.08	0.10
P_2O_5	0.27	0.18	0.26	0.29	0.17	0.31	0.14	0.25	0.27	0.25
CO_2	0.01	0.05	0.41	0.02	0.02	0.39	-	0.07	-	0.08
F	0.03	0.02	0.05	0.03	0.02	0.08	0.11	0.02	0.14	0.02
S	0.03	<0.02	<0.02	<0.02	0.02	0.03	<0.01	<0.01	0.02	<0.01
BaO	0.03	0.01	0.01	0.01	0.01	<0.01	<0.01	0.01	<0.01	0.01
Sum	100.65	100.25	100.17	100.90	100.90	99.95	100.28	99.80	100.00	100.04
CIPW norm										
Q	-	-	-	Ne0.2	Ne1.3	-	-	-	-	1.3
Or	2.9	1.2	1.8	1.2	1.2	5.3	6.0	6.6	9.0	4.1
Ab	24.5	21.1	22.0	35.8	39.6	29.2	20.3	25.1	25.0	33.5
An	24.7	28.3	24.3	18.7	29.7	28.3	28.7	25.8	28.9	22.5
Di	19.6	26.0	15.9	15.9	6.9	4.7	15.9	12.0	1.2	15.8
Hy	8.2	11.5	18.9	-	-	15.9	11.2	14.2	11.6	12.5
Ol	6.8	2.9	4.3	15.5	13.3	2.0	7.2	4.1	12.1	-
Mt	5.2	3.6	3.9	3.0	2.3	4.9	3.9	4.2	3.3	3.5
Il	4.2	3.0	4.8	7.5	3.8	4.3	3.0	3.9	4.1	3.6
Ap	0.6	0.4	0.6	0.7	0.4	0.7	0.3	0.6	0.6	0.6
Pr	0.1	-	-	-	-	-	-	-	-	-
Cc	-	0.1	0.9	-	-	0.9	-	0.2	-	0.2
SAL/FEM	52/45	51/48	48/49	56/43	72/27	63/34	55/42	58/39	63/33	61/36
Modal composition(vol%)										
Quartz						1				1
Plag.	34(Ab)	18(Ol)	22(Ab)	30(Ol)	53(Ol)	33(Ol)		27(An+Ab)		45(An+Ab)
Amph.	37	62	68	58	42	26		27		32
Musc.	5				1			10		2
Biotite				1						
Chl.	1		2		1	12		12		4
Ep/cl.	16	17	2		2	21		19		13
Sphene	7		5			6		5		3
Acc.		3	1	4	1	1				
(Ore)				6						
(Garnet)				1						

Table 5. Chemical, normative and modal compositions of metagabbros (greenstones and amphibolites) from the Kvarnbergsvattnet and Blåsjö areas. (A 24) and (A 25) belong to the Björkvattnet zone, A 1, A 2, A 3, (A 22), (A 23) and (A 26) to the Långviken zone and A 4 and A 5 to the Fjällskaftet metagabbro zone. Locations of samples, see Plate 1.

the contact rocks are generally rich in coarse hornblende porphyroblasts. In the upper part of the Långviken zone, between Kveli and Viken, there occur amphibolitic greenschists which may be of volcanic origin. There are also foliated and strongly saussuritic, possibly volcanic greenstones belonging to the Björkvattnet zone in the Blåsjö area (Nilsson 1964).

The compositions of the analysed metagabbros are shown in Table 5, which also includes for comparison purposes metagabbro analyses from the Blåsjö area (Nilsson 1964). With increasing metamorphic grade the often strongly saussuritic, gabbroic greenstones (Fig. 20a) change gradually into medium- to coarse-grained, massive to weakly foliated amphibolites (Fig. 20b), containing up to 70 % hornblende. In the various diagrams (Figs. 16–19) the metagabbros plot with a considerable spread similar to the Köli metavolcanites. A 4 and A 5 (Plate 1) plot clearly in the spilite field (Figs. 18 and 19) and the alkaline character is probably due to spilitization. The metagabbros from the Blåsjö area contain more potassium (0.7–1.5 wt % K_2O) compared to those in the Kvarnbergsvattnet area and to the volcanic Köli metabasites. The analyses from the Stekenjokk area (Juve 1974), which are sampled in the vicinity of the sulphide ore body, plot somewhat away from the other basic rocks in the CM-AF-R diagram due to lower CM values; this is compensated for by a higher content of total iron.

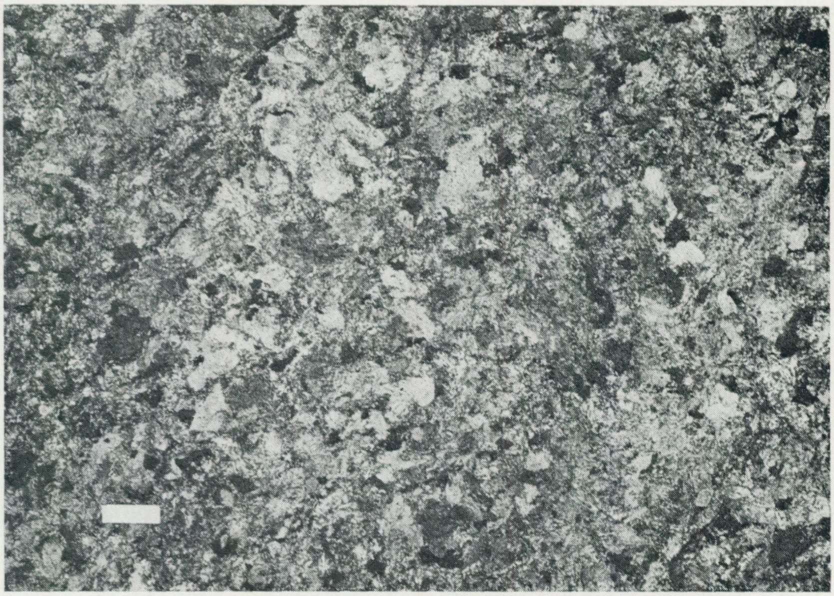
The gabbros were probably intruded as extensive, up to 200 m thick, shallow sills during the deposition of the Köli sequence, as they seem to have passed through the same deformational and metamorphic development as the volcanic greenstones. No dykes related to these intrusions have been found.

QUARTZ KERATOPHYRES AND QUARTZO-FELDSPATHIC ROCKS

White, massive, fine- to medium-grained acid igneous rocks are found at three different levels in the Kvarnbergsvattnet and adjacent areas (Plate 1):

1. In the Skogsbäcken Volcanite Formation west of Björkvattnet (A 11 and 12); an approximately 200 m thick lens-shaped body which is associated with agglomeratic greenstone (A 13), layered quartz keratophyre and greenschist (A 14).
2. In the Blåsjö–Haraön Phyllites between Nordli and Långviken (A 7–9); layers and bodies conformable to the main foliation, the thickness varies from a few centimetres to several hundred metres. The largest body is found east of Nordli (see the geological map-sheet Nordli, Foslie 1959).
3. In the Ankarede Volcanite Formation southeast of Nordli (A 6), east of Kveli and at Stor-Blåsjön (A 10); lens-shaped bodies, up to 300 m thick, occur in a sequence with layered quartz keratophyre and amphibolite.

Fine- to medium-grained quartzo-feldspathic rocks with granoblastic elongate texture occur interbedded with amphibolite in the Blåsjöälven Formation (Seve)



a

b

Fig. 20. Textural changes due to increased metamorphic grade in metagabbros from the Kvarnbergsvattnet area. a = strongly saussuritic greenstone (A 1, Plate 1) from the chlorite zone; b = medium- to coarse-grained, massive amphibolite (A 4) with larger or thinner prismatic crystals of hornblende together with coarse plagioclase, from the garnet-hornblende zone, (thin sections, scales on photos = 1 mm, crossed nicols).

and the Lillvattnet Formation (Seve-Köli transition unit). Most of them are undoubtedly metasedimentary, but sometimes they resemble acid metavolcanites. In order to demonstrate whether such rocks are also present in these formations, four of the most volcanic-looking units were sampled for chemical analysis (A 27, A 29, A 30 and A 31).

The chemical, normative and modal compositions of the above mentioned analysed rocks are shown in Table 6. The analyses have been plotted together with various background analyses in the CM-AF-R diagram (Fig. 16) and in two different diagrams involving the alkali elements (Figs. 21 and 22). Based on composition and geological occurrence, the white, massive, acid igneous rocks are classified as quartz keratophyres (A 6, A 7, A 10, and A 11) and keratophyres (A 8 and A 12), while the quartzo-feldspathic rocks of the Blåsjöälven Formation and the Lillvattnet Formation are classified as metaarkoses. The massive quartz keratophyres and keratophyres are all pre-metamorphic and probably formed during the volcanism as shallow intrusives or even extrusives. They contrast to the layered, often porphyritic quartz keratophyres which are interpreted as water-lain tuffs (Zachrisson 1964). The quartz keratophyres and keratophyres plot outside the fields for unaltered igneous rocks in Figs. 16 and 22 and it is possible that they originated as normal acid to intermediate volcanic rocks, which were subsequently altered in connection with the spilitization of the more basic members (Hughes 1972).

The terms quartz keratophyre or keratophyre are accordingly used in the present paper to designate both fine-grained, layered and medium-grained massive, Na-rich rocks of volcanic or subvolcanic origin, composed mainly of albite ($>$ 35 vol. %) and quartz.

None of the analyses plot within the background trondhjemite fields. Trondhjemites are acid plutonic rocks with a granitic appearance, composed of plagioclase (oligoclase to andesine), quartz and frequently muscovite, while K-feldspar occurs in minor amounts or is missing (Goldschmidt 1916). This difference in mineral composition in comparison with quartz keratophyres is chemically reflected by a higher content of CaO and K_2O.

In southern Västerbotten there occur, in association with mixed volcanites, acid igneous rocks (marked with X in the diagrams), which have been described as albite-granites and trondhjemites (Beskow 1929, Kulling 1933, Svensson 1966). However, as they are geologically and compositionally more related to quartz keratophyres, it is probably more appropriate to classify them as such.

The background Stekenjokk quartz keratophyres plot partly outside the quartz keratophyre field as defined above. The divergent chemistry of these quartz keratophyres may well be explained by alteration during the emplacement of the Stekenjokk ore body, since with increasing sulphur content there is an increase in K_2O and a decrease in Na_2O and total alkalies (cf. Juve 1974).

A 27 with 18 % and A 29 with 30 % modal feldspar plot outside the quartz

Chemical composition (wt %)	A 6	A 7	A 8	A 9	A 10	A 11	A 12	A 27	A 29	A 30	A 31
SiO_2	78.1	73.9	65.6	72.3	75.8	72.9	60.6	84.3	78.3	75.0	76.3
TiO_2	0.27	0.16	0.30	0.30	0.27	0.37	0.80	0.51	0.24	0.53	0.49
Al_2O_3	10.9	14.7	17.3	14.6	12.3	11.8	13.7	7.5	8.8	11.5	11.2
Fe_2O_3	0.1	0.1	0.4	<0.1	1.3	1.9	3.6	0.6	0.1	0.3	<0.1
FeO	2.0	1.0	1.3	2.2	1.7	2.1	4.4	1.2	1.4	2.6	2.6
MnO	0.04	0.03	0.04	0.03	0.06	0.06	0.11	0.04	0.05	0.05	0.04
CaO	1.0	2.4	5.4	2.4	1.0	2.9	4.2	0.9	3.1	1.8	1.8
MgO	0.48	0.45	1.5	0.65	0.32	0.62	2.5	0.61	1.1	1.1	1.1
Na_2O	5.1	5.0	4.3	4.9	5.5	4.1	5.2	2.3	2.7	3.5	3.4
K_2O	0.2	0.7	0.5	0.7	0.2	0.4	0.2	0.9	1.2	1.7	1.2
H_2O^+	0.7	0.7	3.3	1.1	0.5	1.3	1.9	0.7	0.8	0.6	0.5
H_2O^-	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1
P_2O_5	0.02	0.05	0.07	0.07	0.03	0.06	0.14	0.02	0.19	0.12	0.03
CO_2	0.18	0.01	0.26	<0.01	0.50	0.32	1.73	0.15	1.08	0.31	0.02
F	<0.01	0.02	0.01	0.03	<0.01	0.01	0.03	0.01	0.02	0.03	0.01
S	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.12	<0.02	<0.02	0.04	0.13
BaO	0.02	0.03	0.03	0.04	0.02	0.02	0.02	0.08	0.03	0.07	0.07
Sum	99.21	99.45	100.51	99.52	99.70	99.06	99.45	100.02	99.30	99.50	99.00
CIWP norm											
Q	44.3	36.1	24.8	33.9	41.3	41.1	20.5	64.8	52.7	42.9	45.3
Or	1.2	4.2	2.9	4.2	1.2	2.4	1.2	5.3	7.1	10.1	7.1
Ab	43.5	42.6	36.3	41.7	46.8	35.1	44.3	19.5	23.0	29.8	29.1
An	3.8	11.5	24.6	11.3	1.6	12.1	8.9	3.5	7.4	6.2	8.8
C	0.9	1.5	0.6	1.7	2.4	0.2	1.7	1.5	0.4	1.6	1.1
Hy	4.5	2.7	5.5	5.1	2.5	3.3	10.0	2.4	4.9	6.5	6.5
Ol	-	-	-	-	-	-	-	-	-	-	-
Mt	0.1	0.1	0.6	0.1	1.9	2.8	5.3	0.9	0.1	0.4	0.1
Il	0.5	0.3	0.6	0.6	0.5	0.7	1.5	1.0	0.5	1.0	0.9
Ap	-	0.1	0.2	0.2	0.1	0.1	0.3	-	0.5	0.3	0.1
Pr	-	-	-	-	-	-	0.2	-	-	-	0.2
Cc	0.4	-	0.6	-	1.1	0.7	4.0	0.3	2.5	0.7	-
SAL/FEM	94/6	96/3	89/7	93/6	93/6	91/8	77/21	95/5	91/9	90/9	91/8
Modal composition (vol.%)											
Quartz	35	88	76	32	30	33	20	65	61	52	55
Plag.	52(Ab)	(Ab)	(Ab)	63(Ab)	60 (Ab)	42(Ab)	46 (Ab)	18(Ol)	30(Ol)	33(Ol)	34(Ol)
Musc.	3	7	4			3		7		15	11
Bi.		2			4			6			
Chl.	6		6	5	1	11	17		8		
Garn.	4				4			2			
Amph.		3	1								
Ep/Cl			12			9	10		1		
Acc.			1		1	2	8	2			
Average grain size (mm)	0.30	0.10	0.07	0.10	0.50	0.30	0.50	0.20	0.25	0.25	0.25

Table 6. Chemical, normative and modal compositions of quartz keratophyres, keratophyres and quartzo-feldspathic rocks from the Kvarnbergsvattnet area. Locations of samples, see Plate 1.

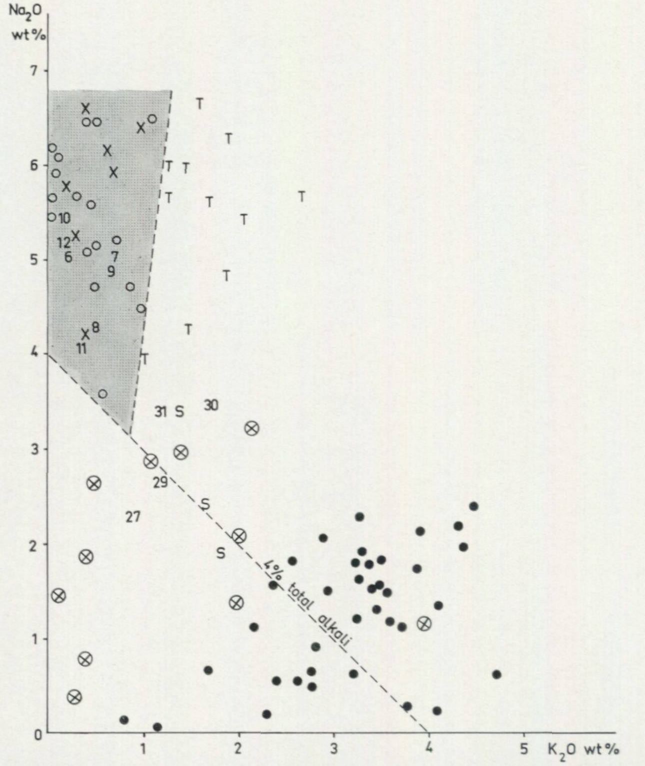


Fig. 21. Alkali diagram (wt %) for quartz keratophyres and quartzo-feldspathic rocks from the Kvarnbergsvattnet area compared to various background analyses. The symbols are the same as in Fig. 16. The shaded area covers the plots of quartz keratophyres.

keratophyre fields and are classified as arkosic metasandstones. A 30 and A 31, which contain 33 and 34 % modal feldspar respectively, plot just inside the quartz keratophyre field in Fig. 16 and outside in Figs. 21 and 22 due to a relatively high K_2O content which is bound in the micas. It is most likely that A 30 and A 31 represent arkosic metasandstones rather than altered or tuffitic volcanites since, firstly, they are closely associated with quartzitic or micaceous epiclastic metasediments and, secondly, since no clear acid volcanic rocks occur in the Blåsjöälven and Lillvattnet Formations. It is evident from Fig. 21 that the meta-arkoses within the Seve and Särv units are richer in Na_2O compared to the background arkoses which, to a large extent, consist of sparagmites from the Caledonian Front.

METASEDIMENTS

Various metasediments from the Kvarnbergsvattnet area have also been chemically analysed (Table 7). A 33, A 34 and A 35 (Plate 1), which represent respectively a phyllite, a biotite schist and a garbenschiefer from the Blåsjö Phyllite,

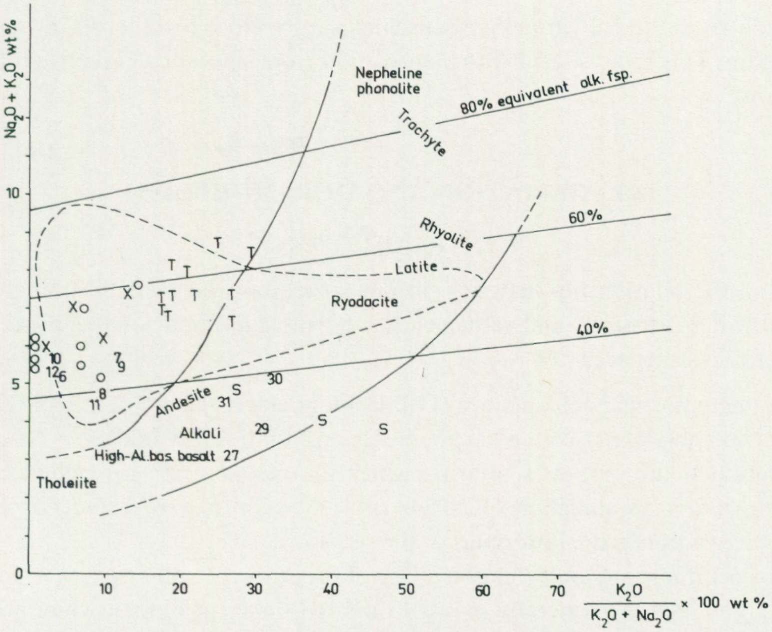


Fig. 22. Compositions of quartz keratophyres, trondhjemites and quartzo-feldspathic rocks plotted in relation to the "igneous spectrum" of Hughes (1972) which includes within its envelope type igneous rocks and rock suites, and also the approximate positions of various volcanic rocks. The "equivalent alkali feldspar content" is the weight percent of alkali feldspar assuming that all the alkali content within the rock is in the form of alkali feldspar. Intrusive and extrusive background keratophyres and quartz keratophyres (Turner and Verhoogen 1960, Donnelly 1966) plot within the field enclosed by the dashed line. The symbols are the same as in Fig. 16.

	A 28	A 32	A 33	A 34	A 35	A 36
SiO_2	70.6	69.1	63.1	56.1	58.8	57.7
TiO_2	0.76	0.94	0.75	0.77	0.86	0.95
Al_2O_3	15.1	13.2	11.2	13.9	16.1	16.8
Fe_2O_3	0.9	0.6	0.6	1.1	1.2	0.1
FeO	3.7	4.7	3.3	4.7	5.7	6.6
MnO	0.09	0.06	0.08	0.09	0.07	0.07
CaO	1.9	1.5	7.2	6.8	3.5	3.2
MgO	1.6	2.8	2.6	4.1	5.0	5.2
Na_2O	3.5	1.5	2.4	2.0	1.9	1.8
K_2O	0.8	2.2	1.8	2.5	3.3	3.0
H_2O^+	1.3	1.7	2.0	2.5	2.4	2.3
H_2O^-	0.2	0.3	0.4	0.4	0.3	0.3
P_2O_5	0.11	0.16	0.14	0.13	0.16	0.17
CO_2	0.04	0.58	4.73	5.34	1.41	0.43
F	0.04	0.07	0.06	0.08	0.10	0.10
S	0.02	<0.02	0.04	<0.02	<0.02	0.40
BaO	0.11	0.04	0.05	0.04	0.07	0.06
Sum	100.77	99.45	100.45	100.55	100.87	99.18

Table 7. Chemical composition of various metasediments from the Kvarnbergsvattnet area (cf. Table 3). Locations of samples, see Plate 1.

and A 36 from the Lillvattnet garbenschiefer, plot close together in the CM-AF-R diagram. This is consistent with a derivation from similar calcareous greywacke sediments.

DEFORMATION AND METAMORPHISM

INTRODUCTION

Based on the relationship between various structures and metamorphic textures, the following deformational sequence has been established for the rocks in the Kvarnbergsvattnet area:

1. Pre-metamorphic deformation (D_1): Folding, development of a bedding foliation and possibly also an axial plane cleavage to the early folds.
2. Interkinematic period (I_1) during which the metamorphism reached its peak with static crystallization of porphyroblastic biotite, garnet and hornblende; migmatization in the lower part of the sequence.
3. Syn-metamorphic deformation (D_2): Formation of the regional foliation (S_{reg}), which is defined by parallel-oriented flakes of biotite, white mica and chlorite as a result of strong, microscopically penetrative deformation (flattening and shear). The regional foliation is either parallel to the lithological layering or to the axial plane foliation of tight to isoclinal folds, many of which are probably strongly modified D_1 folds. The garnets continued to grow after the flattening, which accordingly occurred after but in close connection with the peak of metamorphism. In most outcrops there is a clear transverse or northwest-oriented lineation which is a mineral lineation, a surface-intersection lineation or a striation to rodding. This lineation, which is referred to here as the regional lineation (L_{reg}), is parallel to the elongation of most conglomerate pebbles and to the axes of many folds formed or strongly modified during D_2 and D_3. The regional lineation is thought to define the direction of maximum D_2 elongation and extension in the rocks and also the direction of D_2 and D_3 shear movements.
4. Late-metamorphic deformation (D_3): Formation of major and minor folds with a generally pronounced axial plane crenulation cleavage. The D_3 folds are often sideways-closing with axes parallel or sub-parallel to the regional lineation. The large folds in the western part of the area, the so-called Portfjället folds, formed during D_3. The D_2 and D_3 phases represent the main deformation period. There is clear continuity between these phases and subdivision is made only for descriptive purposes. It is thought that the main nappe translation and also the development of some D_3 structures initiated during the D_2 flattening but continued during D_3.
5. Post-metamorphic deformation (D_4 and D_5): Folding and also faulting, probably in response to basement instability after the main nappe translation.

During D_4 major, open antiforms, synforms, domes and basins with variable orientation developed as well as congruent minor folds with generally steeply inclined axial surfaces. In the western part of the Kvarnbergsvattnet area both the D_2 and D_3 structures were deformed into steep orientations during D_4. The D_5 structures are open or kink-like, reclined to recumbent flexures or folds, which are symmetric or show a down-dip vergence. The axial plane cleavage is generally weakly developed. They were possibly formed as a result of gravity-induced settling of the major steep structures formed during D_4 (Ramberg 1966, Roberts 1967).

METAMORPHISM

The distribution of metamorphic zones in the Kvarnbergsvattnet area is shown in Fig. 23. Together with the P, T diagram (Fig. 24) after Winkler (1976) this gives an approximate picture of the pressures and temperatures which were reached in various parts of the area during the peak of metamorphism i.e. during I_1 and early D_2. The presence of kyanite, sometimes together with K-feldspar, and the absence of index minerals such as andalusite and cordierite indicate that the regional metamorphism was of high pressure or Barrovian type; this is confirmed by the occurrence of locally well preserved retro-eclogites in the Avardo Formation. Following Winkler (1976), the P, T field is divided into four parts corresponding to very low, low (greenschist facies), medium (amphibolite facies), and high metamorphic grades.

Neither zoisite, clinozoisite, lawsonite, pumpellyite nor prehnite, which are index minerals for the transition between very low and low metamorphic grades, have been observed in the Brakkfjället Phyllite, the phyllites of the Brännälven Formation or the Portfjället Conglomerate. Zoisite/clinozoisite is, however, an essential mineral in the metabasites of the Brännälven Formation and Skogsbäcken Volcanites. There is no significant textural difference between the westernmost parts of the Blåsjö Phyllite, which contains zoisite/clinozoisite, and the Brakkfjället Phyllite and, thus, it is considered unlikely that the latter is of very low metamorphic grade.

The biotite isograd is mainly based on microscopic investigations and the occurrence of a few grains in a thin section were considered sufficient to place the rock in the biotite zone; stilpnomelane has not been observed.

The garnet and hornblende isograds coincide and can be followed within the Blåsjö Phyllite. In addition to the garnets which grew during the regional metamorphism, there also occur at four locations small garnets of a later generation (marked with G on the metamorphic map). At Björkvattnet and northwest of Lillvattnet they crystallized together with biotite, muscovite, albite, Fe-sulphides and magnetite in zones of relatively high concentration of ore minerals (Fig. 25).

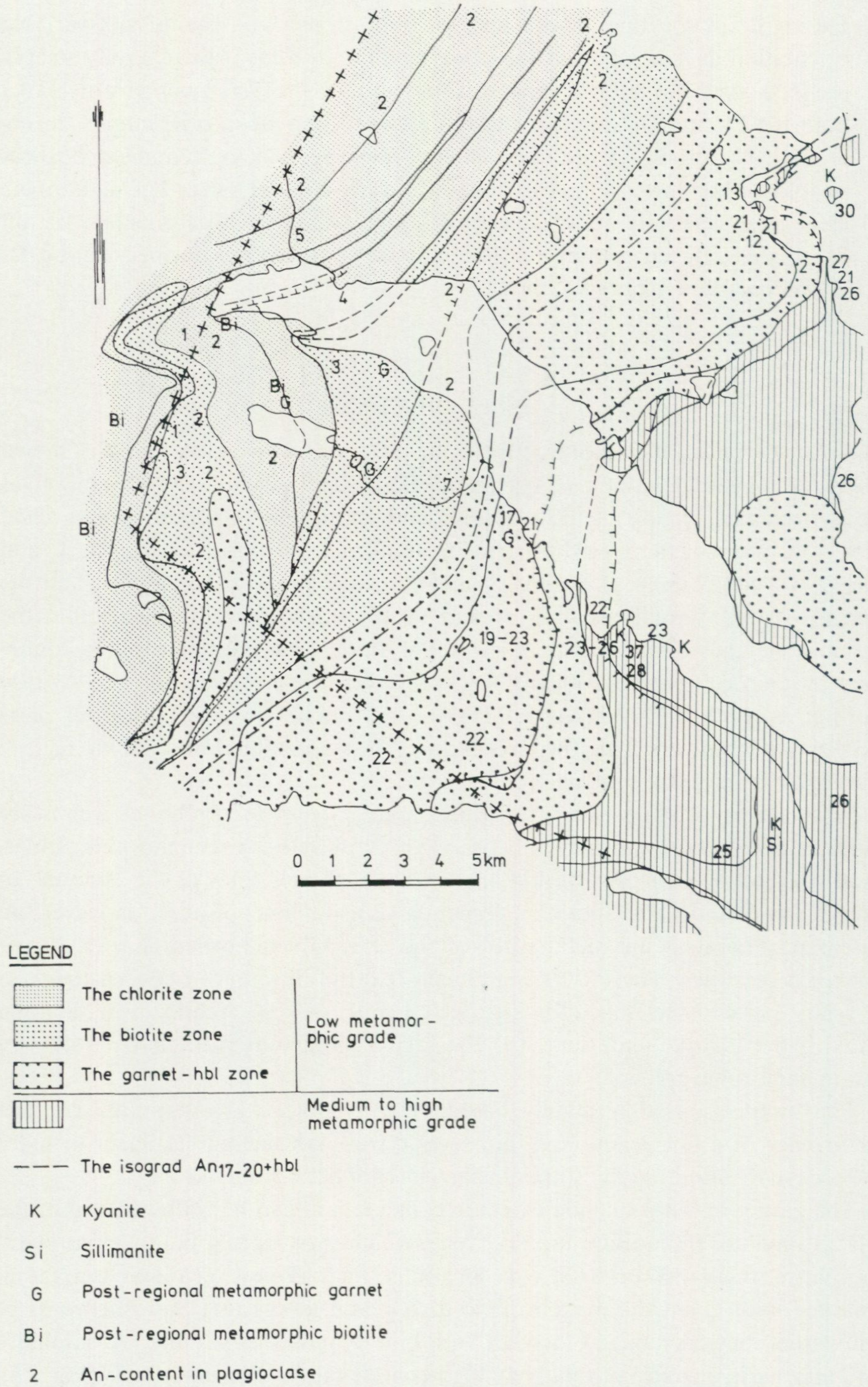


Fig. 23. The distribution of metamorphic zones in the Kvarnbergsvattnet area.

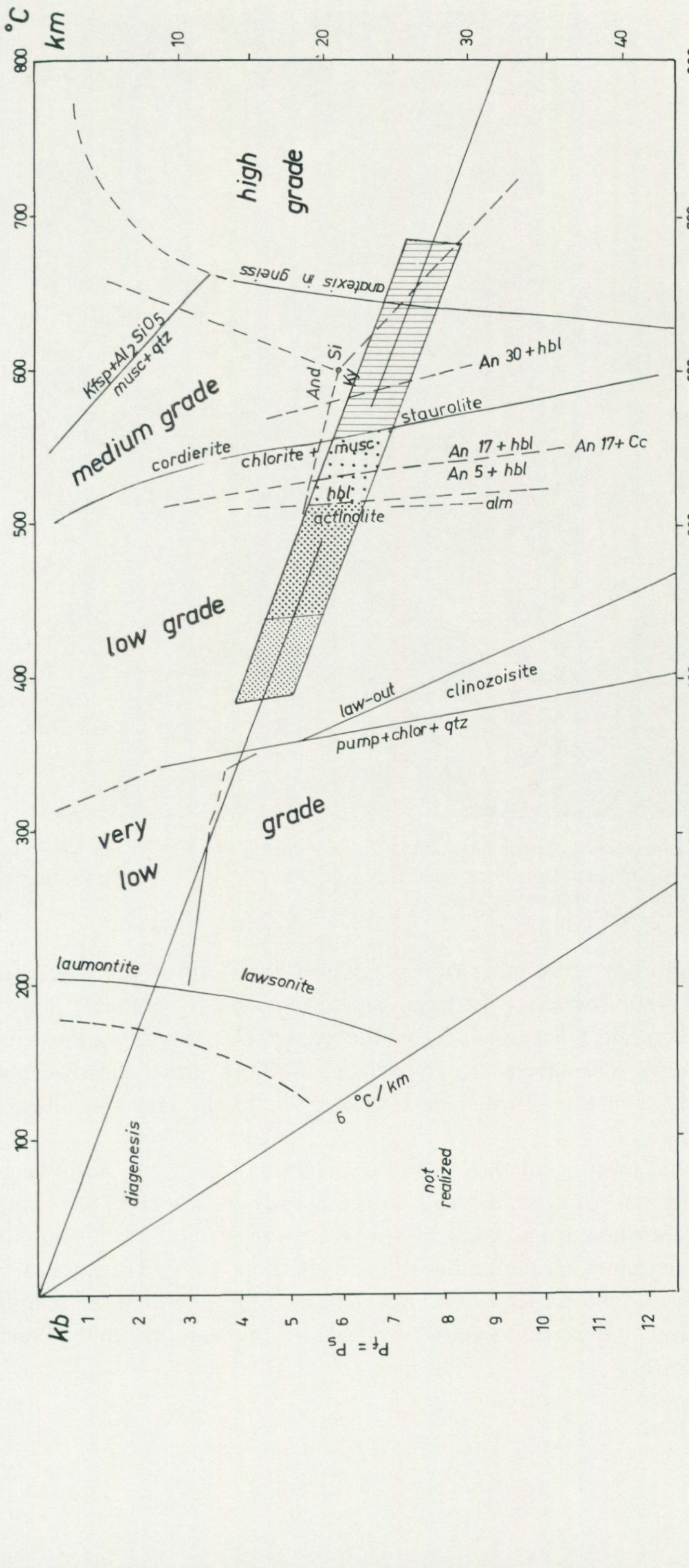


Fig. 24. P,Tdiagram showing the four divisions of metamorphic grade (Winkler 1976) and some important isograds. The shaded area indicates the metamorphic conditions in the Kvarnbergsvattnet area during the peak of metamorphism (I_1 to D_2). For explanation of the screens see Fig. 23.

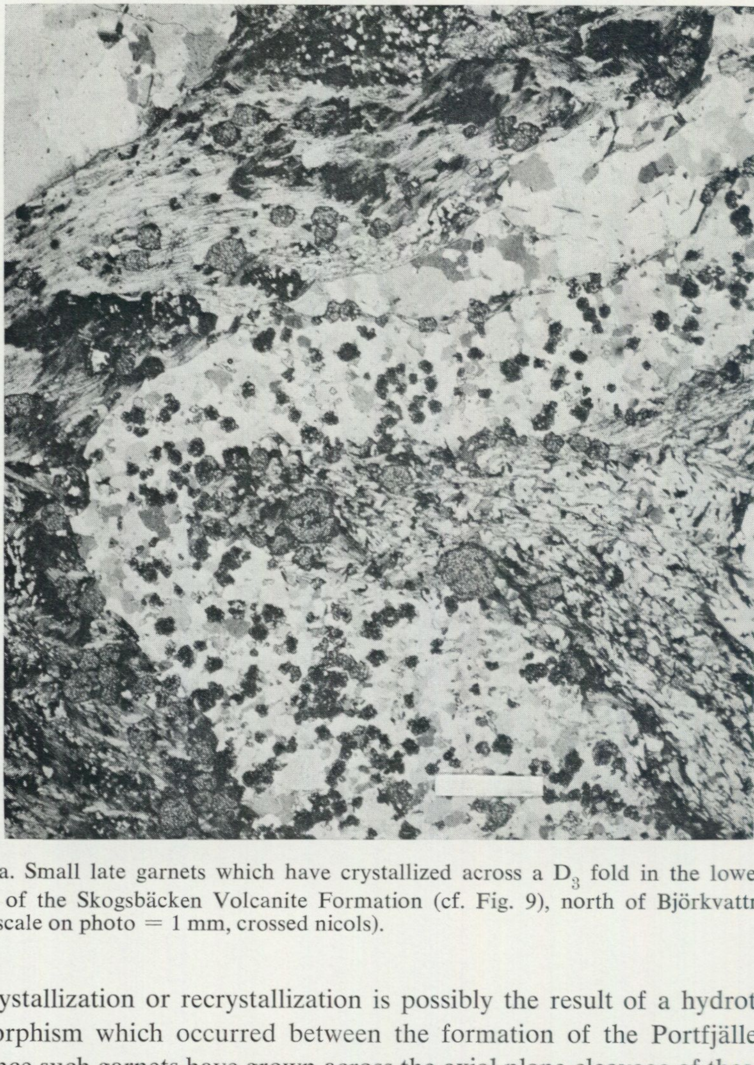


Fig. 25 a. Small late garnets which have crystallized across a D_3 fold in the lower tuffite member of the Skogsbäcken Volcanite Formation (cf. Fig. 9), north of Björkvattnet (thin section, scale on photo = 1 mm, crossed nicols).

This crystallization or recrystallization is possibly the result of a hydrothermal metamorphism which occurred between the formation of the Portfjället folds (D_3), since such garnets have grown across the axial plane cleavage of these folds, and the D_4 folding. The layers of compact ore at Björkvattnet, however, were folded during D_3 and thus must have formed prior to the late crystallization/recrystallization.

The geographic position of the isograd oligoclase (An_{17-20}) + hornblende is less precise. It is, nevertheless, marked on the map (Fig. 23), since the jump in plagioclase composition from An_{0-7} to An_{17-20} is often used as the boundary between the greenschist and amphibolite facies (Eskola 1920, Turner and Verhoogen 1960, Wenk and Keller 1969). Winkler (1976) has defined the boundary between the low- and medium-grade divisions of metamorphism by various reactions leading to:

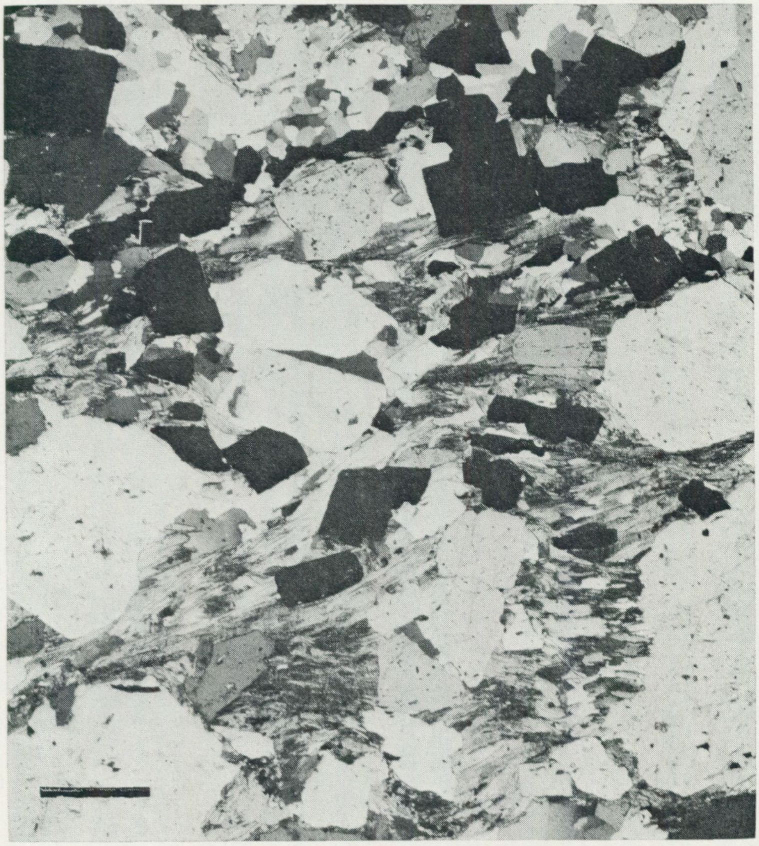


Fig. 25 b. Albite and pyrite which have crystallized across the regional S_2 foliation just above a layer of massive pyrite in the lower tuffite member of the Skogsbäcken Volcanite Formation, north of Björkvattnet (thin section, scale on photo = 1 mm, crossed nicols).

1. the formation of cordierite (without almandine)
2. the formation of staurolite
3. the disappearance of chloritoid
4. the disappearance of Fe-rich chlorite in the presence of muscovite.

The An-content of plagioclase in contact with hornblende is then approximately An_{25-30}.

In the western part of the area chlorite is an essential mineral. As the metamorphic grade increases, it becomes less frequent and in the Lillvattnet Formation "primary" chlorite, generally intergrown with biotite and sometimes in contact with muscovite, occurs only sporadically. The chlorite here has grown or recrystallized in the regional foliation which formed during the D_2 flattening event. The temperature at this time was probably only slightly lower than the maximum I_1 temperature since garnets continued to crystallize and grow both

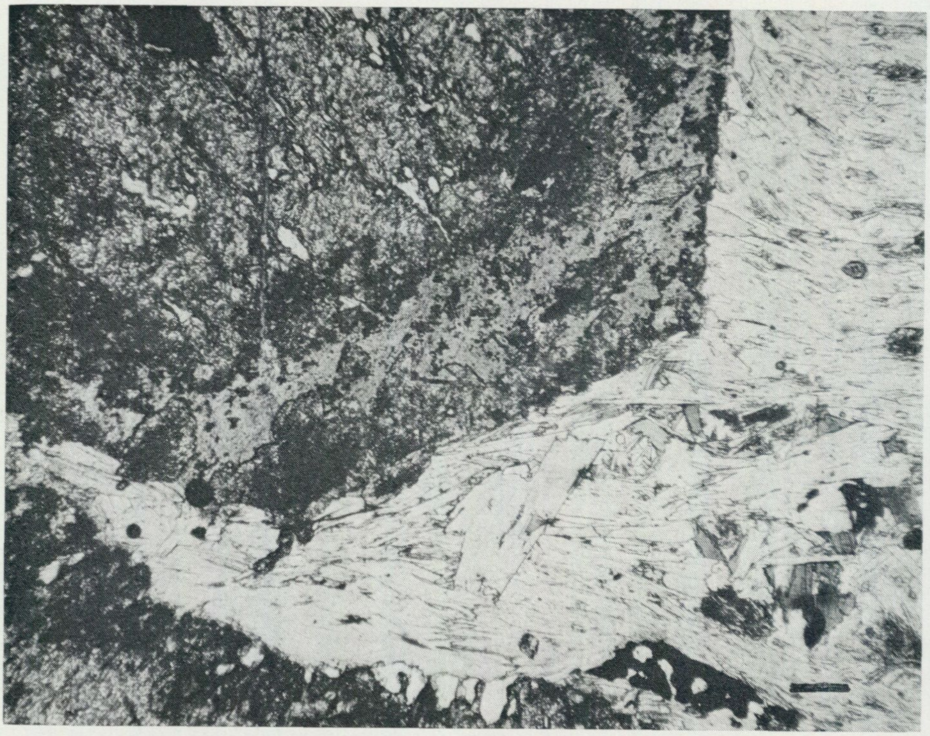


Fig. 26. Chloritized garnet and cross-cutting chlorite in Kvemoen Mica Schist close to the Seve-Köli thrust zone, south of Småvattsbränna (thin section, scale on photo = 0.1 mm, parallel nicols).

during and after the flattening. "Primary" chlorite does not appear to be present in the Lillfjället Gneiss and in the Blåsjöälven Formation. Secondary chlorite, on the other hand, is often found in the eastern parts of the area, either as cross-cutting chlorite blasts or as a product of retrograde alteration in or close to later movement zones (Fig. 26).

Neither chloritoid nor staurolite have been found in the area. However, none of the analysed metasediments (A 27–A 29 and A 32–A 36, Plate 1) have an appropriate bulk composition for the formation of these minerals (Hoschek 1967). The An-content of plagioclase is generally lower than An_{25} within and above the Lillvattnet Formation, whilst in the Blåsjöälven Formation and Lillfjället Gneiss it is approximately An_{25-30}.

Kyanite, marked with K on the metamorphic map, occurs both in the Lillfjället Gneiss and in the Blåsjöälven Formation; scattered grains have also been found in the Lillvattnet Formation where they are almost enclosed by garnet.

Based on the above, the boundary between the rocks showing low and medium grades of metamorphism is located somewhere in the lower part of the Lillvattnet Formation i.e. close to the base of the Seve-Köli transition zone.

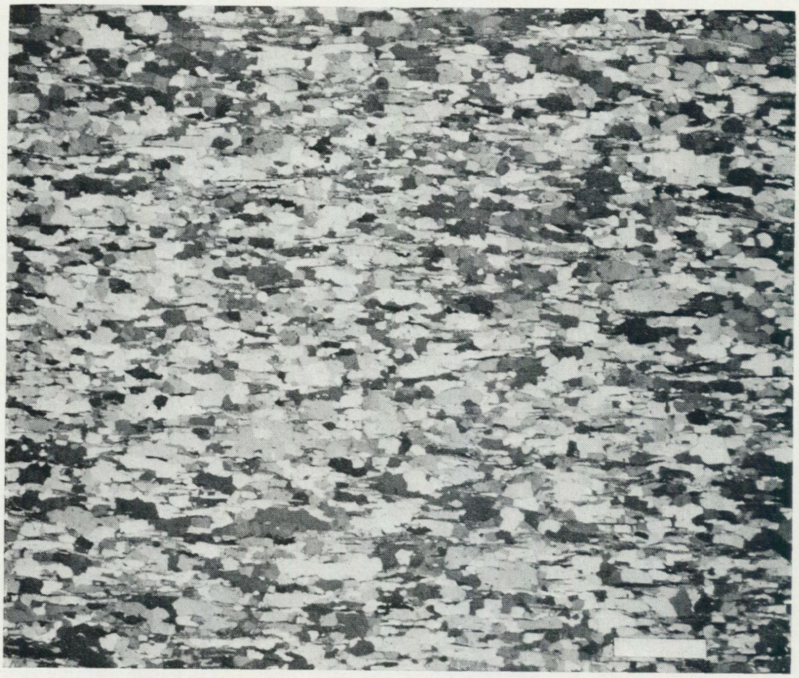
The beginning of anatectic melting by breakdown of muscovite in the presence of quartz and plagioclase defines the beginning of high grade metamorphism if the H_2O pressure is higher than about 3.5 kb (Winkler 1976). The following minerals, representing one or several metamorphic mineral parageneses, are common within single thin sections from the Lillfjället Gneiss and from the migmatitic gneisses of the Blåsjöälven Formation; Plagioclase (An_{30-32}) + quartz + biotite + muscovite + K-feldspar + garnet + kyanite. Kyanite in direct contact with K-feldspar has not been observed but both muscovite and biotite in contact with plagioclase and K-feldspar are common; at Lillfjället sillimanite occurs together with kyanite (Du Rietz 1938). Mobilized pegmatitic material, i.e. neosome, occurs as eyes, patches, layers or bodies conformable to the regional foliation in the Lillfjället Gneiss, the Blåsjöälven Formation and to some extent also in the Lillvattnet Formation. In some areas, for instance at Lillfjället, the gneiss is often soaked by neosome. Essential minerals in the pegmatitic neosome are acid plagioclase (albite-oligoclase), quartz and muscovite, while microcline and garnet occur in subordinate amounts or are missing; at Lillfjället K-feldspar is sometimes the most important mineral (Du Rietz 1938).

To explain the mineral parageneses in these migmatitic gneisses, it seems likely that the boundary to high metamorphic grade was reached during I_1 at many places in the rock units now found in the upper and central part of the Seve. An anatectic liquid phase was formed, which was subsequently squeezed and injected into adjacent, somewhat cooler rock units, or it crystallized more or less in situ as a pegmatitic neosome when the temperature was lowered and the boundary to medium metamorphic grade was once again attained. The coarse, sparkling flakes of muscovite often seen in the gneisses are in this way secondary minerals formed at the same time as the plagioclase neosome. The foliation curves around the pegmatitic minerals, indicating that most of these minerals were injected and/or crystallized before the main deformation.

Anatexis in the presence of kyanite indicates a hydrostatic pressure (= load pressure + possible tectonic overpressure) exceeding 7 kb at a temperature of 650° C (Fig. 24), if the triple point of the Al_2SiO_5-system is placed at 600° C/6 kb i.e. between the triple points of Richardson et al. (1968, 1969) and of Althaus (1967, 1969 a, b). If the tectonic overpressure is neglected, this corresponds to a depth of burial of 25–30 km and a geothermal gradient of 25° C/km.

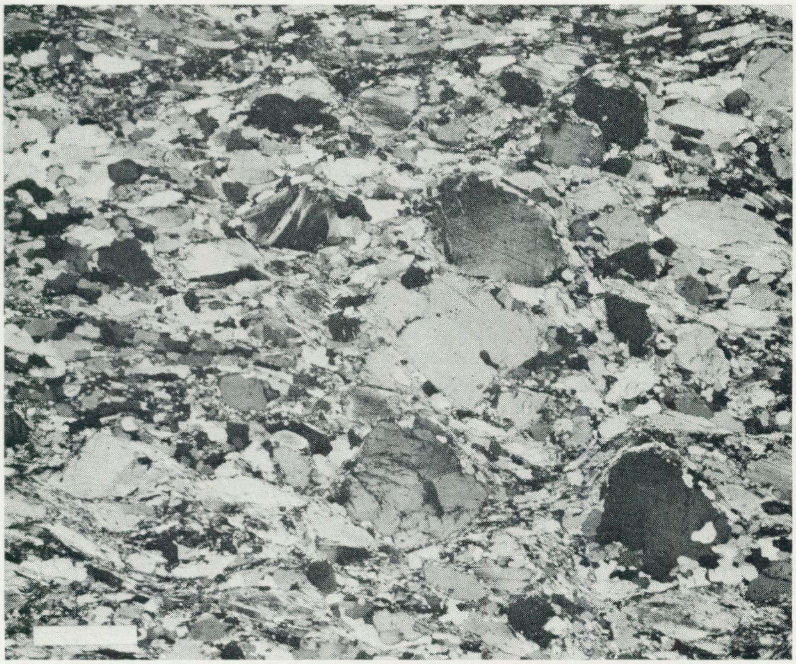
It is suggested that the essential reason for the metamorphism was a depression of the Baltoscandian continental margin, caused by collision and overriding of the Greenlandian plate (cf. p. 103). On this assumption, it is possible that there existed a certain tectonic overpressure during I_1 which eventually gave rise to the D_2 flattening and subsequent movements.

During the main deformation (D_2 and D_3) the isograd pattern was deformed and disturbed, resulting in rapid jumps in the metamorphic grade and regional inversions of the metamorphic zonation (cf. Zwart 1974). South of Kvarnbergs-



a

b



c

Fig. 27. a = Quartzo-feldspathic schist (A 27, Plate 1) with a granoblastic elongate texture from the Lillvattnet Formation, south of Lillvattnet.
b = Coarse-grained Lillfjället Gneiss, Krötterholmen.
c = Somewhat blasto-mylonitic micaceous gneiss (A 28, Plate 1) from the Blåsjöälven Formation, south of Digerhösen (thin sections, scales on photos = 1 mm, crossed nicols).

vattnet there is, on the whole, a gradual increase in metamorphic grade from the Brakkfjället Phyllite down to and including the Lillvattnet Formation. However, a small jump in the metamorphic grade occurs between the Haraön Phyllites and the overlying volcanites east of Kveli (Fig. 23), probably due to strong shear movements in the Haraön Phyllites related to the formation of the Portfjället folds.

Differences in texture and structure indicate an important structural-metamorphic discontinuity between the Lillvattnet Formation and the underlying units in the area south of Kvarnbergsvattnet. In the Småvattsbränna area the garbenschistose Blåsjö Phyllite almost directly overlies the kyanite-bearing migmatitic Lillfjället Gneiss, and there is a considerable stratigraphic and metamorphic gap, corresponding to a large part of the lower Köli sequence, between these two units. Another significant gap occurs at L. Blåsjön, where the Tången Mica Schist is directly underlain by the eclogite-bearing Avardo Formation (Plate 1).

The average grain size has been measured or estimated in quartz-feldspar-rich domains in every suitable thin section. Most rocks are foliated and the quartz-rich domains generally have a granoblastic elongate texture but polygonal, equigranular textures are also common. The grain size increases gradually towards the east, there being clear connection between grain size and metamorphic grade. From 0.05 mm in the Brakkfjället Phyllite and Brännälven Formation it successively increases to 0.15–0.25 mm in the Lillvattnet Formation. In the Blåsjöälven Formation the grain size is 0.2–0.3 mm in the area north of Kvarnbergsvattnet, while it is considerable coarser in the more migmatitic Digerhösen area. At Lillfjället the grain size rapidly increases from about 0.3 mm in the Lillvattnet Formation to 0.5–1 mm or more in the Lillfjället Gneiss (Fig. 27). In the present area an average grain size of about 0.25 mm accordingly marks the transition from low to medium metamorphic grade. Besides giving a crude measure of the metamorphic grade, the grain size makes it possible to recognize syn- to post-metamorphic movement zones, which are anomalously fine-grained.

DEFORMATION

The rocks of the Kvarnbergsvattnet area have been folded several times during D_1 to D_5 and folds of variable size, style and orientation occur within the area. The different folds have been arranged into three groups:

Group I folds: Tight or isoclinal folds where the axial plane cleavage is the most pronounced surface, generally being penetrative down to a microscopic scale (Figs. 40 and 41). It is thought that many Group I folds initiated during D_1 but were strongly modified and, thus, achieved their present appearance during the D_2 flattening event.

Group II folds: More open folds in which a pronounced surface is folded and the axial plane cleavage is a well developed crenulation cleavage (Figs. 46 and 51); the majority of Group II folds formed after the main flattening during D_3.

Group III folds: Open, post-schistosity folds or flexures with no or only weakly developed axial plane cleavage (Figs. 52–54).

The orientations of the lithological layering and the regional foliation are evident from the maps on Plate I, while the orientations of various other structural elements are indicated in Fig. 28. Besides several tectonic discontinuities and the wedging out of many units (Plate I), there are two major structural features evident in the Kvarnbergsvattnet area:

1. The Portfjället folds and their continuation in the Haraön Phyllites towards Långviken (cross-sections B–B^{I} and C–C^{I}, Plate 1).
2. The increase in dip of both the lithological layering and the regional foliation, from a gentle, northwest dip in the eastern part of the area to a vertical dip north of Kvarnbergsvattnet (cross-section A–A^{I}).

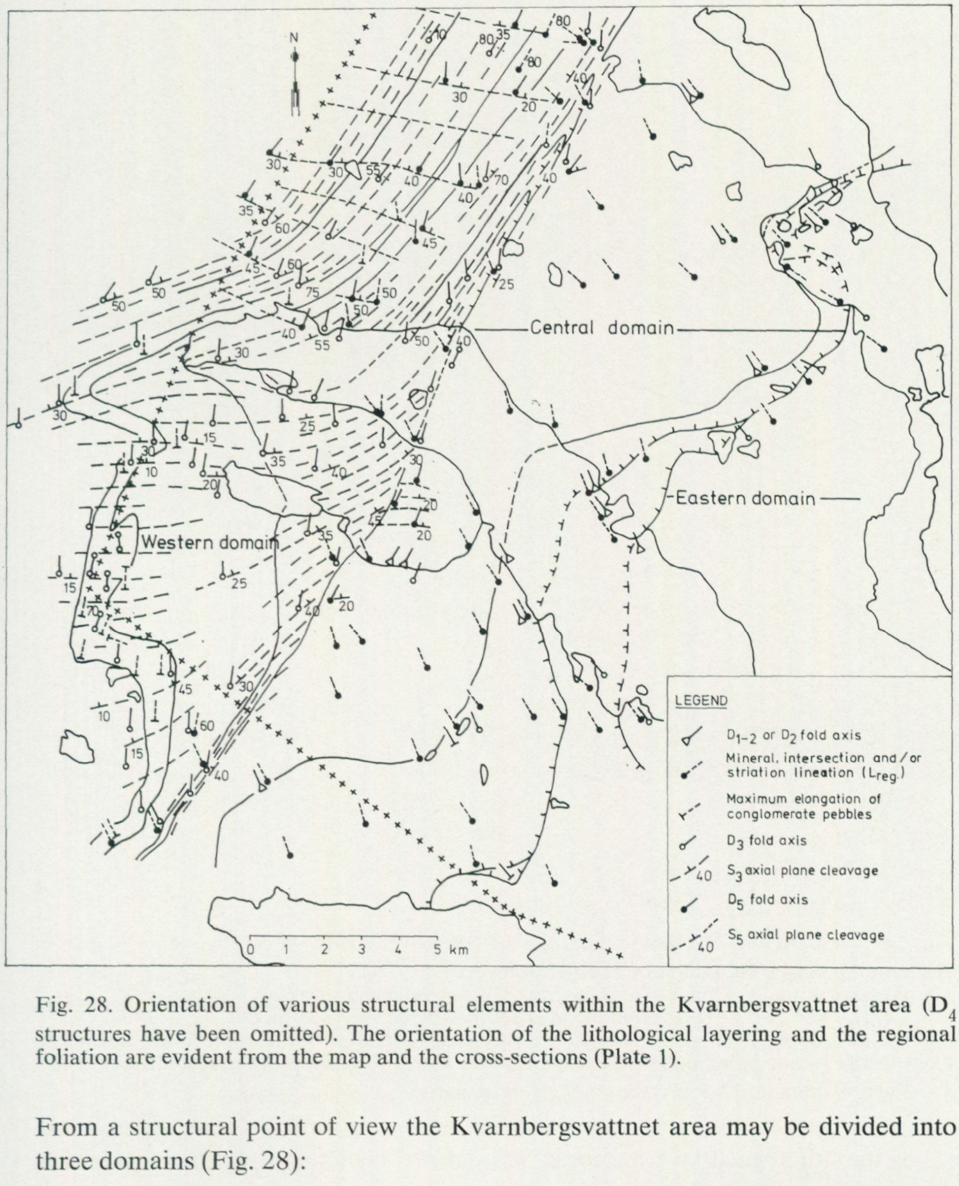


Fig. 28. Orientation of various structural elements within the Kvarnbergsvattnet area (D_4 structures have been omitted). The orientation of the lithological layering and the regional foliation are evident from the map and the cross-sections (Plate 1).

From a structural point of view the Kvarnbergsvattnet area may be divided into three domains (Fig. 28):

1. The western domain, from the upper part of the Blåsjö Phyllite and westwards, is characterized by pronounced folding and poles to the lithological layering from a clear girdle pattern on a stereographic orientation diagram (Fig. 29 a).
2. The central domain, from the Lillvattnet Formation up to and including the eastern part of the Blåsjö Phyllite; the lithological layering is generally planar and dips consistently towards the northwest throughout the domain; poles

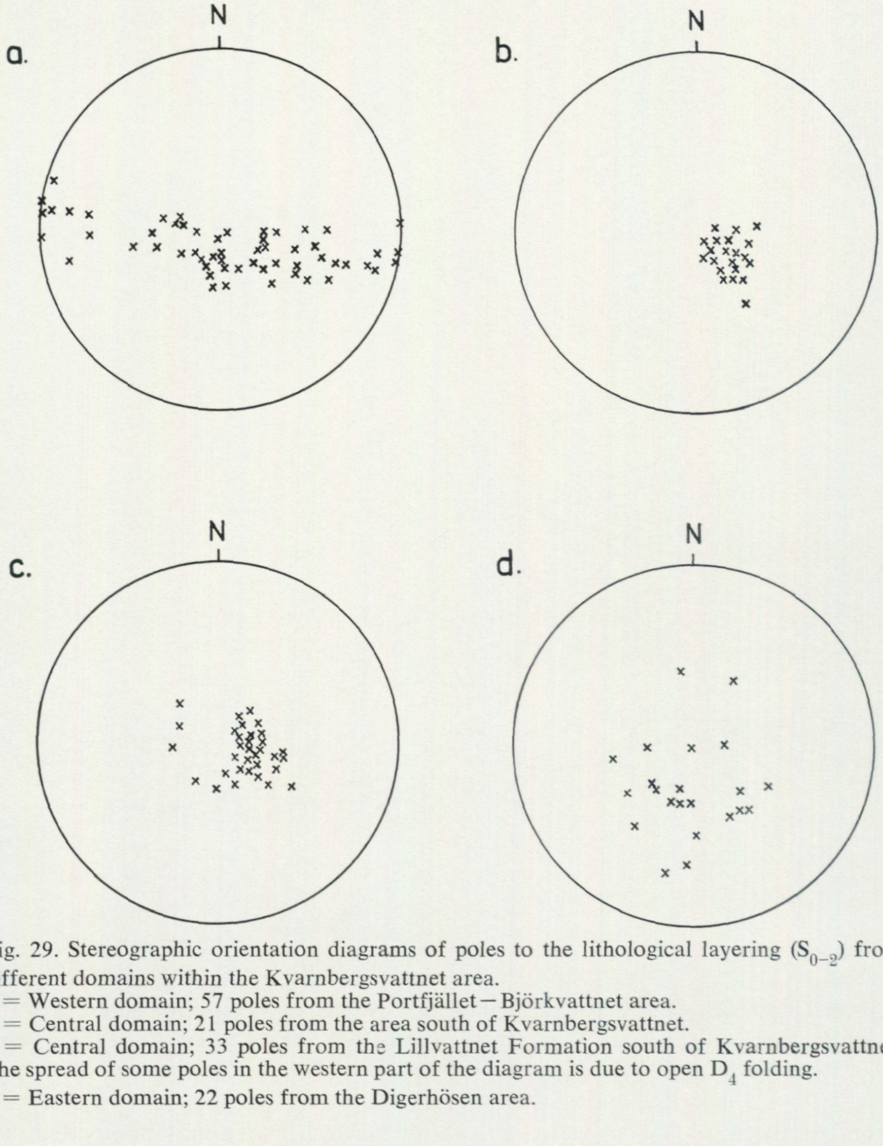


Fig. 29. Stereographic orientation diagrams of poles to the lithological layering (S_{0-2}) from different domains within the Kvarnbergsvattnet area.
a = Western domain; 57 poles from the Portfjället – Björkvattnet area.
b = Central domain; 21 poles from the area south of Kvarnbergsvattnet.
c = Central domain; 33 poles from the Lillvattnet Formation south of Kvarnbergsvattnet. The spread of some poles in the western part of the diagram is due to open D_4 folding.
d = Eastern domain; 22 poles from the Digerhösen area.

to the lithological layering form well defined maxima in the orientation diagrams (Figs. 29 b and c).

3. The eastern domain, including the Blåsjöälven Formation and the Lillfjället Gneiss; the lithological layering is apparently irregularly folded, resulting in a large spread of the poles in the orientation diagram (Fig. 29 d).

The rocks of the central and eastern domains contain porphyroblasts of biotite, garnet and hornblende, permitting an easier assessment of the relationship between the deformation sequence and the metamorphism.

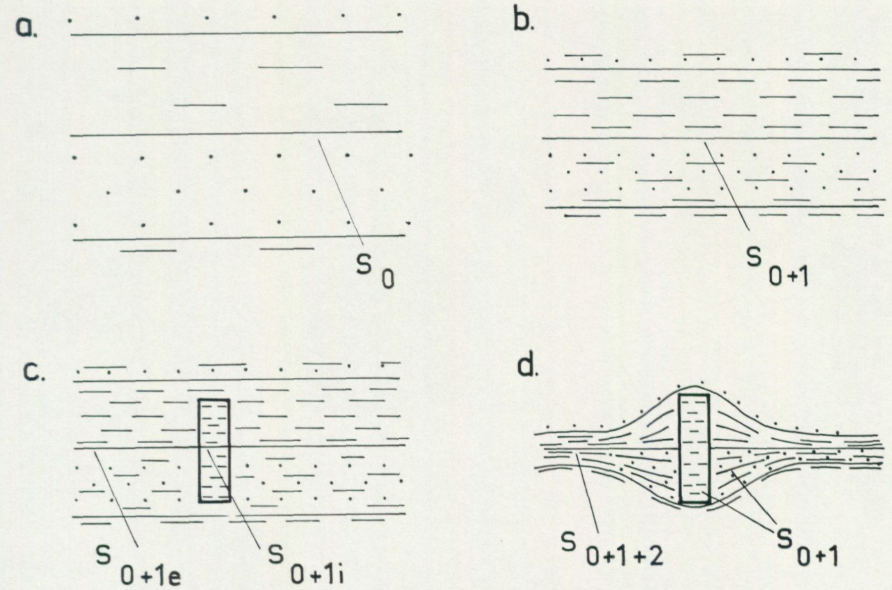


Fig. 30. Schematic illustration of the formation of the regional foliation (S_{0-2}).
a = Weak bedding foliation (S_0) formed during sedimentation, compaction (burial) and diagenesis.
b = Formation of a slaty cleavage parallel to the bedding (S_{0+1}) during D_1 indicating at least 30 % compressive strain.
c = Static crystallization of porphyroblasts across S_{0+1} during the peak of metamorphism (I_1).
d = Formation of the regional foliation parallel to the bedding S_{0+1+2} (or S_{0-2}) by strong D_2 flattening. The only places where S_{0+1} sensu stricto is preserved now is in the I_1porphyroblasts and their pressure shadows.

D_2 FLATTENING AND FORMATION OF THE REGIONAL FOLIATION

The rocks of the central domain, in particular, are characterized by a planar or gently folded phyllitic cleavage or schistosity, containing a clear, northwest-trending lineation. These structural elements, here called the regional foliation (S_{reg}) and lineation (L_{reg}), form a typical LS fabric (Flinn 1965). The regional foliation is either parallel to the lithological layering, which generally represents bedding, or to the axial surfaces of Group I folds.

Bedding is evident or recognizable in many outcrops and is defined by, for example, the interstratification of amphibolite and schist in the Lillvattnet Formation, the alternation of acid and basic volcanites (Fig. 5) and the interlayering of micaceous and quartz-rich layers in the metasediments (Figs. 6 and 8). During D_1 a cleavage was formed as a bedding foliation and possibly also as an axial plane foliation to the D_1 folds. The formation of this bedding cleavage was probably a continuous process involving preferred orientation during diagenesis and compaction, and then accentuation during D_1 (Figs. 30 a and b). The

Fig. 31. Garnets with three zones of growth, namely 1 = A core zone with no or very few inclusions, 2 = an intermediate zone with more and larger inclusions = and 3 an outer, generally thin rim growing across the foliation (S_2). Kvemoen Mica Schist, south of Kvarnbergsvattnet (thin section, scale on photo = 1 mm, parallel nicols).

presence of this foliation of slaty cleavage type in the porphyroblasts and in their pressure shadow indicates a compressive D_1strain exceeding 30 % (Cloos 1947, Ramsay 1967, p. 180).

In the central and eastern domains many porphyroblasts of biotite, garnet and hornblende grew statically across the early bedding foliation (S_{0+1}) during the peak of metamorphism. The rocks were then strongly flattened during D_2 and the regional foliation formed parallel to S_{0+1} (Figs. 30 c and d) or to the axial surface of Group I folds by syntectonic crystallization or recrystallization of micas and quartz. The regional foliation may thus be referred to as S_{0+1+2} or S_{0-2} when parallel to the lithological layering, otherwise it should be labelled S_2. The only places where S_{0+1} sensu stricto occur in the present area is within the porphyroblasts and their pressure shadows or as remnants of a folded foliation in Group I folds.

S_{0+1} is commonly preserved in the garnet porphyroblasts as a planar or S-shaped inclusion trail concordant or discordant to the external foliation. Many garnets consist of three zones of growth (Fig. 31):

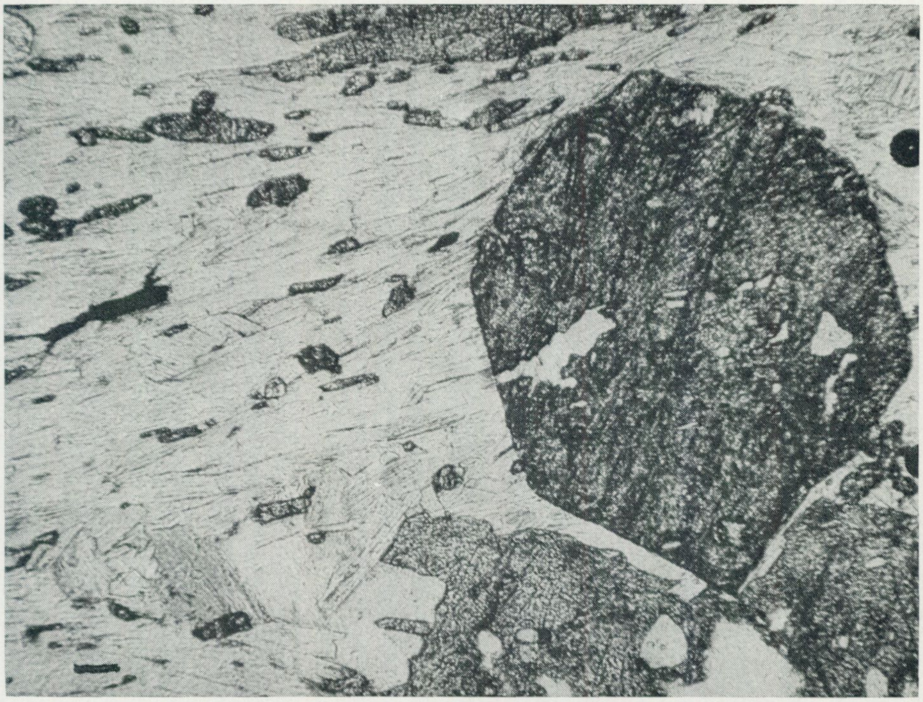


Fig. 32. Garnet which grew across the regional foliation (S_2) and, thus, post-dates the D_2 flattening. Lillvattnet Formation, south of Kvarnbergsvattnet (thin section, scale on photo = 0.1 mm, parallel nicols).

1. A core zone with no or very few inclusions indicating a balance between supply of reactants and growth rate; the inclusions within the core zone are occasionally arranged in a radial pattern.
2. An intermediate zone with abundant and larger inclusions indicating an inbalance between supply of reactants and growth rate; in most garnets the growth of the intermediate zone pre-dates the D_2 flattening event and probably occurred during the peak of metamorphism.
3. An outer, generally thin rim growing across the D_2 foliation; this rim contains few inclusions and indicates a new supply of reactants as a result of the D_2 flattening event.

In several thin sections from the Blåsjö Phyllite there are weakly S-shaped inclusion trails within the core zone of garnet porphyroblasts indicating relative rotation between garnet and matrix before the main flattening.

As mentioned above, most garnets continued to grow after the D_2 flattening event. In addition, a new generation of garnets grew across the regional foliation in the Lillvattnet Formation (Fig. 32). These textures indicate that the main

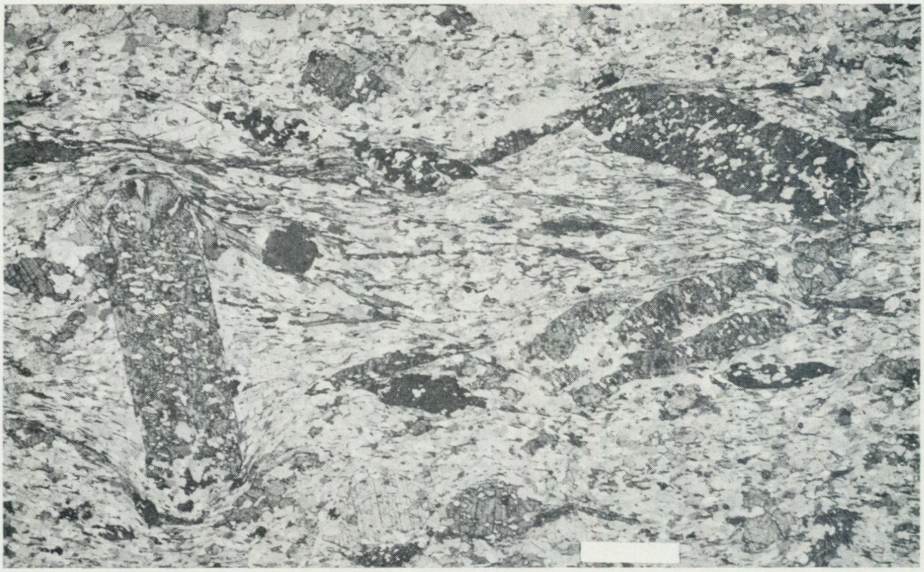


Fig. 33. Hornblende porphyroblasts in a garbenschiefer. The one to the left has remained in an upright position, while the others have been forced almost into parallelism with the regional foliation during the D_2 flattening. Blåsjö Phyllite, south of Kvarnbergsvattnet (thin section, scale on photo = 1 mm, partly crossed nicols).

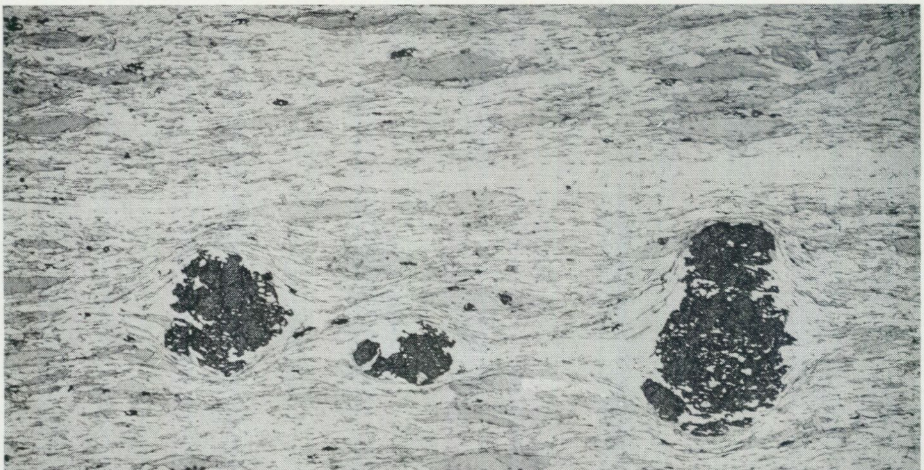


Fig. 34. Garnet- and biotite-porphyroblastic Kvemoen Mica Schist, south of Kvarnbergsvattnet. The inclusion trails in the garnets are sub-planar and concordant with regional S_2 foliation (thin section, scale on photo = 1 mm, partly crossed nicols).

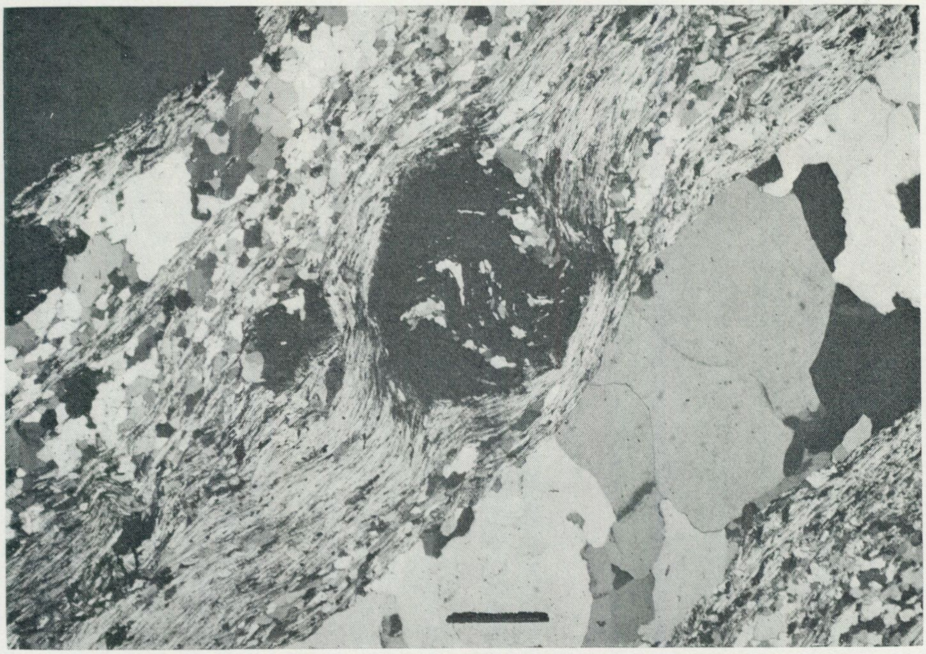


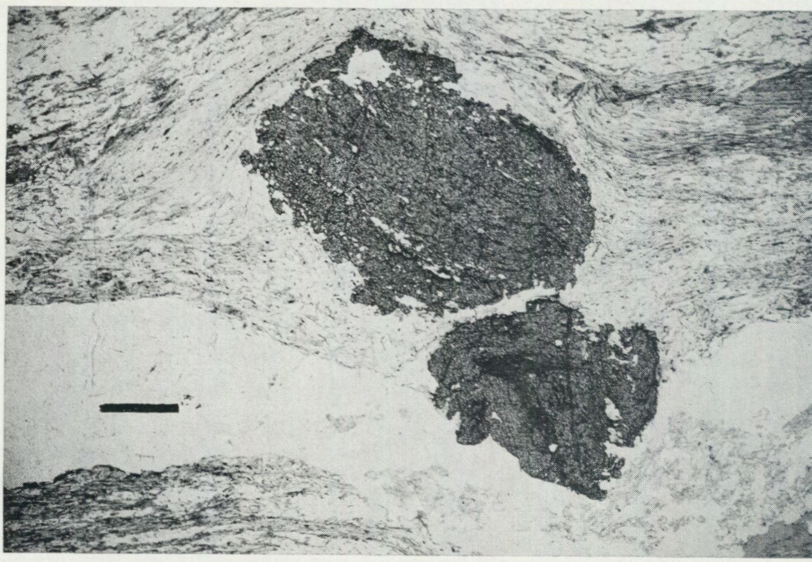
Fig. 35. Garnet with S-shaped inclusion trails, Lillvattnet Formation, north of Kvarnbergsvattnet (thin section, scale on photo = 1 mm, crossed nicols).

flattening event occurred syn-metamorphically within a rather limited time interval, and was followed by a new static stage of mineral growth.

It is possible to estimate the amount of flattening from porphyroblasts where the internal and external foliations are planar concordant. In most thin sections the flattening is about 75 % (Figs. 31, 33 and 34). This implies a considerable reduction in the thickness of the D_1 folded rock sequence by means of simple and/or pure shear during elongation, extension or tectonic flow. The present thickness of the central domain is 3000–4000 m (cross-section C–C^I, Plate 1) Assuming a homogeneous D_2 flattening of 75 %, the pre-D_2 thickness of the central domain could be estimated to be 12 000–16 000 m! With these figures in mind, it is possible to explain a burial of 20 000–25 000 m, corresponding to a hydrostatic pressure of 5–6 kb, which is required to reach the garnet-hornblende zone at a geothermal gradient of 25° C/km (cf. Fig. 24).

It is evident from Figs. 33 and 34 that the D_2 deformation was locally a non-rotational or pure shear deformation. In many other micro-domains, however, there is evidence from the occurrence of S-shaped inclusion trails (Fig. 35) and bodily rotated I_1 garnets, often with discordant internal and external foliations, that the flattening was accompanied by shear movements (Fig. 36 a and b) in a way which is schematically illustrated in Fig. 37.

a



b

Fig. 36. Garnet mica schists from the Lillvattnet Formation, north of Kvarnbergsvattnet.
a = Garnet with planar inclusion trails (S_1) rotated during D_2, and with a pronounced zone of overgrowth post-dating the rotation and main flattening.

b = Garnet with planar inclusion trails rotated during D_2, and with a thin zone of overgrowth post-dating the rotation and flattening. The inclusion trails are discordant to the regional S_2 foliation on the top left part of the large garnet (thin sections, scales on photos = 1 mm, parallel nicols).

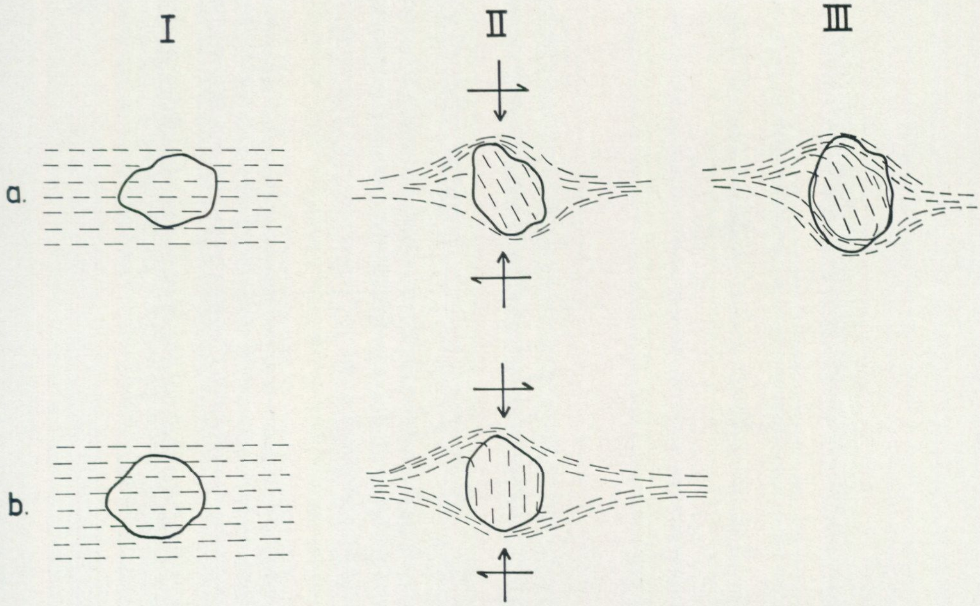


Fig. 37. Schematic illustration of garnet growth in relation to the D_2 flattening and shear. a = Garnet from the Lillvattnet Formation (cf. Fig. 36), b = Garnet from the Blåsjö Phyllite. I. Static nucleation and growth across and including the D_1 foliation during the peak of metamorphism (I_1).
II. Interacting D_2 flattening and shear giving rise to a rigid body rotation of the garnets.
III. Formation of a more or less pronounced zone of overgrowth post-dating the main flattening and shear movements.

In the calcareous sediments, in particular, prismatic crystals of hornblende crystallized and grew in different directions, often from the same nucleus. During the D_2 flattening deformation most crystals were rotated into the regional foliation and garbenschiefers were formed; only a few grains remained in an upright position (Fig. 33). Spry (1969, p. 269) has described and discussed the origin of garbenschiefers. The appearance of the garbenschiefers in the Kvarnbergsvattnet area is very similar to that described by him. However, as far as their origin is concerned the following remarks should be made: 1. The hornblende is not necessarily a post-tectonic mineral; instead, it appears to be interkinematic and, in relation to the most pronounced phase of deformation, the hornblende is pre-tectonic. 2. The hornblende did not crystallize mimetically but grew in many directions and was later rotated into parallelism with the main foliation. 3. The bedding foliation (S_{0+1}) did not act as plane of easy growth, but the hornblende grew at various angles across this foliation.

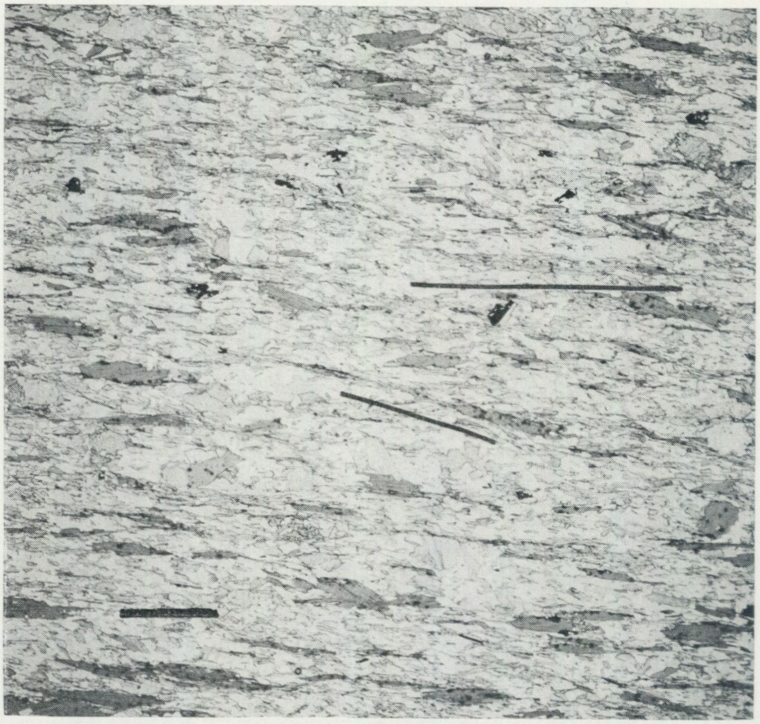


Fig. 38. Surface intersection lineation from the Blåsjö Phyllite, north of Kvarnbergsvattnet. The more pronounced, horizontal foliation is the regional foliation (S_{0-2}), which is cut at low angle by a less developed S_2 cleavage (thin section, scale on photo = 1 mm, parallel nicols).

THE REGIONAL LINEATION

The regional lineation (L_{reg}) within the Kvarnbergsvattnet area corresponds to the well-known and controversial Caledonian transverse lineation (Turner and Weiss 1963, p. 448). It has different morphologies and may be a mineral lineation, a surface intersection lineation or a striation to rodding lineation. The regional lineation is parallel to the axes of many Group I and Group II folds (see p. 58) and often to the direction of maximum finite elongation in the rocks represented by deformed conglomerate pebbles (Fig. 28).

The most conspicuous mineral lineation is formed by biotite. Many hornblende crystals in the garbenschiefers show a random orientation in the foliation plane and there is only a weak tendency towards alignment in L_{reg}. However, the small amphibole needles in the schistose amphibolites, especially of the Lillvattnet Formation, are often arranged in a sublinear manner parallel to L_{reg}.

A surface intersection lineation occurs parallel to the mineral lineation particularly in the Björnhögen Formation and the Blåsjö Phyllite. The more pronoun-

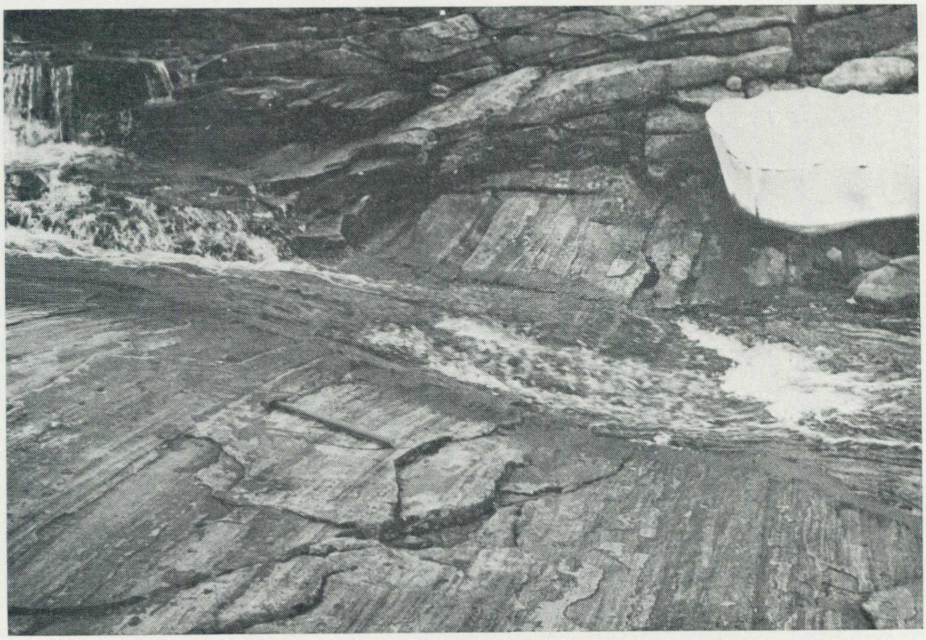


Fig. 39. Pronounced striation in quartzo-feldspathic schist from the Lejaren Formation, south of Härbergsdalen.

ced regional foliation is cut at a low angle by a weakly developed foliation (Fig. 38); biotite and muscovite crystallized contemporaneously along both surfaces. The weaker foliation is not an axial plane foliation but probably formed as a result of the D_2 flattening and is, thus, also a S_2 foliation.

The regional lineation is most frequently a striation lineation, defined by a combination of slickensides with fine furrows and ridges, sometimes growing into a rodding, and a quartz-feldspar mineral lineation (Fig. 39). In contrast to the mica and quartz mineral lineation, the striation lineation is not penetrative down to a microscopic scale but occurs instead on the more pronounced, generally quartz-coated foliation planes. It is thought that this lineation formed, at least partly, on active shear planes and defines the direction of D_2 and D_3 shear during extension and translation.

The conglomerate pebbles are flat within the regional foliation and more or less elongate parallel to L_{reg}. Compared to the Kvarnbäcken Conglomerate the pebbles in the Kvemoruet Quartzite are less elongate and sometimes they are even pancake-shaped. In the southernmost outcrops at Kveli, the Portfjället Conglomerate is unfolded. The pebbles are elongate towards the NNW parallel to a mineral lineation and striation lineation (Fig. 28). From Kveli northwards the conglomerate and S_{reg} are folded in almost every outcrop. The folds are of Group II type and the axial plane cleavage is always a clear crenulation cleavage

(S_3). In the first inner fold arc, between Portfjället and Kveli, the pebbles are often cigar-shaped and strongly elongate to the north parallel to the Portfjället fold axis (D_3). Along the Portfjället ridge they are often pancake-shaped and sometimes difficult to delimit due to very strong flattening. On the eastern slope of the mountain most pebbles are elongate parallel to the almost horizontal local fold axes, whilst some are elongate perpendicular to the fold axes, parallel to a striation lineation, probably L_{reg}. In the major fold arc, west of Kvarnbergsvattnet, all the pebbles are elongate parallel to the fold axis and are flat within the folded foliation (S_{reg}). Northwards S_{reg} steepens into a vertical position (D_4 folding) and at the same time the direction of pebble elongation also becomes steeper until a vertical plunge is reached just north of the Kvarnbergsvattnet area. The elongation is here parallel to L_{reg} and to the axes of D_3 meso-folds of Group II type (Figs. 46 and 47).

The parallelism between L_{reg} and the axes of many sideways-closing D_3 folds indicates that these structures formed, on the whole, in response to the same force regime. The linear structures, thus, define a connection between the D_2 flattening and the later D_3 folding i.e. after a certain amount of flattening spreading initiated and this ultimately lead to folding.

EARLY PRE- TO SYN-METAMORPHIC FOLDNG ($D_1 - D_2$)

In many outcrops tight to isoclinal, often rootless folds occur, with the regional foliation as an axial plane foliation (Group I folds). The fold axes are often parallel to the NW-oriented regional lineation. In the Blåsjö Phyllite, however, many of them trend NNE and there is a marked angle to L_{reg} on the axial planes. The axial plane cleavage or schistosity is generally penetrative down to a microscopic scale (Fig. 40) but occasionally remnants of a folded foliation parallel to bedding occur within the axial plane foliation (Fig. 41).

Group I folds with the fold axes parallel to L_{reg} occur in the Kvemoen Mica Schist (Fig. 42 a). In the hinge zone some biotite porphyroblasts contain open helicitic folds (Fig. 42 b), and in several D_2 pressure shadows to both biotite and garnet porphyroblasts the early folded foliation is preserved (Fig. 42 c). As the porhyroblasts pre-date the D_2 flattening, i.e. they grew mainly during the peak of metamorphism, it is evident that these folds initiated probably as rather open folds before the peak of metamorphism i.e. during D_1. They were then strongly modified during D_2 and their axial plane cleavage mainly developed during the flattening by syntectonic crystallization and recrystallization of micas, generally leading to the formation of a microscopically penetrative axial plane foliation (S_2). Many of the Group I folds are, thus, probably D_{1+2} folds, implying that they initiated during D_1 and were later modified (reactivated) during the D_2 flattening, rather than syn-flattening D_2 folds or D_1 folds sensu stricto in which

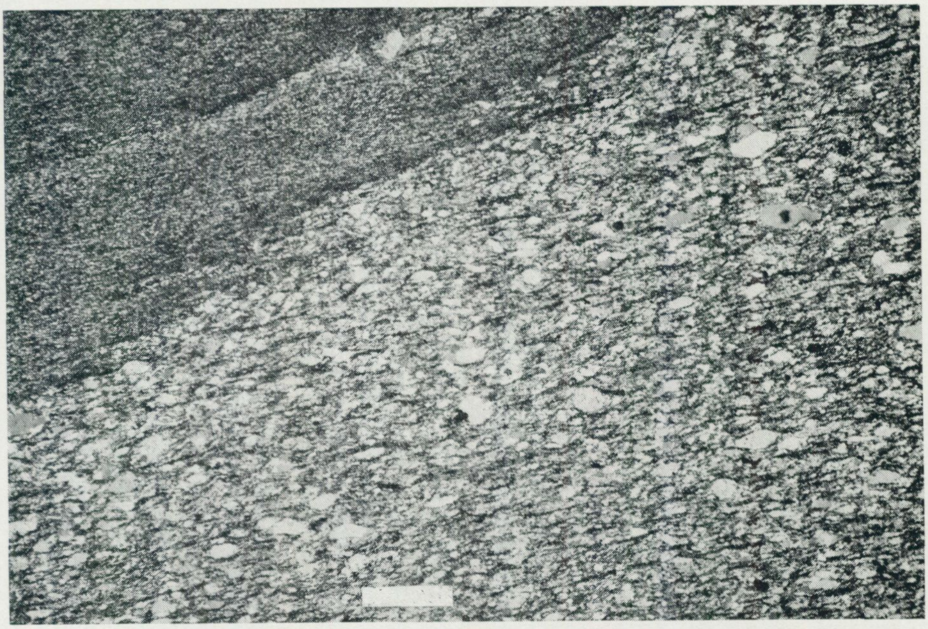


Fig. 40. Penetrative axial plane foliation (S_2) in a Group I fold from the Blåsjö Phyllite, east of Björkvattnet (thin section, scale on photo = 1 mm, partly crossed nicols).

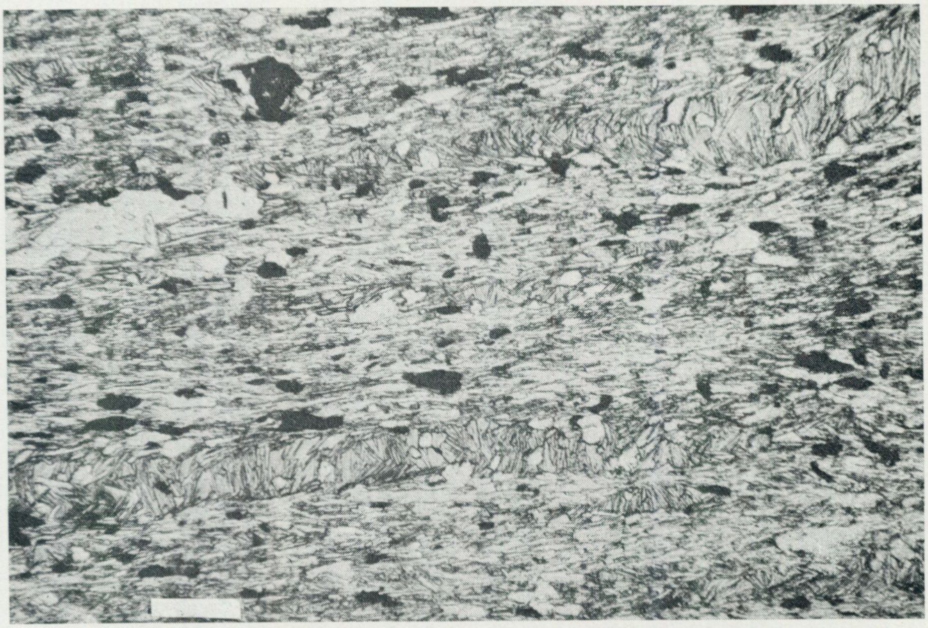
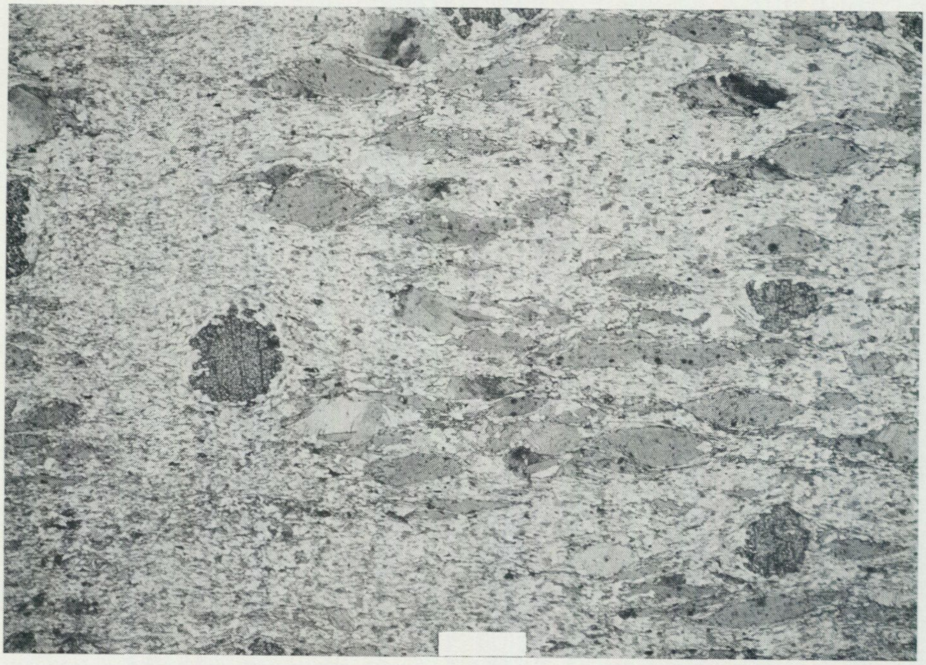
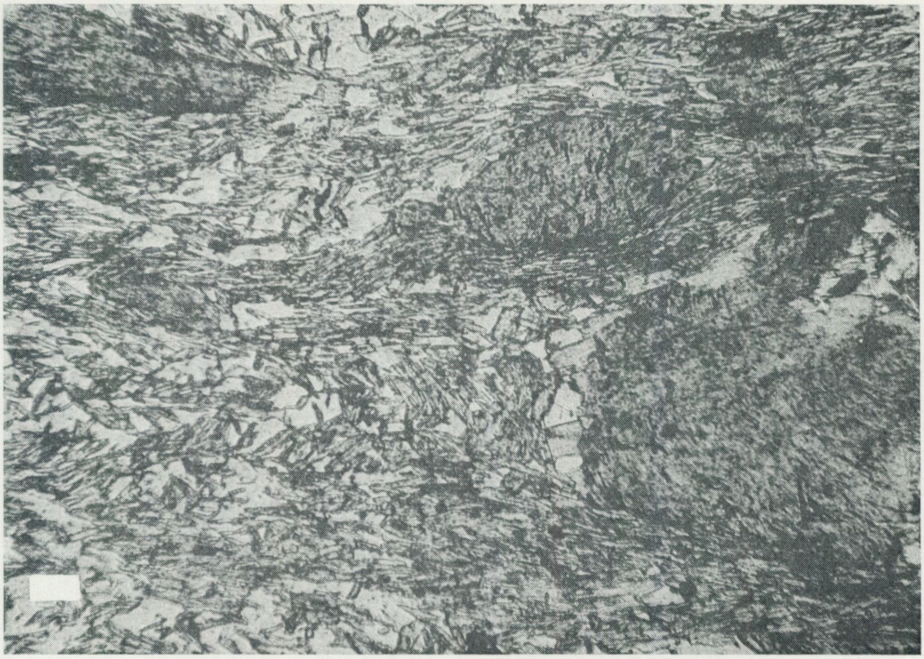


Fig. 41. Almost penetrative axial plane foliation (S_2) with remnants of the bedding foliation (S_{0+1}) in a Group I fold from the Blåsjö Phyllite, north of Stor-Jorm (thin section, scale on photo = 0.1 mm, parallel nicols).



a

b



c

Fig. 42. Microstructures from D_{1+2} folds in the Kvemoen Mica Schist. a = Bedding is marked by a quartz-rich layer which is folded across the photograph. The axial plane foliation (S_2) is penetrative on a microscopic scale. The garnets and most of the biotite crystallized during the metamorphic peak (I_1) and clearly pre-date the D_2 flattening (thin section, scale on photo = 1 mm partly crossed nicols). b = Open helicitic folds in an I_1 porphyroblast of biotite, which is swept around by a penetrative axial plane foliation (S_2). c = Remnants of a folded bedding foliation (S_{0+1}), partly in porphyroblasts of I_1 biotite and partly in a D_2 pressure shadow (thin sections, scales on photos b and c = 0.1 mm, parallel nicols.

the fabric elements were passively deformed and overprinted during D_2 (e.g. the Vesken folds, Zachrisson 1969).

Way-up determinations in the Blåsjö Phyllite demonstrate the presence of relatively large isoclinal folds within the central and western domains. These deduced folds (Fig. 48) are very likely sub-macroscopic folds related to the Group I meso-folds. No real macroscopic Group I fold hinges have been mapped out yet in northern Jämtland, in spite of the presence of several extensive marker units such as, for example, the Portfjället Conglomerate. On the other hand there are some arguments for the existence of major or regional inversions within the Köli sequence (see p. 100). These inversions pre-date the acme of metamorphism and D_2 flattening, as the isograds are not isoclinally folded i.e. they are very likely major D_{1+2} structures.

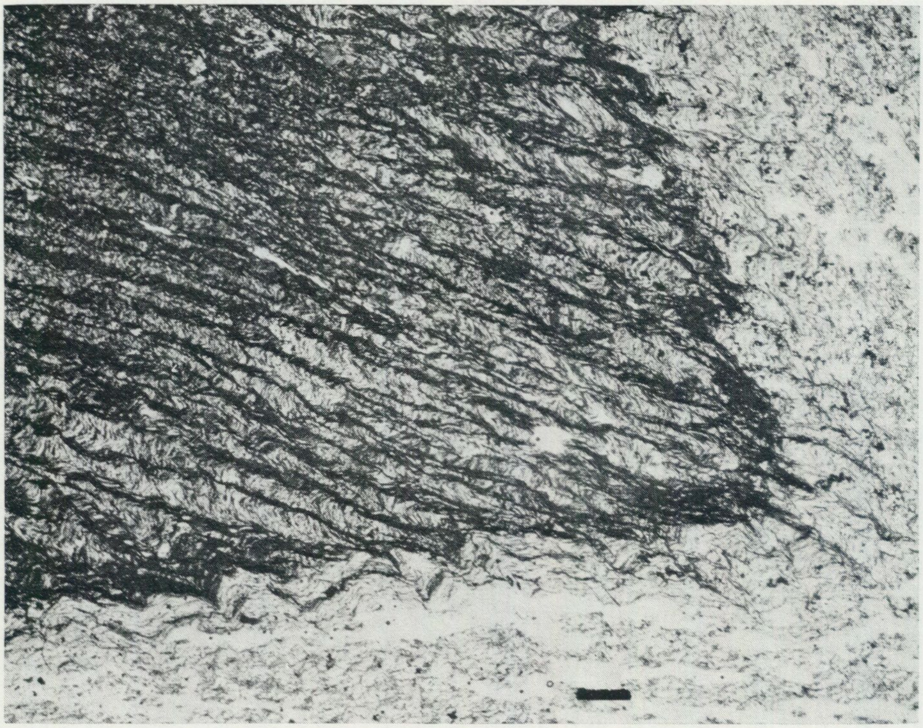


Fig. 43. D_3 fold with a well developed axial plane crenulation cleavage (S_3). Portfjället Conglomerate, from the main fold hinge west of Kvarnbergsvattnet (thin section, scale on photo = 1 mm, partly crossed nicols).

LATE-METAMORPHIC FOLDING (D_3)

A large part of the folds in the Kvarnbergsvattnet area are of Group II type i.e. the axial plane foliation is a clear and well developed crenulation cleavage (Fig. 43). This folding occurred mainly later than the D_2 flattening as the folded surface is generally a more pronounced already flattened S_2 foliation i.e. S_{reg}. In the Blåsjö Phyllite at western Kvarnbergsvattnet, for instance, most of the biotite follows the folded, flattened foliation; only occasionally has biotite crystallized/recrystallized along the S_3 axial plane cleavage. In some areas, however, where the folding has been more intense, there has been significant crystallization of chlorite and micas along S_3. The Group II folds are often sideways-closing with the fold axis parallel to L_{reg} and the axial surface subparallel to S_{reg} (Figs. 44, 45, 46, and 47). It is probable that many of these folds started to develop at different stages during the main deformation period, and there is a complete series of Group I to Group II folds which reflects the progressive character, on a regional scale, of the D_2–D_3 stages of deformation.

Fig. 44. Sideways-closing, northwest-trending D_3 fold in a layered quartzo-feldspathic schist or gneiss, with darker layers rich in biotite and hornblende. Blåsjöälven Formation, north of Gäddede.

Sideways-closing Group II folds which fold the main foliation (S_{reg}) and the pegmatitic neosome are common in the Seve units. Fold axes are parallel or subparallel to L_{reg}, which is commonly a marked quartz-feldspar striation (Fig. 39); the axial plane foliation is often weakly developed, the folded foliation being most pronounced. In the central domain only scattered Group II meso-folds have been found (Fig. 45); to the north of the Kvarnbergsvattnet area, however, several major sideways-closing folds with the same structural characteristics as the Portfjället folds have been mapped out at this structural level (Plate 1).

The most conspicuous structures in the western domain are the major folds clearly defined by the Portfjället Conglomerate. Parasitic folds are found in most outcrops east of Portfjället and around the western end of Kvarnbergsvattnet. In the Haraön Phyllites between Björkvattnet and Långviken, no good marker units occur and the asymmetry of the meso-folds have been used to delineate the macro-folds (Fig. 48). Both the Portfjället Conglomerate and the Skogsbäcken Volcanites are surrounded by less competent, often micaceous metasediments,

Fig. 45. Sideways-closing D_2-D_3 fold from the Lillvattnet Formation, southern shore of Kvarnbergsvattnet. The fold axis is parallel to L_{reg} and the axial plane foliation is a crenulation cleavage.

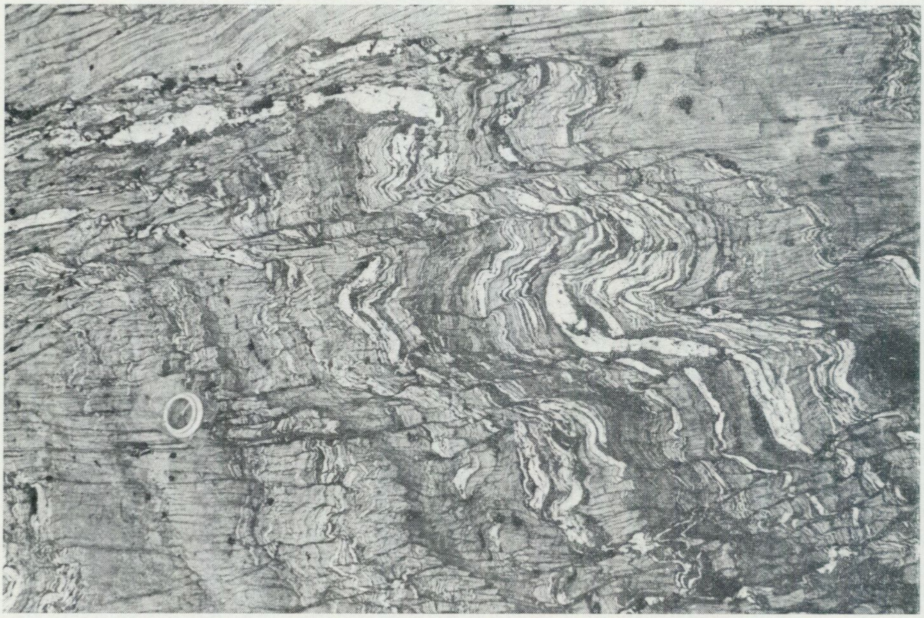


Fig. 46. Sideways-closing D_3 folds with almost vertical fold axes, which are parallel or subparallel to a striation lineation. The striation in turn is parallel to pebble elongation of the nearby Portfjället Conglomerate. Brännälven Formation, Tvärlidklumpen.

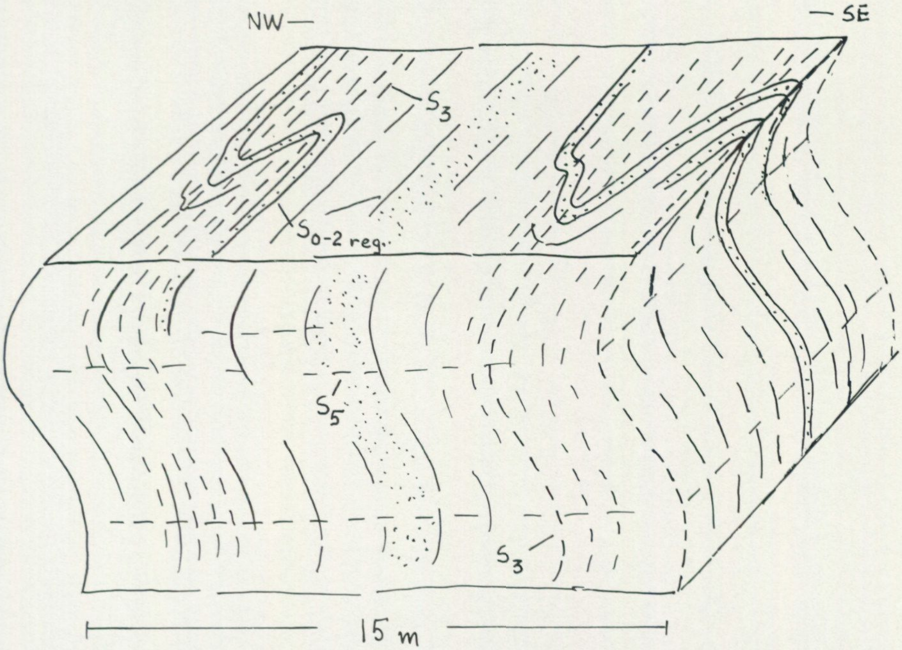


Fig. 47. Schematic illustration of intrafolial sideways-closing D_3 folds in the northern part of Brännälven Formation. The fold axes are almost vertical due to the D_4-D_5 folding, and parallel to a striation lineation (L_{reg}), which in turn is parallel to the elongation of the conglomerate pebbles in the nearby Portfjället Conglomerate. The axial plane foliation is a coarse crenulation cleavage. There is no recrystallization of chlorite or white micas along the cleavage planes.

and competence differences between the different units very likely had a strong influence on their behaviour during the deformation. In particular, the Haraön Phyllites in between the volcanites and the often quartz-rich, more competent Blåsjö Phyllite have very likely been subject to strong shear movements. Probable and apparent shear zones are marked as minor thrusts on the map (Plate I); however, cataclastic rocks have not been found in these zones.

The Portfjället folds are generally of Group II type. It is suggested here that they formed as major D_3 sideways-closing folds, which during subsequent stages of deformation (D_4 to D_5) were refolded and so achieved their present configuration. The axial plane foliation (S_3) to the Portfjället folds can be followed from Portfjället and the western end of Kvarnbergsvattnet towards the northeast to Långviken as a generally well developed crenulation cleavage (Figs. 48 and 49). In the Långviken area, where the folding is more intense, it is often developed as a fine tectonic layering which in broad outlines is parallel to S_{reg} (Fig. 49 c). In this area it is, therefore, sometimes difficult to distinguish between earlier folds, in which the axial plane foliation is of slaty cleavage type, and D_3 folds associated

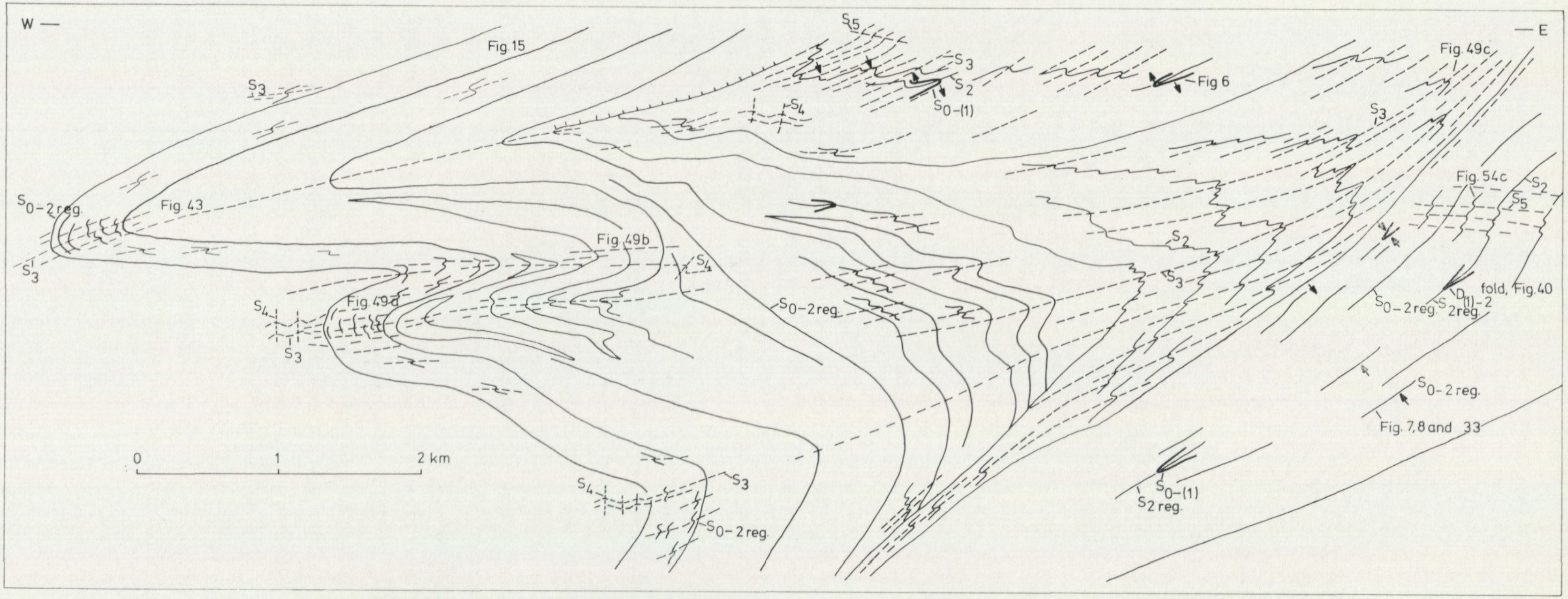


Fig. 48. Cross-section through the Portfjället folds showing schematically the symmetry of meso-folds of different generations. The D_{1+2} folds (coarse lines) are partly deduced from younging directions in graded units (marked with arrows) in the Blåsjö Phyllite.

with the major Portfjället folds. The D_3 fold axes in the Långviken hinge zone have a constant trend towards N and the intersection between S_{reg} and S_3 gives rise to a pronounced N-trending surface intersection lineation. The D_{1+2} or D_2 fold axes, on the other hand, vary in trend between NNE and WNW. In several outcrops between Björkvattnet and Långviken a northwest-trending striation lineation (L_{reg}) is found on S_3 with a marked angle to the D_3 fold axes. In other outcrops a similar lineation is clearly D_3 folded, indicating a rather complex progressive deformation from D_2 to D_3.

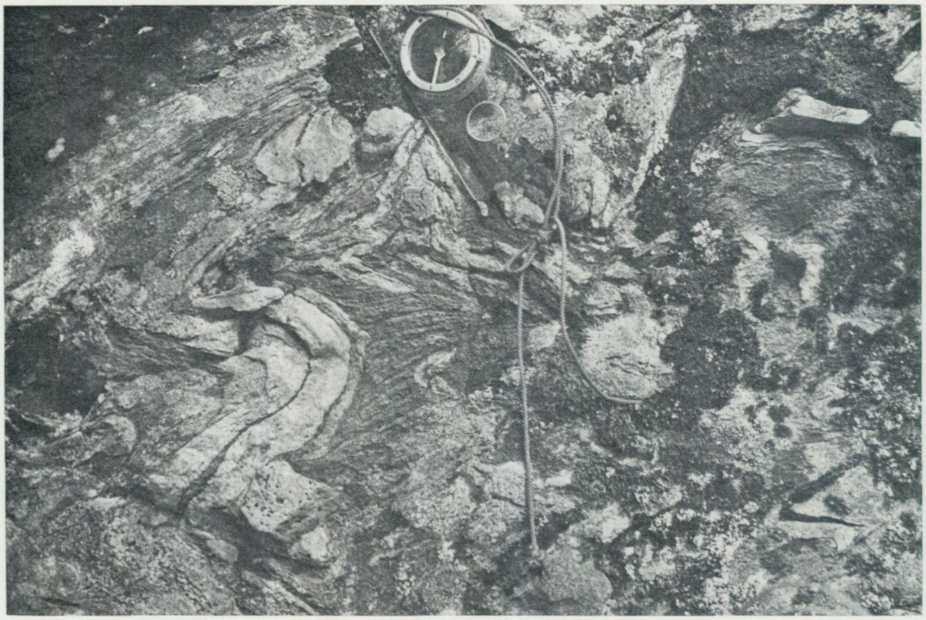
In the Brännälven Formation S_{reg} is often folded in sideways-closing folds (Figs. 46 and 47) and the axial plane cleavage (S_3) is occasionally the most pronounced foliation. In the eastern part of the Brakkfjället Phyllite S_3 is developed as a coarse crenulation cleavage, being axial planar to a major antiformal structure (Figs. 50 and 51); in the western part D_3 folding is less pronounced or absent. From a plunge angle of 20–30° N in the south, the fold axis shallows so that it is horizontal just outside the present area. Further north, in the Blåsjö area (see inset map) it steepens rapidly to 50–90° SSW and the antiformal structure changes into a sideways-closing fold in which the fold axis is parallel to L_{reg}. The major synform at the northern end of the Blåsjö area, the so-called Leipik synform, does not continue southwards into the Kvarnbergsvattnet area. Instead, the axial surface trace can be followed into contact with the Rørvik Group, where it probably is sheared out. The axis of the Leipik synform plunges 45–90° SW, and it is suggested that this synform, like the Portfjället folds and other major sideways-closing folds, was formed during D_3 in connection with strong shear movements.

POST-METAMORPHIC FOLDING (D_4 AND D_5)

Several types of Group III folds, formed during D_4 and D_5, occur in the Kvarnbergsvattnet area (Figs. 52 and 53). They refold and possess a quite different style and orientation to earlier structures. Axial plane cleavages are generally weakly developed. Flexures or minor asymmetric folds with axes trending NE and E–W are most common.

The D_4 folds are parasitic to open antiformal or synformal structures (Plate 1), which deform the major thrust planes and, therefore, post-date the main nappe translation. They probably developed in response to basement instability, during which large culminations, such as the Grong-Olden Culmination and the Børgefjell Window, were formed.

In the northwestern part of the Kvarnbergsvattnet area S_{reg} and S_3 are gradually deformed into a vertical orientation (cross-section A–A^I, Plate 1), and passing westwards into the Limingen Group the dip is reversed (Plate 1). South of Kvarnbergsvattnet S_{reg} increases from a moderate dip in the Kvemoruet Quartzite to vertical in the Blåsjö Phyllite at Högsätern. A similar pattern in the



a

b

c

Fig. 49. D_3 folds and axial plane foliations (crenulation cleavage) related to the major Portfjället folds (cf. Fig. 48).

a = D_3 folded flattened pebbles of quartzite within the Portfjället Conglomerate, Portfjället.
b = Quartz keratophyre and greenschist, Skogsbäcken Volcanite Formation, west of Björkvattnet.
c = Fold hinge in graphitic and grey phyllites. The axial plane foliation is a closely spaced crenulation cleavage with relatively strong recrystallization of chlorite and mica along the cleavage planes. Haraön Phyllites, Viken.

Trondheim region is the central Stjørdalen structure which has been interpreted in various ways, both as a syncline and an anticline. It is suggested here that these structures, which clearly post-date the formation of the S_3 foliation, are part of regional folds or flexures (cf. the cross-section in Fig. 1) formed during D_4.

In the western part of the area and at Högsätern many folds of Group III type occur with flat-lying or moderately dipping axial surfaces (Fig. 54). The most conspicuous folds in the Brännälven Formation and the Brakkfjället Phyllite are often of this type. They fold S_{reg}, S_3 and, further north, also S_4. Fold axes and axial surfaces (including a weak axial plane cleavage) dip towards NNE at varying angles, more steeply around Brännälven compared to the northern part of the area (Fig. 28). In the Brakkfjället Phyllite the macroscopic folds have a wave-length exceeding several hundred metres.

Folds of this type and generation only occur on steep-standing foliations, and possibly these folds formed as a result of gravity-induced settling of steep struc-

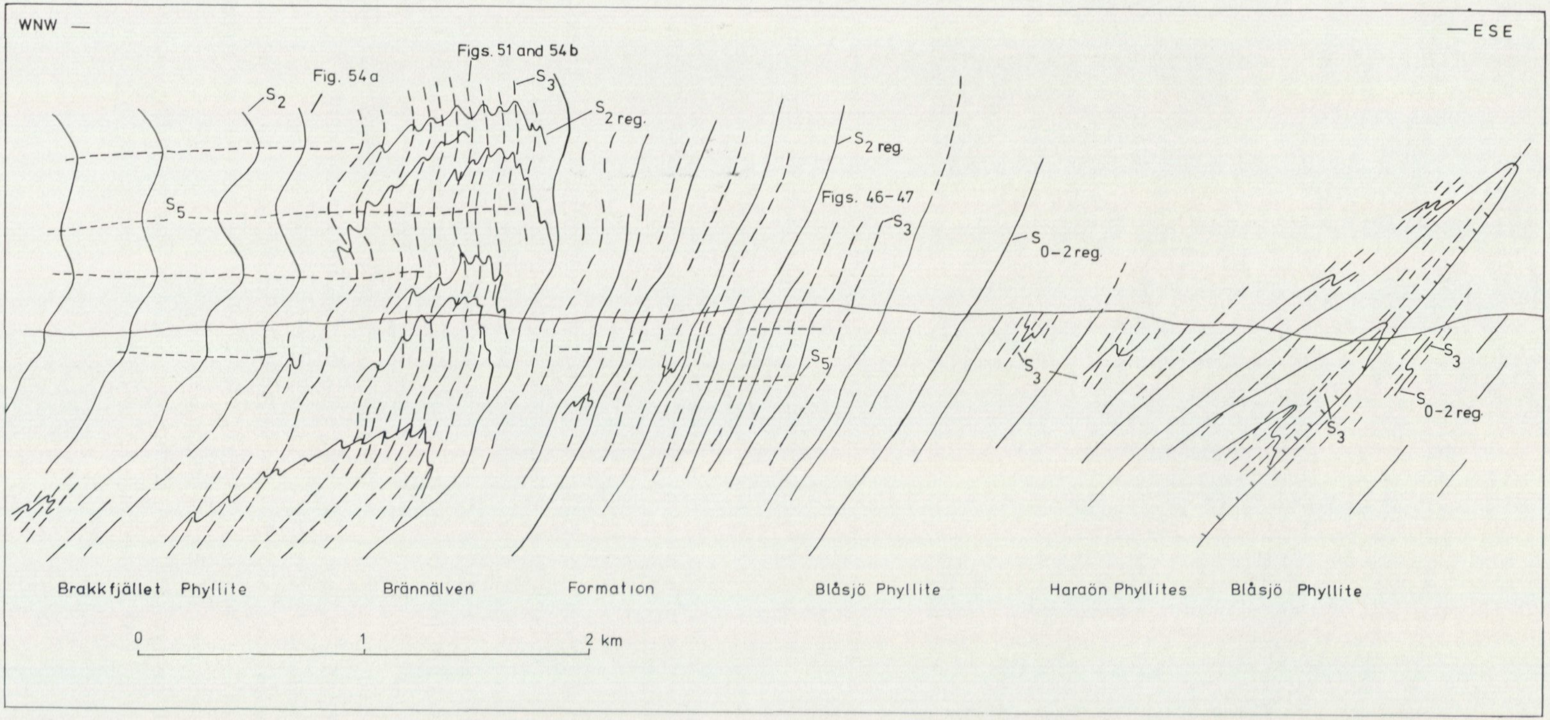


Fig. 50. Cross-section through the western domain north of Kvarnbergsvattnet showing schematically the principle structural features of the $D_3 - D_5$ folding.

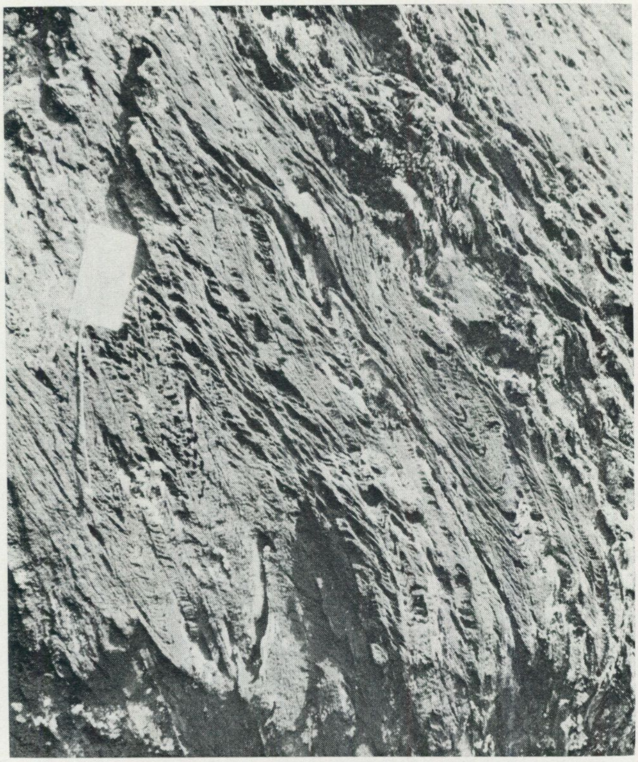


Fig. 51. Coarse axial plane crenulation cleavage (S_3) in the northeastern part of the Brakkfjället Phyllite.

tures which were established mainly during D_4. This stage of deformation is descriptively distinguished as a separate one (D_5), even though it is thought that there is a close connection between D_4 and D_5.

TECTONIC DISCONTINUITIES, THRUST AND SHEAR ZONES

Important tectonic movements took place after the peak of metamorphism, mainly during D_2 and D_3, and resulted in vast nappe translation. Thrust faulting probably also occurred during formation of the D_4 structures. Any pre-metamorphic D_1 cataclastic zones would have been completely recrystallized during I_1 and, thus, can only be inferred from breaks in the stratigraphy. Only those thrust zones or tectonic discontinuities which are stratigraphically apparent and/or accompanied by pronounced mylonites or phyllonites have been marked on the maps.

The presence of an important tectonic discontinuity at the transition between the Seve and the Köli in northern Jämtland is most convincingly demonstrated

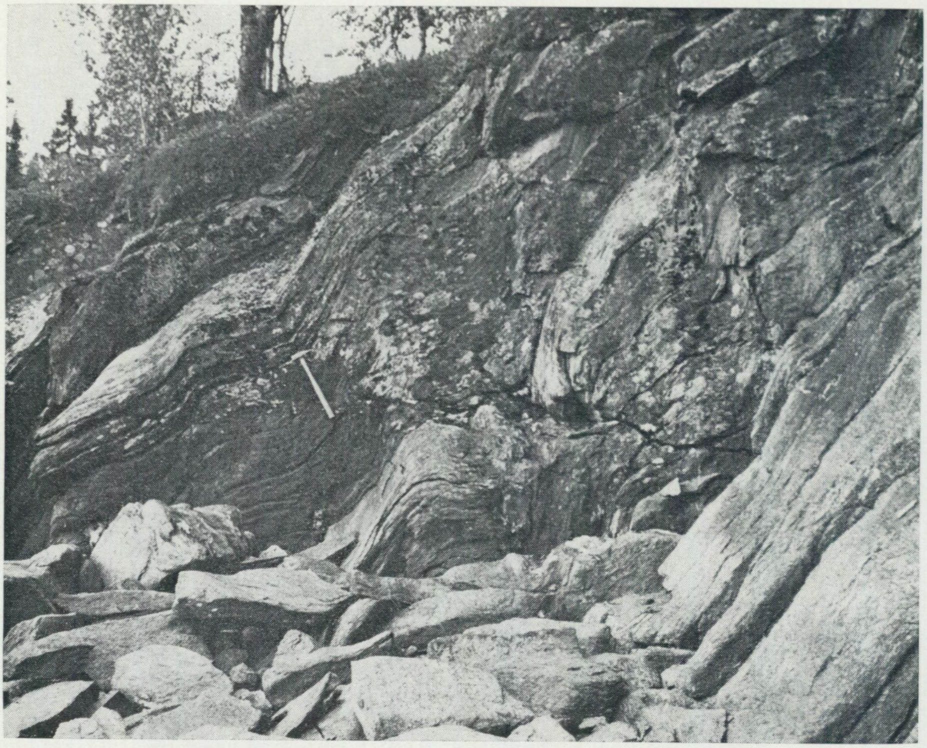


Fig. 52. Open post-schistosity D_4 folds with E-W-trending axes. Lillvattnet Formation, southern shore of Kvarnbergsvattnet.

in the area between Kvarnbergsvattnet and Lejaren (Plate 1), where firstly the Lillvattnet Formation and subsequently the Lillfjället Gneiss, the Blåsjöälven Formation and the Avardo Formation wedge out beneath the Tången Mica Schist unit. At Lejaren typical Köli rocks almost directly overlie a quartzo-feldspathic unit, the Lejaren Formation, which structurally belongs to the lower part of the Seve. Just north of the inset map equivalent units to both the Blåsjöälven Formation and the Lillfjället Gneiss reappear. To a large extent this structural pattern is thought to be caused by extension and sideways spreading during D_2–D_3, and the Lejaren Formation and the Klumplidklumpen units, in particular, can be looked upon as cross-sections through macroscopic, transversely-oriented folds.

The formation of the major sideways-closing folds was probably accompanied by or connected with strong shear movements which have resulted in stratigraphic breaks at different levels. Apparent shear zones in the Haraön Phyllites have been marked as minor thrusts on the main map. The shear zone at the western end of Kvarnbergsvattnet is confirmed by the slingram measurements.

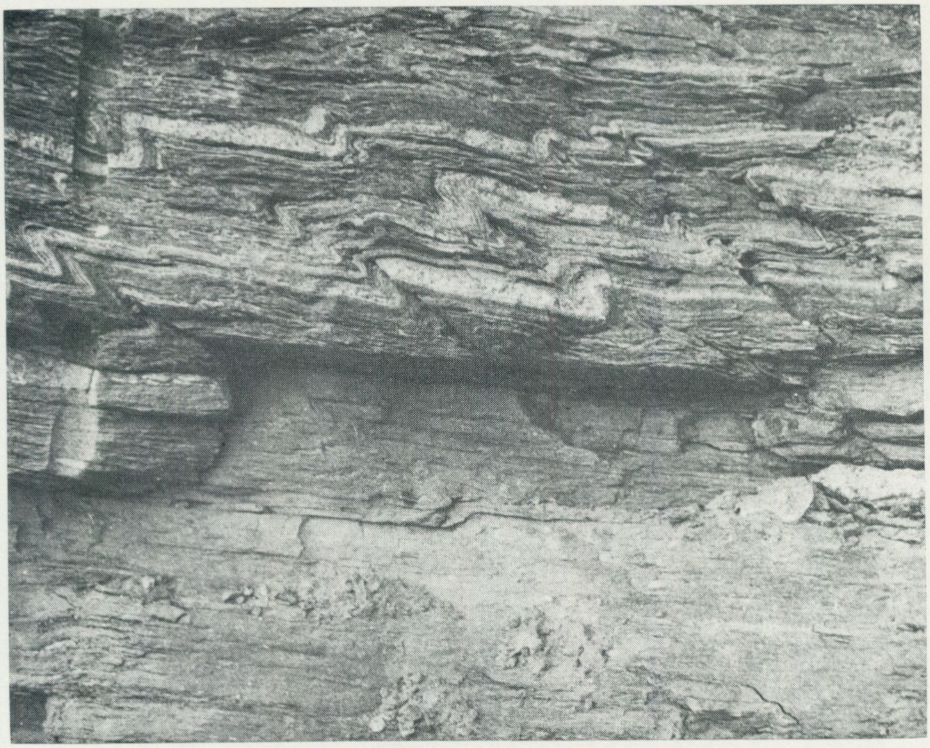
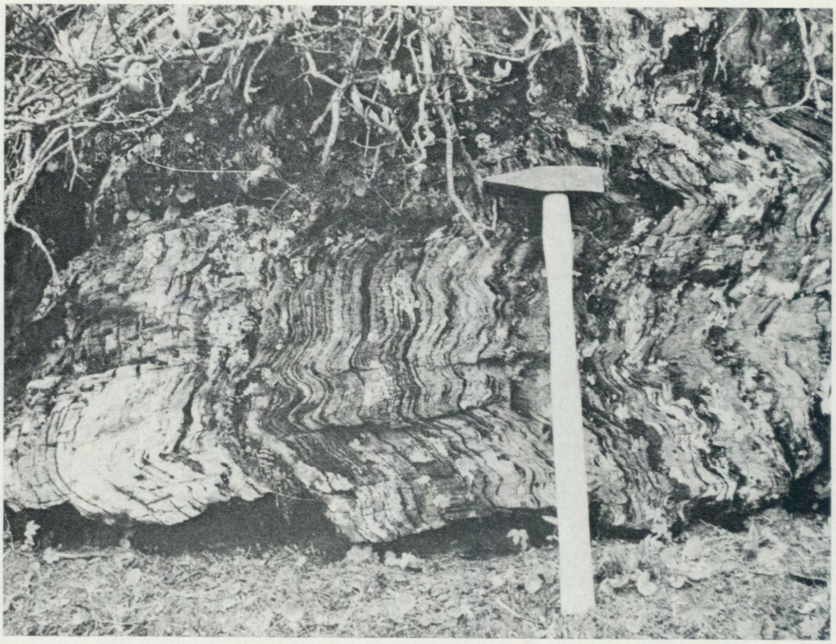


Fig. 53. Asymetric post-schistosity D_4 folds with northeast-trending axes. Lillvattnet Formation, south of Kvarnbergsvattnet.

Nothing is known at present regarding its continuation and regional importance. It is possible that a major D_3 discontinuity exists at the base of the Haraön Phyllites from Kveli to Långviken and continues northwards along the partly dashed line on the inset map, thus cutting out the lower part of the Blåsjö Phyllite in the northernmost part of the area.

It cannot be excluded that the joint sole thrust plane of the Gellvernokko–Leipik Nappes (Zachrisson 1969) continues within the Brännälven Formation southwards from the Blåsjö area and through the Kvarnbergsvattnet area down to the Grong Culmination. As neither stratigraphic breaks nor mylonites have been found in the Brännälven Formation, this thrust zone is not marked on the map.

From the map it is clear that the Holand Formation, the Kvemoruet Quartzite and the Björnhögen Formation successively wedge out, and north of Kvarnbergsvattnet the garbenschistose Blåsjö Phyllite is found directly overlying the Ankarede Volcanites. Northeast of the map area, equivalent units to the Kvemoruet Quartzite and the Björnhögen Formation reappear. The question



a

b

c

Fig. 54. D_5 folds with northeast-trending axes.
a = From the northwestern part of the Brakkfjället Phyllite. The regional foliation parallel to bedding (S_{0-2}) is folded.
b = From the northeastern part of the Brakkfjället Phyllite. D_5 folds deforming coarse S_3 crenulation cleavage, which is axial plane foliation to the major antiformal fold in the eastern part of the Brakkfjället Phyllite.
c = From Högsätern. D_5 kink-folds deforming the regional foliation (S_2).

whether this is a depositional feature, i.e. an unconformity, or a tectonic discontinuity is left open. No cataclastic rocks have been found at the base of the Blåsjö Phyllite; at the same time there are no transgressive sediments at this level between Kvarnbergsvattnet and Småvattsbränna.

During the D_2–D_3 shear movements the rocks were locally strongly deformed and transformed into mylonites or phyllonites. Subsequent recrystallization after the movements had ceased lead to the formation of blasto-mylonitic textures where the matrix is exceptionally fine-grained (0.01 mm or less). More or less blasto-mylonitic gneisses are common in the Seve at many levels, indicating a rather penetrative D_2 shear deformation. It is likely that the shear movements were concentrated in certain zones as the temperature was successively lowered. In some units of garnet-mica schist in the Lillvattnet Formation all the garnets are D_2 rotated (Fig. 36) and the matrix is more fine-grained compared to the adjacent schist. After the rotation the garnets continued to grow and a new outer rim was formed across the often discordant, flattened external foliation. This

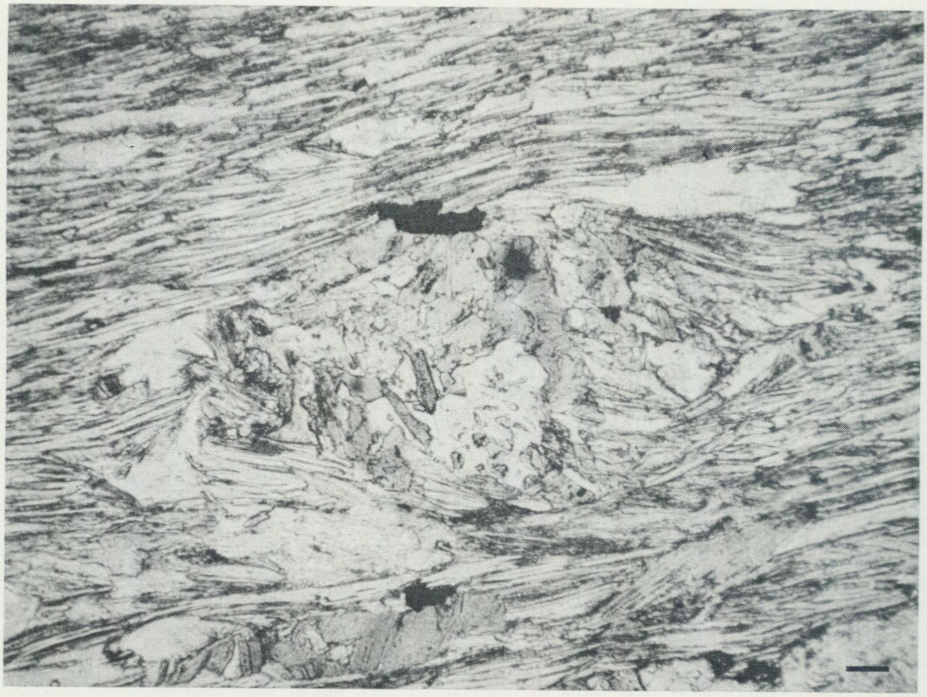


Fig. 55. Phyllonite with remnant of the original rock, from the base of the Kvemoen Mica Schist, north of Kvarnbergsvattnet (thin section, scale on photo = 0.1 mm, parallel nicols).

indicates that the D_2 shear movements were more intense in these units and took place here during a limited time interval.

The most important tectonic discontinuities and thrust zones within the Kvarnbergsvattnet area occur at the base of the Lillvattnet Formation and between the Lillvattnet Formation and the Kvemoen Mica Schist, where up to 20–30 m thick units of phyllonite and mylonite occur; such zones are best exposed in the Småvattsbränna area. The sudden change in texture (Fig. 27) and tectonic style between the Digerhösen rocks and the Lillvattnet Formation indicates a major D_{2-3} tectonic discontinuity at this level, although no cataclastic rocks are exposed apart from certain blasto-mylonitic gneisses in the upper part of the Digerhösen rocks. At N. Digerhösen, the marginal part of the ultrabasic body are altered to talc-rich, schistose rocks, which very likely took up all possible shear movements at this level. Furthermore, within the Lillvattnet Formation there occur several minor, 1–3 m thick units of talc-rich, ultrabasic schistose rocks which probably acted as shear zones during the D_3 deformation.

The appearance and composition of the phyllonites and mylonites varies considerably. The phyllonites are commonly greyish green in colour and very rich in biotite, muscovite and chlorite; talc is locally present (Fig. 55). Often they

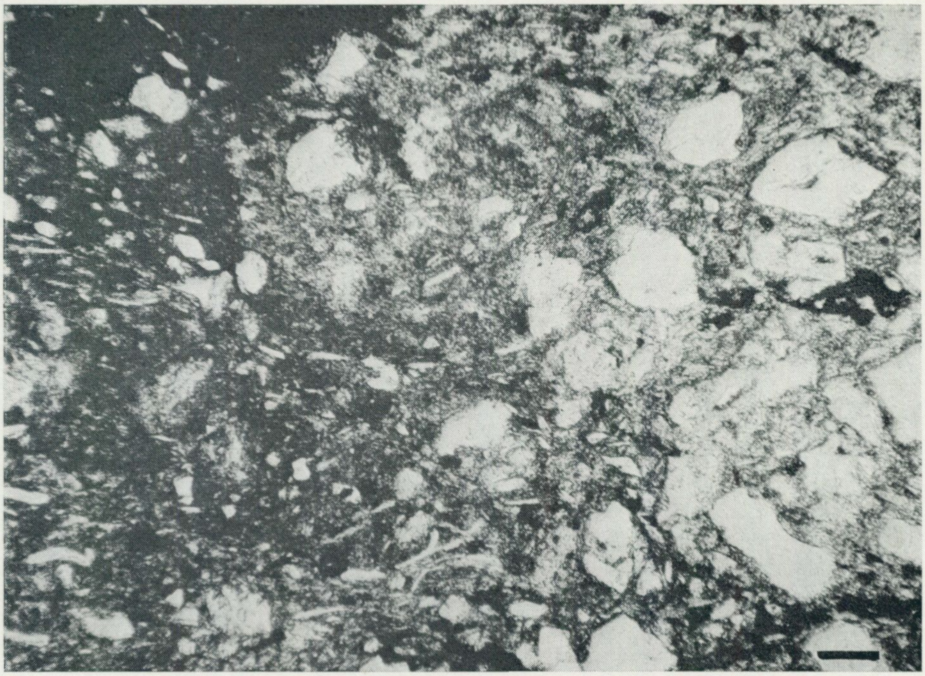


Fig. 56. Mylonite with very weak recrystallization of the crushed material, southeast of Småvattsbränna (thin section, scale on photo = 0.1 mm, under parallel nicols).

are calcareous and strongly graphitic. Their structure is generally wavy or lenticular with quartz-rich lenses swept around by the mica and chlorite-rich phyllonitic foliation. The foliation is, besides, often irregularly folded in contrast to the adjacent more planar units. The textures of many rocks incorporated or affected by these thrust movements are chaotic and include, for instance, broken and granulated plagioclase and hornblende crystals together with recrystallized, randomly oriented chlorite and biotite. The common occurrence of chlorite and biotite, often in contact with muscovite and quartz, show that these movements zones were active after the main metamorphism. The movements also caused retrogression, generally chloritization of the garnets, in the adjacent rock units and retrogressed garnets in the present area are only found in or close to late shear zones (Fig. 26).

In several mylonites from the Småvattsbränna area there occur crushed, non-recrystallized quartz and calcite, indicating very late movements (Fig. 56). In some phyllonites albite, calcite, sphene and biotite grew across the phyllonitic foliation and, thus, post-date the thrust movements (Fig. 57). Exactly the same kind of albite and biotite are found together with garnets and ore-minerals in the tuffites north of Björkvattnet (Fig. 25). Probably all these minerals were formed during local hydrothermal metamorphism related to shear zones.

Fig. 57. Albite and ore minerals growing across a phyllonitic foliation of the same type as in Fig.55. From the base of the Kvemoen Mica Schist, north of Kvarnbergsvattnet (thin section, scale on photo = 1 mm, parallel nicols).

About 2 km north of Viken a minor, 1–2 m thick mylonite zone occurs at the base of the interbedded calcareous phyllite unit. As there is only a very weak recrystallization of the crushed calcite and quartz, it is likely that the mylonitization is related to the D_4 or D_5 movements.

STRUCTURAL CORRELATIONS

A comparison of the deformational sequences between the Kvarnbergsvattnet area and four other areas in Västerbotten (Zachrisson 1969, Trouw 1973, Stephens 1977) and the northern Trondheim region (Roberts 1967) is shown in Table 8 (see back cover). The most important characteristics of each stage of deformation are listed and an attempt is made to correlate the different sequences.

The correlation between the structural sequences of S. Västerbotten (Zachrisson 1969) and the Marsfjällen area (Trouw 1973) differs here in some respects from that made by Trouw (1973), who compared his F_1 and F_2 phases with the pre-F_1 (the Vesken Fold) and F_1 phases respectively of Zachrisson. According to the opinion of the present writer, the F_1 phases of Trouw and Zachrisson show the same general characteristics as the D_2 phases of the Kvarnbergsvattnet and Tärnaby areas (Stephens 1977), during which a penetrative cleavage or schistosity

(S_{reg}) developed axial planar to tight or isoclinal folds. On a mesoscopic scale the Vesken Folds do not appear to have any axial plane cleavage but are clearly transected by S_{reg}, which corresponds to S_1 of Zachrisson and probably also of Trouw (Stephens, pers. comm.).

D_2 was followed in certain domains by folding (D_3) with development of locally intense axial plane cleavage (S_2 in the Marsfjällen area). It is probable that those F_1 folds of Zachrisson which deform a schistosity are of the same generation as the D_3 sideways-closing folds in northern Jämtland. The F_2 phase of Zachrisson comprises in the main the D_4 stage of the Kvarnbergsvattnet area.

According to Roberts (1967) the Stjørdalen fold is a first generation, fan-shaped anticlinal structure. The Hegsjøfjell area, mapped by Foslie, reveals a major example of refolding. Roberts correlates the Stjørdalen anticline with the early Hegsjøfjell fold. In the present author's opinion the Hegsjøfjell fold most likely correspond to the D_3 sideways-closing folds in northern Jämtland; in accordance with these folds it has a clear axial plane crenulation cleavage (F. Kautsky, pers. comm.). On this basis the Verdal Synform (Springer Peacey 1964) is a D_4 fold. The Stjørdalen structure is possibly part of a regional D_4 flexure comparable to the steepening and overturning of the regional foliation in the Kvarnbergsvattnet – Grong areas (cf. the cross-section in Fig. 1).

THE KVARNBERGSVATTNET AREA AS A PART OF THE CENTRAL SCANDINAVIAN CALEDONIDES

REVIEW AND DISCUSSION OF THE USAGE OF THE TERMS SEVE AND KÖLI

Seve and Köli were introduced by Törnebohm (1872) as stratigraphic names in the Scandinavian Caledonides. Seve is an old roman name for the mountain range between Sweden and Norway i.e. the Scandes. The name "Seve mountain" was used on geographical maps of Scandinavia chiefly during the nineteenth century. Köli is derived from Kölen or Kjölfjället which are old but still used names for the mountains between Jämtland and Nord Trøndelag.

Törnebohm (1872) divided the rock sequence of southern Jämtland into the following stratigraphic units:

The Köli group: Garbenschiefer, phyllite etc. corresponding to a part of the Trondheim region.

The Seve group: Quartzite, sparagmite, mica schist, amphibolite and gneiss.

Silurian

Dala sandstone and Cambrian sandstone

Precambrian basement

He supposed this sequence to be a normal stratigraphic one. However, this interpretation was incompatible with the stratigraphy further south, in the Norwegian Mjøsa area, where thick quartzites and sparagmites belonging to the Seve group clearly underlie the Silurian. This problem was solved by Törnebohm (1888) by applying the theory of nappe tectonics for the first time in the Scandinavian Caledonides, when he suggested that a large part of the Precambrian Seve group was thrust over the Silurian.

Törnebohm (1896) later presented the following stratigraphic subdivision for the Central Scandinavian Caledonides:

- Devonian formations(?)
- Silurian formations
  - Upper Silurian
  - Lower Silurian
  - Cambrian (= Primordial)
- Younger Algoncian formations
  - The Seve group
  - The Dalecarlian sandstone group
- Older Algoncian and Archean formations

The Seve group was now divided into a clastic facies, the so-called sparagmite formation, which was autochthonous to parautochthonous, and a crystalline facies, the Åre schists, which were allochthonous and belonged to his Big Thrust Nappe. The name Köli was no longer used, but these rocks were included in the Silurian Røros schist group.

In the description to the county map of Jämtland the mountain schists were divided by Högbom (1920) into Seve and Köli schists in the following way (author's translation):

Hornblende mica schist ('Garbenschiefer') Biotite phyllite Phyllite with limestone	Köli schists
Garnet gneiss and amphibolite with limestone ('Åreschists') Light mica schist and sparagmite schist Augen gneiss Porphyry schist	Seve schists
Mountain quartzites and mountain sandstones	

The terms Seve and Köli were retained as convenient designations for two, petrographically distinct groups of crystalline schists, characteristic of the Caledonian nappe region. The clastic sparagmite formation was no longer assigned to the Seve schists, but was classified among the lower autochthonous or parautochthonous mountain sandstones.

The Augen gneiss and porphyry schist units were distinguished by Asklund (1938) as a separate tectonic unit, the Granite-mylonite Nappe. Furthermore, Strömberg (1955) discovered that a large part of the light mica schists and sparagmite schists with intrusions of Ottfjället dolerite form a separate nappe unit, which he named the Särv Nappe. In his tectonic subdivision of the southern part of the Swedish Caledonides, Asklund (1961) used Seve and Köli as names for two lithologically distinct groups within the Real Seve Nappe, which in turn was a part of the Great Seve Nappe (Table 9, Col. I). At the same time Asklund (1960, 1962) used the name "real Seve nappe" only to embrace the "highly metamorphosed part of the crystalline basement of the Köli schists – the western Cambro-Silurian rocks" – composed of mica schists and gneisses together with amphibolites and marbles, i.e. he clearly distinguished between Köli schists and rocks belonging to the "real Seve nappe".

The major part of the Upper thrust rocks were given the name Seve-Köli Complex by Kulling (in Strand and Kulling 1972) (Table 9, Col. II). In a broad sense he defined Köli as low-to middle-grade metamorphic schists, often of a shaly composition, while the Seve was of higher metamorphic grade (including gneissic rocks) and composed of generally more competent lithologies compared to the Köli. The term "Seve" was also used as a pure tectonic name in the Main Seve Nappe, which comprises Kulling's Middle and Upper thrust rocks. The Storfjäll Nappe Complex (Västerbotten) and the Virihaure Nappe (Norrbotten), which to a large extent are composed of Köli-like rocks, were distinguished by Kulling as separate tectonic unit above his Seve-Köli Complex within the Upper thrust rocks. The lower part of the Storfjäll Nappe Complex is of higher metamorphic grade compared to the immediately lower Köli units, and contain garnet and staurolite.

Zachrisson (1973) introduced the name Seve-Köli Nappe Complex for a major tectonic unit in the metamorphic allochthon (Table 9, Col. III). In Zachrisson's terminology, Seve is used to designate the high-grade, lower part of the complex, which is composed of gneisses and mica schists with significant intercalations of amphibolite. The Seve is overlain, in some areas with tectonic contact, by the Köli, which refers to the low-grade Cambro-Silurian rocks of so-called western facies i.e. marine metasediments intercalated with acid and basic volcanic rocks and tuffites. In northwestern Jämtland Zachrisson (1969) distinguished two nappes – the Gellvernokko and Leipik Nappes – which are composed of Köli lithologies. The Leipik Nappe is overlain in the Grong region by an even higher tectonic unit, the Gjersvik Nappe (Oftedahl 1956). These nappes were, together with the Hattfjelldal Nappe (northwest of Børgefjell, mainly limestone) and S. Storfjäll Nappe, included as Köli nappes in the Seve-Köli Nappe Complex

<table>
<tr><th colspan="3">Asklund 1961</th><th colspan="3">Kulling 1972</th><th colspan="3">Zachrisson 1973</th><th colspan="2">Gee 1975</th></tr>
<tr><td colspan="3">Jämtland-Härjedalen</td><td colspan="3">Swedish Caledonides</td><td colspan="3">Swedish Caledonides</td><td colspan="2">Jämtland - Nord Trøndelag
Tectonic and stratigraphic units</td></tr>
<tr><td colspan="3"></td><td colspan="3">Uppermost thrust rocks</td><td colspan="2">Beiarn Nappe
Rödingsfjäll Nappe</td><td rowspan="5">Metamorphic allochthon</td><td>"Upper Nappe"</td><td>Trondheim Supergroup</td></tr>
<tr><td>KÖLI SCHISTS</td><td rowspan="2">Real Seve Nappe (Egentliga Seveskollan)</td><td rowspan="4">Great Seve Nappe (Stora Seveskollan)</td><td rowspan="2">Upper thrust rocks</td><td rowspan="2">Storfjäll Nappe
SEVE-KÖLI COMPLEX</td><td rowspan="4">Main Seve Nappe</td><td>Köli nappes
- - - - - - -
KÖLI</td><td rowspan="2">SEVE-KÖLI NAPPE COMPLEX</td><td rowspan="2">SEVE-KÖLI NAPPE COMPLEX</td><td>KÖLI SUPERGROUP</td></tr>
<tr><td>SEVE ROCKS</td><td>SEVE</td><td>SEVE SUPERGROUP</td></tr>
<tr><td colspan="2">Särv Nappe</td><td colspan="2" rowspan="2">Middle thrust rocks</td><td colspan="2">Särv Nappe</td><td>Särv Nappe</td><td>SÄRV GROUP (locally on basement)</td></tr>
<tr><td colspan="2">Granite-mylonite Nappe</td><td colspan="2">Granite-mylonite and Augengneiss</td><td>Offerdal Nappe</td><td>CRYSTALLINE BASEMENT and RISBÄCK GROUP</td></tr>
<tr><td colspan="3">Quartzite nappes and Jämtlandian nappes</td><td colspan="3">Lower thrust rocks
Lowermost thrust rocks</td><td colspan="3">Lower thrust units and Parautochthonous sediments</td><td>Lower nappes of Jämtland including Olden Nappe</td><td>JÄMTLAND SUPERGROUP (locally on basement)</td></tr>
<tr><td colspan="9">Basement and autochthonous sediments</td><td>Stable platform</td><td>JÄMTLAND SUPERGROUP BASEMENT</td></tr>
</table>

Table 9. A summary of the recent usage of the terms Seve and Köli.

(Zachrisson 1969), which was delimited upwards by the high-grade Helgeland Nappe Complex and the Rödingsfjäll Nappe.

In a later paper (Gee and Zachrisson 1974) the upper boundary of the Seve-Köli Nappe Complex was placed at the base of the Gula Group in the Trondheim region (Table 10). The terms Seve and Köli were used by Gee (1975 a, b) as names for supergroups on a general lithostratigraphic basis, pending descriptions of local stratigraphic sequences and their correlation (Table 9, Col. IV). The western Trondheim sequence, i.e. the Gula, Støren, Lower and Upper Hovin, and Horg Groups, were referred to as the Trondheim Supergroup (Gale and Roberts 1974) and treated as a separate tectonic unit – the "Upper Nappe" – possibly equivalent to the Helgeland Nappe Complex. One principal reason for this subdivision was that the Trondheim Supergroup contains Lower Ordovician faunas of North American affinity, indicating a different depositional environment compared to the Köli Supergroup, which is thought to have been deposited on the Baltoscandian side of the proto-Atlantic ocean. The "Upper Nappe" belongs in a plate tectonic model (Gee 1975 a) to the Greenlandian plate which overrode the Baltoscandian continental margin, i.e. among other units the Seve and Köli Supergroups, during the Lower Silurian.

This approach implies that the extension of the Köli is more limited than before. Now it only refers to those "eugeosynclinal" rock units which were deposited along the Baltoscandian continental margin, or to rock units which can stratigraphically be correlated with the Björkvattnet–Virisen sequence. Using this approach, it is uncertain whether typical Köli units such as the Brännälven Formation and the Brakkfjället Phyllite belong to the Köli at all as these units probably correspond to the Gula Group in the northern Trondheim region (see table 10 and discussion later).

In the present author's opinion, there will always be a need for overlapping regional names of informal character such as Seve and Köli for large lithological units with similar appearance and a specific tectonic position. It is, therefore, suggested in this paper, that Seve and Köli should be used in a broad sense as names for two major litho-tectonic units within the allochthon of the Scandinavian Caledonides. It is then admissible to distinguish and name various lithostratigraphic units (formations, groups, supergroups), and tectonic units (e.g. the Leipik Nappe, the Storfjäll Nappe Complex etc.) within the Seve and Köli.

In the central Caledonides the Seve is underlain, in turn, by the Särv and Offerdal (Granite-mylonite) Nappes. The names Real, Great or Main Seve Nappe should be avoided and the name Metamorphic allochthon can be used instead for the allochthon as a whole (Table 9, Col. III).

In southern Västerbotten and in Jämtland the Köli is delimited downwards by a pronounced tectonic discontinuity, which at the same time is accompanied by a change in lithology. In the Kvarnbergsvattnet area the boundary is transitional (cf. p. 16 and Plate 1), being defined by a zone of discontinuities and including rocks (the Lillvattnet Formation – Tången Mica Schist) which are difficult to classify as Seve or Köli. If there is no pronounced tectonic boundary between the Seve and Köli in northern Västerbotten (Stephens 1977) and in Norrbotten (Kulling 1964 and in Strand and Kulling 1972), only lithological criteria or lithostratigraphic correlations can be used to distinguish these units from each other.

The upper boundary of the Seve-Köli Nappe Complex is placed at the Rödingsfjäll–Helgeland discontinuities. The Rørvik and Limingen Groups and the Gjersvik Nappe, which all consist of typical Köli lithologies, are accordingly included in the Seve-Köli Nappe Complex.

Placing the upper boundary of the Köli at the base of the Helgeland Nappe Complex implies that the whole Cambro-Silurian rock sequence of the Trondheim region corresponds to the Köli north of the Grong Culmination – and represents simply the western continuation of the upper part of the Seve-Köli Nappe Complex (Table 10).

The Seve and Köli units were probably deposited in two different geotectonic environments (p. 36). It is thought that Seve rocks to a great extent are non-marine, Precambrian metasediments and metavolcanites formed during a period of rifting and break up of the Baltoscandian and Greenlandian shields. It cannot be excluded that strongly deformed basement rocks also occur in the Seve. The Köli, on the other hand, consists of marine, Lower Palaeozoic metasediments and metavolcanites which probably formed within or marginal to the proto-Atlantic ocean during ocean-floor generation and later plate convergence and collision.

The most important characteristics of the contrasting Seve and Köli lithologies are listed below:

SEVE	KÖLI
Quartz-rich to quartzo-feldspathic schists and gneisses (metasandstones).	Phyllites to mica schists (metapelites).
Micaceous para-gneisses, often migmatitic.	Large units of micaceous to quartz-rich calcareous phyllites to metagreywackes, often with graded bedding.
(Graphitic rocks are rarely met with.)	Graphitic (organic matter) rocks are common.
(No fossils have been found.)	Limestones and phyllites with Ordovician and Silurian fossils.
(No conglomerates have been found.)	Monomict and polymict conglomerates or conglomeratic units occur at several stratigraphic levels.

Extensive units with alternating amphibolites (subalkalic metabasalts) and micaceous to quartzo-feldspathic schists or gneisses (arkosic metasandstones). (No acid volcanites have been found.)	Several extensive units with quartz keratophyres and greenschists – greenstones – amphibolites (more or less spilitic metabasalts).
Thick and extensive units of non-pillowed amphibolites.	Extensive units of often pillowed greenstones.
(Trondhjemitic or keratophyric intrusive rocks are only occasionally met with.)	Intrusions of trondhjemite and quartz keratophyre at several levels.

The metamorphic grade within the Seve-Köli Nappe Complex is highest in the central part of the Seve. From there it decreases both upwards and downwards, and the biotite zone is attained in the lower part of the complex in several areas. At the transition to the Köli, the metamorphic grade is always higher in the Seve. In the central Trondheim region, which according to the present definition belongs to the Köli, the metamorphic grade reaches its maximum with index minerals such as kyanite, sillimanite and staurolite in the eastern part of the Gula Group. In the lower part of the Storfjäll Nappe Complex staurolite and garnet occur. The lower Köli sequence in the Kvarnbergsvattnet area belongs to the garnet-hornblende zone and the basic rocks are metamorphosed to amphibolites. This means that large parts of the Köli are of higher metamorphic grade than large parts of the Seve. Furthermore, since the isograds often are discordant to stratigraphic boundaries and to tectonic discontinuities, metamorphic grade cannot be used as a crucial criterion for the litho-tectonic affinity of certain rock units.

By using the names Seve and Köli in the way described above, the rock sequences in most areas of the Central Caledonides can simply and descriptively be divided into broad, clearly defined litho-tectonic units, and it is possible to use these names in present and future works without causing confusion. In accordance with its former usage the name Köli then also refers to the Cambro-Silurian of "western facies", which by lithology and tectonic position differs from Cambro-Silurian of "eastern facies" along the Caledonian Front.

STRATIGRAPHIC AND TECTONIC CORRELATIONS

The continuation of the formations recognized in the Kvarnbergsvattnet area southwards towards the Grong Culmination and northwards into the Blåsjö area is shown on the inset map (Plate I), which also shows the relationship eastwards and westwards to the Seve and Grong sequences respectively. In order to discuss more regional correlations with areas in southern Västerbotten and in the Trondheim region, a correlation table has been compiled (Table 10). Lithologically similar units with equivalent tectonic or structural position have been placed beside each other in this table, which differs then from a stratigraphic correlation table, where lithology and/or age determine the relative position of different units.

The correlations are based mainly on maps and papers by Carstens (1960), Foslie (1926 and various maps), Gee (1975 a and b), Kisch (1962), Nilsson (1964), Olesen et al. (1973), Rui (1972), Springer Peacey (1964), Strand and Kulling (1972), Wolff (1960, 1967, 1973), Zachrisson (1964, 1969, 1973), and others and also on the author's own visits to the Nordli, Hegsjøfjell and Inndalen–Meråker areas.

In at least four areas the younging direction has been determined at the transition from one formation or group to another by means of fossils or from the direction of derivation of conglomeratic pebbles (Table 10):

1. In the western part of the Björkvattnet–Virisen area the fossiliferous Ashgillian limestone is underlain by the Llandoverian Broken Series and, hence, the rocks are inverted.
2. The pebble material of the Limingen Group and of polygenous, volcanogenic conglomerates at the transition to the Gjersvik Nappe originated from the latter (Foslie 1926) and, thus, the younging direction is easterly. Due to locally pronounced D_4 folding the Gjersvik unit structurally underlies the Limingen Group in the area west of Kvarnbergsvattnet (cf. the cross-sections in Fig. 1).
3. In the Meråker area the L. Fundsjø conglomerate contains pebbles from the overlying Fundsjø group (Chaloupsky & Fediuk 1967). The younging direction is, thus, towards the east and the volcanites are inverted.
4. In the eastern Hølonda–Horg area fossils and conglomerates indicate a westerly younging direction for the Støren–L. Hovin sequences.

Local, mesoscopic way-up determinations in the Kvarnbergsvattnet area (Fig. 48) are too scattered and non-systematic to establish anything but early, pre- to synmetamorphic folding.

The rock units corresponding to the Tjopasi Group (Table 10, Col. III), i.e. the lower part of the Köli, are thickest in Västerbotten and northern Jämtland. In the Tännfors area they are thin, and further south on the western side of the Riksgränsen Antiform, the Tjopasi units are often completely missing.

Most of the ultrabasic rocks in the Seve-Köli Nappe Complex occur in the upper Seve and the lower Köli. Serpentinite conglomerates, probably of Middle Ordovician age by analogy with the fossiliferous, Llanvirnian Otta conglomerate, are found in several areas in the lower part of the eastern Köli.

The thick, generally calcareous and often turbiditic greywacke – phyllite unit (Lövfjäll "Series", Lasterfjäll Calcareous Phyllite and Blåsjö Phyllite) is thought

NORTHERN TRONDHEIM REGION	GRONG DISTRICT - NORTHERN JÄMTLAND	NORTHERN JÄMTLAND & SOUTHERN - CENTRAL VÄSTERBOTTEN		
	HELGELAND NAPPE COMPLEX (mica schist, gneisses, granitoid intrusive rocks, amph.)			
	GJERSVIK NAPPE-GROUP (greenstone, gabbro, trondhjemite)			
UPPER HOVIN GROUP (sst., phyllite, polymict cgl.) LOWER HOVIN GROUP (congl. sst., meta-rhyolite, diorite, limestone, volcanogenic cgl.)	LIMINGEN GROUP (often conglomeratic calc. phyllite and sst., conglomerates, limestone, metabasite)			
STÖREN GROUP (metabasite, qz keratoph.)	RØRVIK GROUP (phyllites, often graphitic and quartz-rich, metabasite)			
GULA GROUP (phyllites to schists, often graphitic, metabasite, migmatitic gneiss)	BRAKKFJÄLLET PHYLLITE			
	BRÄNNÄLVEN FORMATION	LEIPIK NAPPE		
		Phyllite, greenschist, qz-porphyry, limestone, graphitic and calc. phyllite	REMDALEN GROUP	
GUDÅ-HEGSJØFJELL CONGLOMERATE	PORTFJÄLLET CONGLOMERATE	REMDALEN QUARTZITE CONGLOMERATE		
FUNDSJØ GROUP (metabasite, qz keratoph.)	SKOGSBÄCKEN VOLCANITE FORMATION	STEKENJOKK and LASTERFJÄLL QZ KERATOPH. and GREENSCHIST	LASTERFJÄLL GROUP	
SULÅMO GROUP (L. Fundsjø cgl., grey and black phyllites, calc. metasst., metabasite)	HARAÖN PHYLLITES	Grey and graphitic phyllite LASTERFJÄLL GREENSCHIST		
KJØLHAUGEN GROUP (grey and calc. phyllites, metagreywacke with cgl., metagabbro) SLÅGAN GROUP (black phyllite and metasst.) KJØLHAUGEN GROUP Garbenschiefer, calc. phyllite, metagabbro in the TÄNNFORS AREA	BLÅSJÖ PHYLLITE	LASTERFJÄLL CALCAREOUS PHYLLITE (metagabbro in the upper part)		VIRIS QUARTZITE LÖVFJÄLL PHYLLITE BROKEN SERIES
Graphitic phyllite, greywacke, polymict cgl., limestone, quartzite, metabasite, ultramafite in the TÄNNFORS AREA	HOLAND FORMATION KVEMORUET QUARTZITE	BELLOVARE FORMATION (greensch., limest., quartzite, quartzite cgl.)		SLÄTDAL LIMESTONE VOJTJA CONGLOMERATE
	BJÖRNHÖGEN FORMATION	Dark phyllite, greywacke, polymict cgl., limestone	TJOPASI GROUP	GILLIKS SERIES
	ANKAREDE VOLCANITE FORMATION	Greenschist, qz keratoph.		SEIMA SERIES
	KVEMOEN MICA SCHIST KVARNBÄCKEN CONGLOMERATE	Dark phyllite Serpentinite and quartzite cgl.		RO SERIES
		Varied sed. and volc. rocks		
	LILLVATTNET FORMATION			
	SEVE UNITS			

Table 10. Regional correlations within the Seve-Köli Nappe Complex of the central Scandinavian Caledonides. Abbreviations: cgl — conglomerate, qz — quartz, sst — sandstone.

to be equivalent to the Kjølhaugen Group in the Trondheim area. Llandoverian graptolites occur in the Broken "Series" which underlies the Lövfjäll "Series" in the type area (Kulling 1933). In the Kjølhaugen area, similar fossils have been found in the Slågån Group which occurs structurally within the Kjølhaugen Group. On the assumption that the correlation between the Lövfjäll "Series" and the Kjølhaugen Group is valid, the Slågån black shales should be older than the metagreywackes (Gee and Zachrisson 1974). According to Wolff (1976), the Kjølhaugen Group is of Upper Ordovician age and stratigraphically equivalent to the Upper Hovin Group in the western Trondheim sequence, while the Slågån Group is the youngest unit in the eastern Trondheim region and forms the core of an overturned syncline.

The Haraön Phyllites most likely correspond to the upper part of the Sulåmo Group, i.e. the Meråker Phyllite, in the Trondheim region.

West of the phyllite–greywacke unit there occurs both south and north of the Grong–Olden Culmination an extensive volcanite unit (the Hersjø–Fundsjø –Skogsbäcken–Stekenjokk volcanites) which forms a major marker unit. The volcanites are overlain by a quartzite conglomerate (the Gudå–Skjärkerstøtarna –Hegsjøfjäll–Portfjället–Remdalen conglomerate) which is often associated with limestone. Subsequently there follows a thick unit (the Gula–Sonvass–Brännälven–Rørvik–Remdalen units) composed mainly of often graphitic metasediments with layers of metabasites, which are especially well developed in the northern areas. Calcareous phyllites similar to the Brakkfjället Phyllite are also found in the Gula Group, whilst polymict conglomerates and limestones occur in the eastern parts of this and equivalent units on both sides of the Grong–Olden Culmination. In the Hegsjøfjäll area graphitic phyllites and usually quartz-rich phyllites to mica schists are the dominant rock types of the Gula–Sonvatn Group.

The metamorphic grade is somewhat higher in the Hegsjøfjäll area compared to the areas north of the Grong Culmination, and west of the Hegsjøfjäll conglomerate the phyllites are garnetiferous and the metabasites amphibolitic. As the eastern part of the Gula–Sonvass Groups is followed southwards, the metamorphic grade increases and, in the Meråker and Tydal areas, kyanite, sillimanite and staurolite occur and the rocks are in part migmatitic. From this central zone the metamorphic grade decreases both westwards and eastwards. The presence of conglomerates and limestones in these higher grade rocks, indicates that they represent more strongly metamorphosed Köli lithologies.

The only fossiliferous locality at this level is situated at Nordaunevoll, where Tremadocian graptolites occur in dark phyllites associated with the volcanic Hersjø Formation. If the correlation between the Hersjø, Fundsjø and Skogsbäcken volcanites is correct and if the younging direction is easterly in the Meråker area, then it is probable that these volcanites are Lower–Middle Ordovician in age (equivalent to the Ankarede volcanites), and that also the rock sequence of the western Kvarnbergsvattnet area is inverted. The inversion line is most likely located in the central part of the Blåsjö Phyllite. Here the isoclinal D_{1+2} folds, which possibly are meso-structures to this early inversion, are most frequent.

There are some other arguments for the proposed inversion:

1. In the tectonic model it is suggested that the mixed acid-basic volcanicity occurred in an archipelago-island arc environment which developed in connection with plate convergence and subduction during the Ordovician. This phase in the tectonic evolution pre-dates the deposition of the flysch-type phyllite–greywacke unit (i.e. the Blåsjö Phyllite etc.). Interpreted in this way, the tectonic evolution picture supports an inversion as it is unlikely that a new period of mixed, probably island arc volcanicity, post-dated deposition of the Silurian Blåsjö Phyllite.
2. Accepting a Llandoverian age for the boundary between the Broken and Lövfjäll "Series" (Lasterfjäll Group) and a Lower to Middle Silurian age for the deformation and metamorphism of the Seve-Köli Nappe Complex (Gee 1975 a), there is barely sufficient time for deposition of such a thick sequence as that represented in the Lasterfjäll and Remdalen Groups (Table 10).
3. The location of the sulphide ores at Björkvattnet and Stekenjokk in the structurally lower part of the associated, largely pyroclastic volcanites (Zachrisson 1971, Juve 1974); most stratiform, volcanogenic (sedimentary-exhalative) deposits are found in often graphitic, pelitic metasediments near the top of pyroclastic volcanic piles (Stanton 1972). Also the unilateral position of the "alteration assemblage" zone and the metal zoning of the Stekenjokk ore body indicate that the volcanites, on the whole, are inverted (Juve 1977).
4. According to the opinion of the present author the Brännälven Formation corresponds to the Rørvik Group in the Grong district and the Gula Group in at least the Hegsjøfjell area (northernmost Trondheim region). Most authors have favoured a pre-Tremadocian age for the Gula Group, whereas others have suggested Ordovician/Silurian (cf. Gale and Roberts 1974). It is, thus, unlikely that the Brännälven Formation and the Brakkfjället Phyllite should be the youngest units in the Kvarnbergsvattnet area, younger than the Portfjället Conglomerate, the Skogsbäcken Volcanite Formation, the Haraön Phyllites and the Blåsjö Phyllite, the base of which is supposed to be of Llandoverian age (Zachrisson 1969).

Besides the Rørvik Group (Brännälven Formation) the western Köli north of the Grong Culmination consists of the Limingen Group and the Gjersvik Nappe-Group. The Limingen Group is probably equivalent to the Hovin Groups in the Snåsa Synform and the northwestern part of the Trondheim region. No fossils have been found in the Limingen Group but the Snåsa Limestone has yielded fossils of probable Middle Ordovician age. The Gjersvik Nappe is

intruded by gabbroic, dioritic and trondhjemitic rocks. Intrusives of this type are absent in the Limingen Group, but these lithologies are represented in the pebble material in the conglomerates between the two units and within the Limingen Group (Foslie 1926).
This indicates:

1. that the intrusions were closely related to the volcanicity,
2. the presence of a marked erosional unconformity,
3. an easterly younging direction and
4. that the Gjersvik discontinuity (Oftedahl 1956) is of minor importance in a regional context.

However, there is possibly a pronounced tectonic break between the Rørvik (Gula) Group and the overlying conglomeratic calcareous phyllites of the Limingen Group, if the latter corresponds to conglomeratic Upper Hovin rocks in the Snåsa Synform. At the transition between the Rørvik and Limingen Groups west of Kvarnbergsvattnet, there occur relatively thick units of pillowed greenstone (Zachrisson 1966) which may be equivalent to the Støren – Storstadsmarkas – Tromsdalen greenstones. The rocks of the Gjersvik Nappe, which is the highest unit in the Köli sequence, might very well correspond in age to the Støren volcanites.

A POSSIBLE TECTONIC MODEL FOR THE CENTRAL PART OF THE SCANDINAVIAN CALEDONIDES

The tectonic evolution outlined here has borrowed essential features from a plate tectonic model put forward by Gee (1975) for the Geotraverse area in the Central Caledonides.

It is suggested in the present paper that the Seve amphibolites originated as flood basalts in a non-marine milieu during a Precambrian to Late Precambrian continental break up, significant factors being:

1. The uniform basaltic volcanicity.
2. The non-spilitic character of the amphibolites.
3. With the exception of two localities at Sylarna (southern Jämtland) no pillowed amphibolites have been observed.
4. The close alternation with probably non-marine, arkosic metasandstones.
5. Many flood basalts elsewhere are related to continental disruption, initiated by the growth of a spreading ridge system beneath a continent.

The separation line or lines were probably situated west of the present Norwegian coast.

The age of the Ottfjället dolerites, which cut through arkosic metasandstones of the Särv Nappe, has recently been determined by the Rb/Sr whole-rock isochron method to be 735 ± 260 m.y. (Claesson 1976). It is possible that the intrusion of these dolerites, which requires considerable crustal extension, is related to the Seve volcanicity (Strömberg 1969). Extension of the crust was probably associated with block faulting which, in turn, lead to rapid erosion and deposition of tectonic arkoses. The oldest sediments in the Caledonian Front are pre-Varangian continental arkoses or sparagmites which were deposited in rift basins during a period of active faulting (Bjørlykke 1974).

As the Baltoscandian and Greenlandian continents moved apart a Caledonian geosynclinal marine basin or ocean, the proto-Atlantic ocean, was formed, in or marginal to which the Gula – Sonvatn – Brännälven – Rørvik – Remdalen units, and most of the units between the Seve and the Ankarede Volcanites were deposited.

The relative movement direction was reversed probably during the later part of the Cambrian and the continents began to move towards each other, thus closing the proto-Atlantic ocean. During the Lower and Middle Ordovician mixed acid and basic volcanites were formed and ultrabasic rocks were injected above zones of subduction. Possibly more than one subduction zone developed in or around an extensive island arc or archipelago system, as the ocean floor was consumed. The serpentinite conglomerate at Otta contains Llanvirnian fossils, which provide a minimum age for the injection of these ultramafites.

The Lower Hovin Group of the Western Trondheim region contains faunas of North American affinities, indicating deposition marginal to the Greenlandian continent, while the Otta conglomerate contains fossils of distinct Baltic affinities along with subordinate American elements (Gee and Zachrisson 1974). Gradual mixing of the faunal assemblages during the Ordovician reflects increased proximity of the Greenlandian and Baltoscandian margins (Whittington and Hughes 1972, Williams 1973). The volcanites in the Støren, Løkken and Grong areas are dominated by basic, often pillowed extrusives. Based on trace element data Gale and Roberts (1974) demonstrated the presence of ocean-floor metabasalts in the lower parts of these volcanites, while greenstones with island arc affinities occur in the upper parts in the Løkken and Grong areas. No real oceanic crust with complete ophiolite complexes, composed of ultrabasic rocks, layered gabbros, sheeted dykes and pillow lavas, have been described from the Central Caledonides.

At the end of the Ordovician and the beginning of the Silurian there was a change in depositional environment and thick flysch-like units such as the Upper Hovin, Horg and Kjølhaugen Groups, the Blåsjö Phyllite etc. accumulated, possibly as a result of incipient continental collision, with a tendency for the Greenlandian plate to override the Baltoscandian continental margin. The former was then uplifted and eroded while the latter was depressed and a marine flysch turbidite-basin developed in front of the advancing western plate. Basic volcanicity continued until the Llandoverian at least in the Björkvattnet – Virisen area (Kulling in Strand and Kulling 1972).

The main phase of orogenic deformation involving folding, metamorphism and vast nappe translation occurred during the Wenlockian and Ludlovian. The early inversions (D_1) pre-date the acme of metamorphism. It is possible that they formed as a result of gravity-induced, large scale sliding and piling up of sediments, possibly as fold nappes, in an eastern basin, which was then further depressed resulting in regional metamorphism at high pressure (Barrovian type) of the rocks within the Seve-Köli Nappe Complex. The metamorphic conditions in the medium- to high-grade parts of the Kvarnbergsvattnet area, require a burial of 25–30 km (cf. page 51).

Translation of the Seve-Köli Nappe Complex over the units of the Jämtland miogeosynclinal basin followed after the acme of metamorphism. The rocks were strongly flattened, elongated, sheared and folded during this main period of deformation (D_2 and D_3). Late orogenic movements (D_4 and D_5) probably continued into the Devonian.

In the central part of the Scandinavian Caledonides there is no structural evidence for an important phase of deformation prior to the main Silurian orogenic deformation. Furthermore, evidence for earlier metamorphism, for instance in connection with an Ordovician subduction-island arc environment characterized by blueschist metamorphism and paired metamorphic belts, is also lacking. In the Bergen area, however, there is a major unconformity, indicating pre-Ashgillian folding and metamorphism of Lower Palaeozoic rocks (Sturt and Thon 1976), and in the Scottish Caledonides the Moine-Dalradian sequence was deformed and metamorphosed from Upper Cambrian to Middle Ordovician (Dewey and Punkhurst 1969). This testifies to a very complex deformational sequence for the Caledonian eugeosynclinal basin as a whole.

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SGU = Sveriges geologiska undersökning
NGU = Norges geologiske undersökelse

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TABLE 8

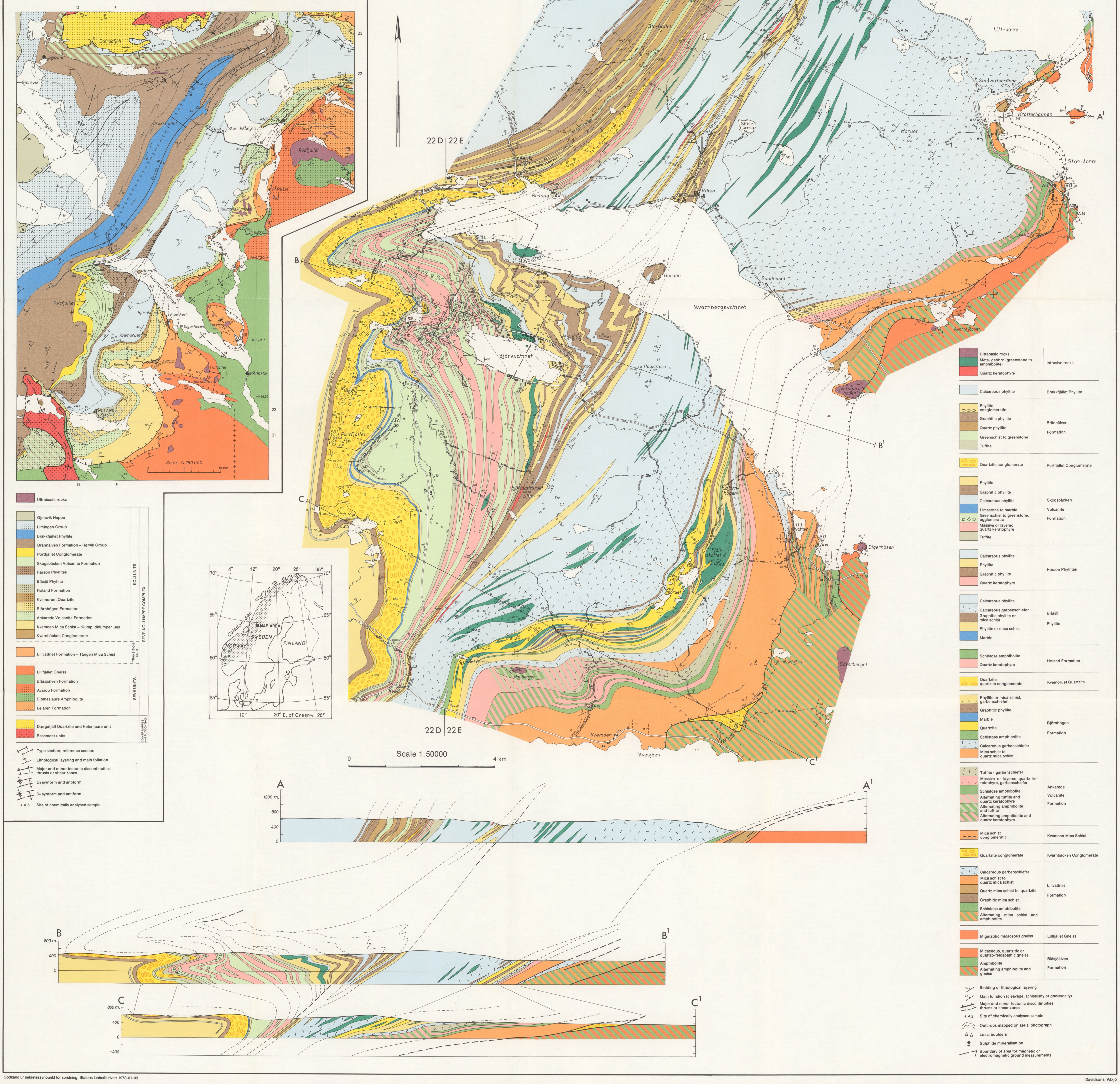
Structural comparison and correlation between different areas within the Seve-Köli Nappe Complex.
Abbreviations: ax. — axial, pl. — plane, cren. — crenulation, cl. — cleavage.

Northern Trondheim region (Roberts 1967)	S. Västerbotten (Zachrisson 1969)	The Marsfjällen area (Trouw 1973)	The Tärnaby area (Stephens 1977)	The Kvarnbergsvattnet area (present paper)
F_3 episode: Formation of open to tight, generally N-NE trending folds with fairly flat-lying ax. pl. cren. cl.; the sense of overturn is constantly down-dip.	F_3 phase: Formation of zig-zag folds with flat-lying axial surfaces.	F_4 phase: Local gentle folding and crenulation, S_4: subhorizontal.	D_4 phase: Gravity-controlled disturbance of the basement/cover. Development of major, open to gentle folds and late kink folds.	Post-metamorphic deformation (D_4 and D_5): D_5 - development of open, major and minor, often kink-like, reclined to recumbent folds or flexures during gravity settling of steep, earlier structures.
F_2 episode: Formation of open to tight, generally NE trending folds with no or weakly developed ax. pl. cren. cl.; development of the open Tømmerås anticline, the Verdal synform and the near isoclinal folds north of Snåsa and at Teveldalen. Major thrusting delineating the Trondheim Nappe.	F_2 phase: Formation of NNE-NE-trending folds congruent to open synforms and antiforms with low plunge and steep ax. pl. cren. cl.	F_3 phase: Folding on several scales, local development of mainly steep cren. cleavages with variable strike; limited mylonitization.		D_4 - development of major and minor antiforms, synforms, domes and basins and congruent minor folds. In the western part S_{reg} and S_3 were deformed into a vertical orientation and further west the dip was reversed.
F_1 episode: Formation of the regional schistosity and a general metamorphic fabric; the regional schistosity is ax. pl. cl. to tight or isoclinal minor folds. Elongation of the congl. pebbles, quartz rodding, boudinage and orientation of acicular minerals. Development of the Stjørdalen anticline and the early Hegsjøfjell fold.	F_1 phase: Formation of isoclinal, generally minor, transversely (NW) oriented folds and a strong schistosity, subparallel to bedding. Some F_1 folds deform a schistosity and their ax. pl. cl. is a cren. cleavage. These folds have the same orientation as other undisputable F_1 folds and are themselves deformed by typical F_2 folding.	F_2 phase: Open to close folding of the bedding and S_1 on several scales; formation of cren. cleavages, a transposition schistosity (S_2) or a rotated schistosity (S_{1+2}) and a NW-oriented mineral lineation; F_2 trends towards NNE or NW; rotation of syn-F_2 garnets; thrusting. F_1 phase: Tight folding, formation of a slaty cleavage (S_1); intense deformation indicated by deformed conglomerates; rotation of syn-F_1 garnets.	D_3 phase: Thrusting during D_3 (and late D_2); intense deformation of the regional phyllitic cleavage in certain zones, continuous development of both major and minor folds and important thrusts. Development of a locally intense crenulation cleavage. D_2 phase: Collapse of the pile during the later part of D_2; development of a regional phyllitic cleavage and penetrative lineations inc. pebble elongation. Associated with occasional minor folds.	Late-metamorphic folding (D_3): Formation of major and minor, often sideways-closing folds (the Portfjället folds) with a generally pronounced ax. pl. cren. cl.; continued SE shear and translation. Syn-metamorphic deformation (D_2): Strong penetrative deformation (flattening); development of the regional foliation, which locally is ax. pl. cl. to tight or isoclinal folds. Many of these folds are probably strongly modified D_1 folds. Development during D_2 and D_3, in connection with NW-SE directed extension, shear and nappe translation, of the transversely oriented regional lineation (mineral, surface intersection and striation lineations) parallel to the elongation of many congl. pebbles and to the axes of many D_{1+2}, D_2 and D_3 folds.
				Interkinematic period during which the acme of metamorphism was reached.
	Pre-F_1 phase: Formation of large recumbent folds (the Vesken folds), which are cut across by the S_1 schistosity.		D_1 phase: Establishment of a tectonic pile during D_1 (and early D_2). Synclinal repetition of the stratigraphy.	Pre-metamorphic deformation (D_1): Folding and development of a bedding cleavage.

GEOLOGICAL MAP OF THE KVARNBERGSVATTNET AREA

Northern Jämtland, Central Swedish Caledonides

Tomas Sjöstrand 1977



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