Geology and Structure of the Dombås-Lesja Area, Southern Trondheim Region, South-central Norway

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Investigations in the southernmost part of the Trondheim region have established the presence of a new tectonic unit, the Andbergshøi Complex, interposed between the Trondheim Nappe and the western Precambrian basement. This unit is represented mainly by Precambrian orthogneisses and an Eocambrian cover sequence. The lithostratigraphy within the Trondheim Nappe is divided into three main groups, each of which is subdivided into two or more formations. Lithostratigraphical correlations between the formations and groups in the present area and those in other parts of the Trondheim region (Gula Group, Støren or Fundsjø Group, Lower Hovin or Sulåmo Group) are proposed.

The small-scale structures in the various tectonic units show up to five phases of deformation. All these phases are accompanied by mineral growth, the first three of which are the most penetrative. In the Trondheim Nappe, the first deformation and metamorphic episode (F_1/M_1) is restricted to Gula Group lithologies. The metamorphic development during the Caledonian orogeny can be regarded as a combination of two types of metamorphism, which may be indicative of two major stages in the orogenic development of the region.

The basal thrust plane of the Trondheim Nappe transects the major structures of the nappe (NE-trending open to tight F_3 folds), as well as the metamorphic mineral zones developed during the Barrovian metamorphism. Within the nappe itself, some of the major lithological units are bounded by tectonic contacts; this is especially noticeable at the Gula Group/Støren Group boundary. These relatively early tectonic contacts were later cut by the major thrust plane of the Trondheim Nappe.

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Introduction

The area described in this account extends over 450 km² between Dovre, Dombås and Lesja in central southern Norway (Fig. 1). The mountain regions of Jotun and Dovrefjell rise above this part of the Gudbrandsdal valley to the southwest and north, respectively. The landscape is typical of the late glacial period, and is covered by a variety of moraine deposits; consequently the area is often poorly exposed. Although, this region was crossed by the main Oslo–Trondheim road, there has been little previous geological work carried out in the mapped area.

Geological setting

On the geological map of Norway (Holtedahl & Dons 1960) the area is shown to consist mainly of three different complexes. These are from NW to SE:

Gneissic rocks of the western basement.

Sparagmitic cover.

Various schists and greenstones of the Trondheim region.

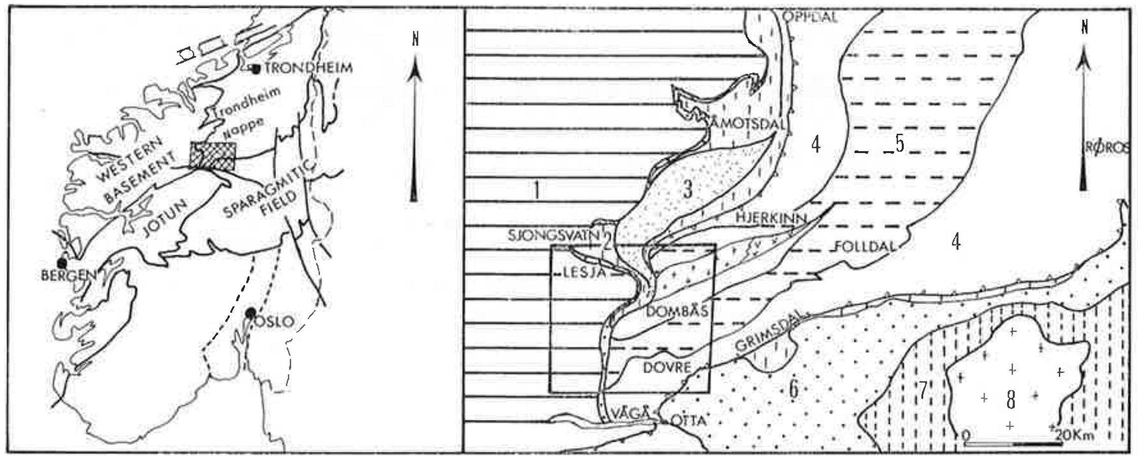


Fig. 1. Geological location of the present study area: 1) Western basement. 2) Andbergshøi Complex. 3) Snøhetta unit. 4) Trondheim Nappe. 5) Gula Group. 6) Kvitvola–Muen unit. 7) Sollia unit. 8) Eastern basement.

Earlier workers in the Swedish section of the Caledonides have distinguished what they consider to represent 'middle' and 'upper' thrust units. The rocks of the middle thrust unit are represented in the southern area (Dovre, Otta) by allochthonous quartzitic and arkosic rocks of assumed Eocambrian (Vendian) age. This unit represents the western continuation of the Kvitvola Nappe, and has been defined further to the south as the Muen Nappe by Prost (1970). The upper thrust units which are considered to come from the most internal part of the orogen are represented here by the Trondheim Nappe.

In the western part of the area just beneath the Trondheim Nappe basal thrust, another tectonic unit has recently been recognized; this is here called the Andbergshøi Complex (Guezou et al. 1972) (Fig. 1). Underlying the Andbergshøi Complex occurs a thin plate of sparagmitic rocks which constitute a parautochthonous cover to the western gneissic basement.

The present work is based on detailed lithostratigraphic studies and mapping, and has been particularly concerned with defining the western boundary to the Trondheim Nappe. This part of the south-central Norwegian Caledonides in fact constitutes a key area in our understanding of the tectonic development of this segment of the orogen (cf. Wegmann 1925).

The term 'Trondheim Nappe' was first used by Kulling (1961) but the name was adopted more formally by Wolff (1967) who gave a comprehensive summary of the previous work in the Trondheim region. Earlier, Strand (1961) had concluded that the Trondheim region metasediments were almost certainly allochthonous. Törnebohm (1896) described the general structure of the southern Trondheim region, and his map provides a fairly accurate picture of the tectonic discontinuity between the gneissic basement and the overlying rocks of the sparagmitic and Trondheim sequences. Törnebohm's views concerning the large thrusts were rejected in Scandinavia for many decades. Bjørlykke (1905) provided detailed descriptions of the rocks along geological sections in the Dovrefjell region. His profile through the Trondheim sequence in this area essentially showed a broad synform with gneissic rocks in the core (the Gula schists), and also indicated the effects of later folding of the basement and the Trondheim sequence.

The first detailed geological map of the southern Trondheim region was published by Strand (1951) who suggested that the southern part of the Trondheim Nappe merged southwards into the Otta Nappe. Strand also made lithostratigraphical correlations with the northern Trondheim region.

Wegmann (1925, 1959) discussed the tectonic features of the area and especially the intricate structures at the western border of the southern Trondheim region. He developed the concept of 'la flexure de la Driva' (Wegmann 1959) where the Gula schists are taken to constitute a separate allochthonous unit thrust above the Trondheim sequence (Wegmann 1925). Unfortunately there was little field evidence forwarded to support this hypothesis, and his speculation appears to have gathered little support in Norway.

The interpretation of the major fold structure of the Trondheim Nappe sequence has been the subject of a long-standing controversy, namely whether it is 'synclinal' or 'anticlinal'; a summary of these interpretations has been given by Roberts (1967). Detailed investigations in the northern Trondheim region led Wolff (1967) and Roberts (1967, 1968a) to conclude that the central fold structure was of a broad anticlinorial mushroom type, with flanking synclines both to the west and to the east. Earlier, Vogt (1945) and Strand (1951) had perpetuated the alternative synclinorial interpretation. Heim (1972) favoured a further interpretation in which two major nappes were represented; the Gula schists were here considered to be overthrust by metavolcanics and sediments of Ordovician age. Detailed structural studies further north led Olesen et al. (1973) to support the antiformal interpretation.

Tectonostratigraphic succession

In this area, which consists of rather high-grade metasediments, metavolcanics and intrusive rocks, four distinctive lithostratigraphic and tectonic units have been recognized. These are from NW to SE:

1. The western gneissic basement.
2. The parautochthonous sparagmitic cover.
3. The Andbergshøi Complex.
4. The Trondheim Nappe.

In addition, a fifth unit occurs in the south-eastern corner of the map area — the western extension of the Kvitvola–Muen Nappe constituting the Rondane sparagmitic field — but this is not considered in the present account.

THE WESTERN GNEISSIC BASEMENT

This gneissic tract, occurring in the western part of the mapped area (Fig. 1), principally comprises a monotonous series of acidic orthogneisses termed the 'Liafjell orthogneisses' by Santarelli (1972). The orthogneisses appear to originate from intrusive granite complexes indicated by the presence of networks of aplitic dykes and some dark micaceous schlieren. The characteristic facies is a pale grey gneiss with an eyed texture shown by small lenses of quartz and K-feldspar with micas deflecting around them. There are also frequent occurrences of augen gneisses with small augen of microline and relics of plagioclase (An_{20}). These rocks have suffered severe flattening, with granulation of K-feldspar and stretching of quartz ribbons around the augen. The foliation of the rocks is generally defined by biotite and epidote. In the Lesja area basic dykes occur; these are so strongly folded and flattened that they are now lying roughly parallel to the general gneissic foliation. The age of the basal gneisses in western Norway has long been a matter of contention (Strand 1960). Now, however, the homogeneous gneisses (many have granitic to dioritic composition) are accepted as being of undisputed Precambrian age with metamorphic ages of 1708 ± 60 and 1025 ± 85 MA. (Bryhni 1966, 1973; Brueckner et al. 1968; Pidgeon & Råheim 1972; Sturt et al. 1975) (Rb/Sr whole rock isochrons, λ (Rb 87) $= 1{,}39.10^{-11}.a^{-1}$). These gneisses have undergone polyphase deformation during both Precambrian and Caledonian orogeneses.

THE PARAUTOCHTHONOUS SPARAGMITIC COVER

South-east of Lesja the basal gneisses are overlain by rocks of sparagmitic character, essentially quartzites rich in K-feldspar. Further to the south at Vågå and in Skjervedal, there is a thick unit (300 m) of sparagmite of pale green colour and flaggy habit. Towards the north, this unit thins rapidly to 20 m along the basement contact. Rosenqvist (1941) observed a quartz conglomerate near the base of this unit at Trollheimen; in the present area this wedges out tectonically along the contact with the gneisses.

Three dominant rock-types have been distinguished:

(i) Pale green feldspathic quartzites with uniform bedding; the rock splits readily along the muscovite foliation.

(ii) Coarse-grained feldspathic quartzites; K-feldspar clasts up to 1 cm across show late overgrowths of albite. In some areas the rocks have the appearance of fine-grained augen gneisses.

(iii) Fine-grained feldspathic quartzites (leptitic in aspect) with little development of foliation. These could possibly have originated from rhyolitic tuffs.

Bordering the gneisses, the thick pile of sparagmite is reduced to a thin unit of stripy grey and white mylonites. These derive from the mylonitization of feldspathic quartzites and contain a high content of white mica, albite and quartz.

The various clastic facies, mentioned above, are equivalent to the light sparagmite which according to Prost (1971) is of Varegian age. A good correlation can be made between the lower and middle Varegian and the Vangsås Formation (Prost 1972). However, it must be pointed out that from Vågå to Lesja there is an increase in metamorphic grade within the sparagmite. In the Lesja area and further north the metamorphic grade reaches middle to upper amphibolite facies, and as a result the general appearance of the rock is modified. Southwards the continuity of the sparagmitic rocks between Vågå and Sel is broken owing to the presence of a 'rehgmatic' fault zone (Caire 1975; Prost 1975). On a purely lithofacies basis, however, these two sparagmitic occurrences at Vågå and Sel are considered to represent Varegian (Vendian) sediments.

THE ANDBERGSHØI COMPLEX

The Andbergshøi Complex occupies an intermediate structural position between the 'infrastructure' (the reactived western basement) and the lower part of the highest structure, i.e. the Trondheim Nappe (Guezou et al. 1972). To the south in Skjervedal this complex is enveloped by the sparagmitic cover. Two main lithological units are distinguishable. The first, informally called the *Veslfjell group*, consists of Precambrian gneisses and quartzites; the second, the *Bottheim group*, comprises mainly metavolcanics with some sediments. These two units are both represented along the road from Lesja to Dombås.

Veslfjell group

The Veslfjell group contains a number of distinctive lithologies, although a definite stratigraphy is not obvious. The lithologies are as follows:

(a) *Orthogneisses* of different types which are very similar to the basement gneisses.

(b) *Leptitic gneisses*; these are fine-grained rocks with a pale pink colour, low mica content and poorly developed foliation.

(c) *Dioritic gneisses*; these are generally banded and contain significant amounts of biotite, amphibole, garnet and allanite. K-feldspar is less abundant than plagioclase ($An_{20\text{-}30}$). These varieties occur as slices and tectonic lenses within various augen gneisses and migmatitic gneisses. In the areas of Andbergshøi, Fillingsæter and further north in Åmotsdal (Wheeler 1974) these tectonic sheets, which are partly mylonitized, occur in antiformal or synformal cores within metavolcanics and metasediments.

(d) Coarse *augen gneisses*; these usually enclose lenses of orthogneisses and resemble the augen gneisses of the Driva valley. The augen, usually of K-feldspar, quartz and biotite, are mostly rounded and vary from a few cm up to 15 cm across; the foliation is defined by biotite, epidote and white mica and wraps around the augen. The augen gneisses also enclose small lenses of foliated amphibolite with a foliation discordant to that in the gneisses.

(e) *Migmatitic gneisses* are present along the contact with the coarse-grained augen gneisses. Scattered oblong augen are present in mica schists, and quartzo-feldspathic veinlets occur as infillings along joints and shear zones in the rock. This migmatisation process seems to be restricted to an area enclosed by amphibolites. In this way amphibolites have effectively shielded the mica schists from migmatisation away from this restricted area.

(f) *Feldspathic quartzites*: these occur as thin sheets which are imbricated together with gneisses within the volcanics and sediments of the Bottheim group. Two distinctive rock-types occur: (1) well-bedded, locally flaggy quartzite with porphyroclasts of K-feldspar and abundant haematite grains. This type is very similar to the sparagmite rocks; (2) well-bedded meta-arkoses characterised by varying amounts of white mica and of K-feldspar porphyroclasts in a groundmass of fine-grained quartz, crushed feldspar grains and some epidote.

Bottheim group

The Bottheim group consists of both acidic and basic metavolcanics and metasediments. Superposed folding precludes any estimation of the unit thicknesses within this group, as well as the establishment of the true lithostratigraphic relations between the different rock-types.

The basic metavolcanics, now amphibolites, occur in a great number of layers which never exceed 60 m in thickness. They are closely associated with acidic volcanics such as metakeratophyres. Chemical analyses of these rocks show significant differences from similar rocks occurring in the Trondheim Nappe; this is particularly marked in the lower sodium content. The volcanics are interlayered with metasediments and three important marker horizons are present: (1) A fine-grained, grey, quartzitic gneiss, which is similar in composition to quartz keratophyres, though with a higher content of micas. This probably originated either as an acidic volcanic rock or as a tuffite. (2) One or more impure marble layers, less than 1 m thick. (3) An albitite with zoisite (so-called 'zoisitite'), the origin of which is rather enigmatic. Its association with marble and meta-tuffites suggests that it probably represents a sediment formed during volcanic activity.

The most common metasediments are feldspathic mica schists which may contain some small lenses of quartz and feldspar. Locally they are highly aluminous resulting in mica schists rich in garnet, kyanite and staurolite. Banded quartzites are sometimes present, the banding resulting from the presence of thin micaceous partings. A conglomerate has been found in one locality, interbedded with mica schists. The matrix consists of quartz, calcite, plagioclase and micas, and the pebbles have been deformed into lenses of quartz and marble.

The Andbergshøi Complex is very similar in the character of its sediments and volcanics to comparable tectonic units described from further north in Sjongsvatn og Åmotsdalen (Fig. 1). The Bottheim group is considered to be equivalent to the Sjongsæter group (Scott 1967) and to the Blåhøi group in Åmotsdal (Wheeler 1973).

With regard to correlations and age relationships of the different allochthonous cover sequences which occur immediately above the basal gneisses and the sparagmitic rocks, Scott (1967) and Wheeler (1973) considered that obvious correlations could be made with the Cambro–Ordovician sequence in the Trondheim Nappe. Heim (pers. comm. 1971) also suggested that a Cambro–Ordovician sequence may well be represented along the western border of the Trondheim Nappe. Bryhni (pers. comm. 1972) and Gyøry (pers. comm. 1972), however, regard these metamorphic supracrustal rocks as being of Precambrian age, and possibly equivalent to the Telemark supracrustals. The present author is of the opinion that there are in fact two distinctive rock sequences. One, consisting principally of quartzites and gneisses, is believed to be of Precambrian age; the other, the Bottheim group, is quite different and constitutes a well-defined structural unit which has an overthrust relationship to undisputed sparagmitic rocks. The tectonic slices of orthogneisses and quartzites are a characteristic feature within the Andbergshøi Complex, and represent a distinctive tectonic development as compared with that of the Trondheim Nappe. In spite of a high metamorphic grade, the sedimentation and volcanic activity of the Bottheim group may be compared to that of the Seve unit in Sweden.

THE TRONDHEIM NAPPE COMPLEX

The Trondheim Nappe complex occupies the greater part of the investigated area, and consists of metamorphic sedimentary and volcanic rocks varying from lower greenschist to middle amphibolite facies. A detailed investigation of the rock sequence has been made in order to establish a lithostratigraphical succession. These observations have allowed tentative correlations to be made between the present area and eastern and northern parts of the Trondheim region. The map pattern of the various lithological units is generally that of long strips aligned parallel to the regional strike of the major structures. The boundaries of these units are often tectonic and it is therefore difficult to establish the true stratigraphic order of the sequence or to determine its primary thickness.

The starting point of the stratigraphic reconstruction in this southern marginal zone of the Trondheim Nappe was the thick sequence of basic volcanics which is found in the Gudbrandsdal valley around Dovre. Farther to the east the lavas, or greenstones, can be traced over large distances to Folldal. To the south-west, they merge into the greenstones of the Vågå area. In the southernmost part of the Trondheim region the minimum age of the thick metavolcanics has been established as middle Arenigian by the presence of fossils in the overlying Otta serpentine conglomerate. In the present area the metavolcanics and associated subordinate sediments are here referred to informally as the Musadal group (Fig. 2).

The Musadal group

The Jønndal formation. A great number of greenstone layers and amphibolites apparently represent extrusive basic lavas. Structures in the rocks are typical of a magmatic origin and include pillow structure, broken pillow breccias and fluidal porphyric structures. Because these rocks have been affected by strong deformation and metamorphism, there are no reliable way-up criteria which can be used to decipher the geometric relationships of the sequence. In association with the pillow lavas and massive amphibolites, there are some amphibolites which contain boudins or sill-like bodies of quartz–keratophyric rocks.

Intrusive igneous rocks occur in the form of strongly foliated saussuritized

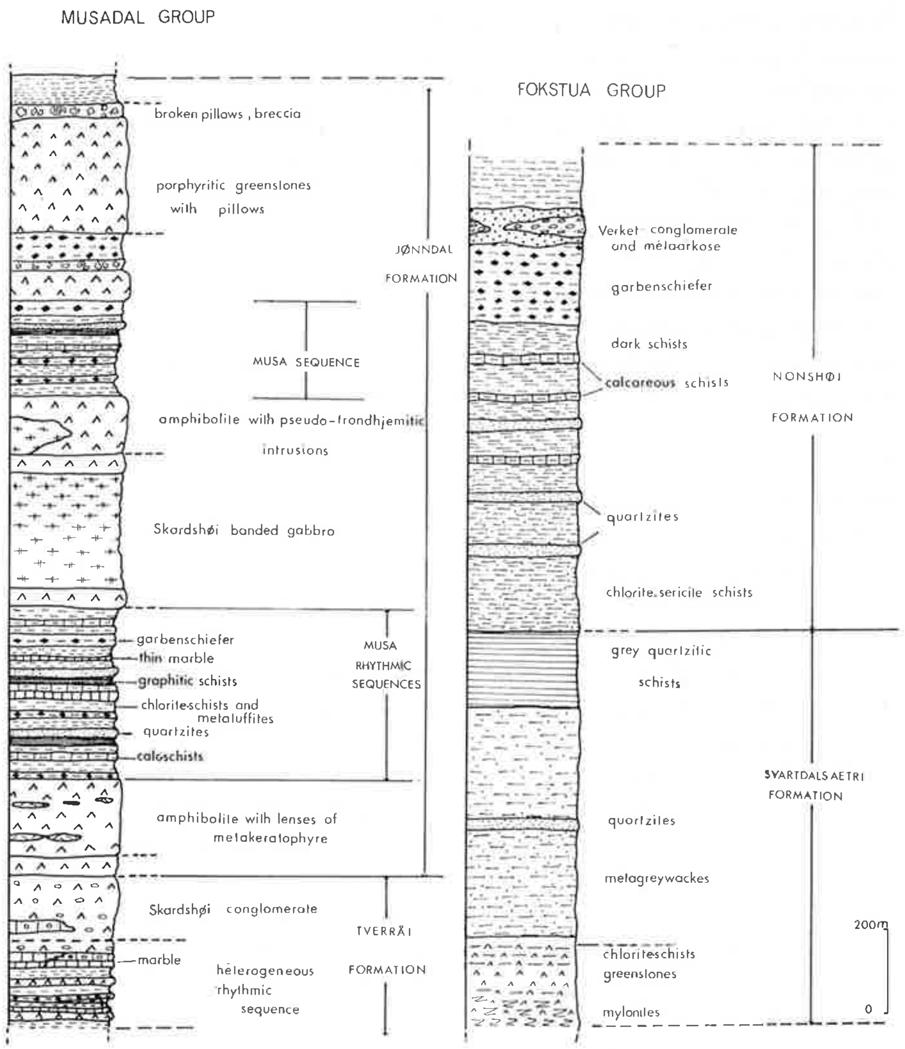


Fig. 2. Lithostratigraphic succession of the Musadal group and Fokstua group.

gabbro which is interlayered with light-coloured dioritic rocks. An important feature of the Trondheim region is that although the greenstones are characteristically associated with diorites and gabbros, there is generally a lack of ultramafic rocks which could be expected in an ophiolitic association (Guezou & Poitout 1974, Roberts 1975). One can speculate whether the ultramafics were cut out systematically by thrusting, or whether in fact true layered ultramafic rocks were missing during the magmatic phase. In order to make a comparison with a typical ophiolitic suite, e.g. the peri-Mediterranean alpine belt, we may consider the metasediments which occur within the greenstone sequence in this southern area. The Jønndal formation contains a variety of metasediments interfolded with the amphibolites. These metasediments constitute a rhythmic sedimentary sequence, the *Musa sequence* (Fig. 2), which consists of

three different members: (a) thin layers of impure quartzites which grade into pelitic schists of tuffaceous origin containing chlorite and albite; these include 'garbenschiefer'; (b) calcareous schists which pass laterally into thin marble layers (from 2 cm up to 6 cm in thickness); (c) frequent layers of graphitic schists which are never more than 4 m in thickness.

Such rhythmic sequences separate distinctive units of greenstones; for example, they appear between amphibolites with lenses of metakeratophyres and units of massive amphibolite. An analogous type of sedimentation within an ophiolitic suite has been recorded in several areas of the Mediterranean alpine belt (Marcou 1970).

Sedimentary intercalations of this type occurring within the greenstones of the present area have never been described from the northern and central parts of the Trondheim region. It thus seems important to mention this occurrence, considering general regional interpretations in terms of a possible fragmented ophiolitic sequence (Gale & Roberts 1974). In the case of the present area, however, without any magmatic and structural evidence or detailed chemical data, no paleotectonic comparisons are really possible. The rhythmic sedimentary sequences interlayered within effusive lava units containing broken pillow breccias are considered by the author to separate distinctive flows. Some of these greenstones could then represent comparatively shallow water eruptions in a relatively quiet sedimentary environment.

The Tverrâi formation. The Tverrâi formation is similar to the rhythmic sequences in the Jønndal formation. The rocks are strongly folded with the Skardshøi conglomerate occurring in the cores of megascopic folds. Pelitic schists and carbonaceous schists are dominant, and these contain some tuffitic layers. Garbenschiefer are also well developed within layers of muscovite–biotite schists, and there is a high modal percentage of quartz and albite in some of these rocks. Layers of amphibolite are numerous in this sequence, but do not exceed 6–8 m in thickness. A thin marble horizon containing a considerable amount of fuchsite occurs in pelitic schists just beneath the Skardshøi conglomerate (Fig. 2). A marked tectonic contact exists between the Tverrâi formation and the Skardskollan formation (= Gula schists) (Plate 1, Fig. 11).

The stratigraphic position of the Skardshøi conglomerate is somewhat uncertain because of a décollement style of deformation and ubiquitous disharmonic folds which were possibly produced by gravity. In the area under investigation the conglomerate contains quartzitic and calcic pebbles in a green matrix consisting of epidote, amphibole, chlorite and fuchsite. Locally, the conglomerate contains only quartzitic pebbles in a calcitic matrix and then resembles a conglomeratic marble. The pebbles are generally elongated and flattened, but where they have the appearance of small almonds of quartz and calcite they are considered unlikely to be true pebbles.

In the present area and also further east in the Grimsdal and Folldal areas (Heim 1972, Quenardel 1972a, 1972b, Pinna 1974), different conglomerate occurrences appear to belong to only one tectono–stratigraphic niveau. In the

Røros area, Rui (1972) described a 'heterogeneous banded rock sequence' which resembles the rocks of the Tverrâi formation containing the Skardshøi conglomerate. To the north in the Holtsjøen area, Rui (1972) described this banded rock sequence as probably being in contact with black graptolite-bearing schists of Tremadocian age (Vogt 1940). Further north, in the Meråker and Færen area the Gudå conglomerate (Wolff 1964, 1973) occupies approximately the same tectono-stratigraphic position as the Skardshøi conglomerate (Fig. 4). The actual stratigraphic position of the Skardshøi conglomerate is ambiguous. In the present area the green matrix is of amphibolitic composition; moving upwards, amphibolite layers and basic tuffs gradually appear. The pebbles in the conglomerate were probably derived from chert and limestone and no clasts of volcanic material have been found. Considering both the character of the conglomerate and the rhythmic sedimentary sequence of the formation as a whole, the present author regards the Tverrâi formation as the basal unit within the Musadal group. The widespread development of this particular conglomerate and the associated rocks is thought to represent an important stage of sedimentary deposition preceding the main volcanic activity in early Ordovician time.

The Fokstua group

The Fokstua group consists of two formations, the Svartdalsætri formation and the Nonshøi formation, which occur in a major synformal structure within the Trondheim Nappe (Plate 1). The northern and southern margins of the synform are tectonically bounded by the Ståkåhøi group (Gula Group). To the north a mass of trondhjemitic rocks is thrust above the Fokstua group, while south of Dombås the synform is in thrust contact with graphitic schists of the Ståkåhøi group. The Svartdalsætri formation appears again in a tectonic wedge along the northern border of the map area and the northern contact of the Ståkåhøi group. This formation occupies the lower part of the Fokstua group. The lithologies of the two formations within the Fokstua group consist largely of metagreywackes, sandstones and pelites with calcareous layers (Fig. 2). A conglomerate occurs near the top of the Nonshøi formation in a restricted area along the south-western border of the synform; it thins rapidly both to the east and to the west in a synclinal structure. This conglomerate — the Verket conglomerate — is a polymict conglomerate which forms lenses within grey feldspathic sandstones. The pebbles consist of quartzites, fine-grained schists and some quartz–keratophyric rocks, but no pebbles of greenstones have been observed. The matrix is pelitic with a high content of calcite. Both matrix and pebbles of this conglomerate are very similar to those of conglomerates in the upper part of the Lower Hovin Group (e.g. the Dølplass conglomerate (Mosson & Quesnel 1970) in the Folldal area, Sætersjø conglomerate (Rui 1972) in the Røros district, Brenna conglomerate in the Meråker area (Wolff 1967)). Moreover, these conglomerates always occur as large lenses within sandstones and dark phyllites or schists. Thus, it would appear that the various pelites and metagreywackes of the Fokstua group below this conglomerate may be correlative with the rocks of the Lower Hovin or Sulåmo Groups (Fig. 4).

In the Svartdalsætri formation (Fig. 2) chlorite-rich quartz schists or metagreywackes are the dominant rocks; there are also some quartzitic subgreywackes present near the western margin of the formation. Higher up, pelitic schists occur and these grade upwards into chlorite–sericite schists of the Nonshøi formation. The Svartdalsætri formation occurring along the northern border of the Trondheim Nappe contains a single horizon of strongly sheared greenstones below the greywackes. The Nonshøi formation displays a rhythmic sequence of sedimentation with green banded quartzites interlayered in pelitic and graphitic schists. To the north, in the Hjerkinn area, the Svartdalsætri formation passes into the rocks of the Elgsjøtangen group (Heim 1972).

The Ståkåhøi group (Gula Group)

Within the map area the Ståkåhøi group occurs in the southern limb of a major late, synformal structure. One of its formations also crops out to the north of the trondhjemite massif. This group is equivalent to the Gula schists forming the central part of the Trondheim Nappe (Fig. 1) and has been divided informally into 4 formations: the Grønhøi, Nysæterhøi, Åteigen and Skardkollan formations (Fig. 3).

The Grønhøi formation. A clastic unit characterized by quartzitic layers with cross-bedding and meta-arkoses in recurrent thin layers occurs in the lower part of the Grønhøi formation. This member has been strongly folded and sheared, and in places has the appearance of a pseudo-conglomeratic schist. Higher members consist of graphitic schists with interbedded, often micaceous, quartzitic layers and some horizons of volcanic tuffs. The volcanics are better developed higher up in the sequence.

The Nysæterhøi formation. The Nysæterhøi formation contains the entire development of the sulphide-rich graphitic schist unit. Towards the nappe border, the western graphitic schists contain a variety of basic metavolcanics. This volcanic association of amphibolites and greenschists provides a prominent marker horizon within the graphitic schists. Nilsen (1974) has referred to this association as the 'Gula greenstones'. The upper lithologies of the formation show a sedimentary evolution in two different trends: one member with carbonaceous rocks, mica schists and gneisses with significant amounts of calcite, amphibole and epidote; and a second with pelitic rocks, mostly mica schists rich in kyanite, staurolite and micas. The coarse-grained clastic rocks and the graphitic schists are lacking in this upper part of the Nysæterhøi formation.

The Åteigen formation. The Åteigen formation contains only one facies of banded schists with layers of carbonates (calcite and dolomite), epidote, quartz and plagioclase (An_{40}) and layers rich in Fe, Al and Mg (pargasite, biotite, iron ores).

This formation is similar to the calc–silicate-bearing rocks of the central and eastern parts of the Gula Group. These schists and gneisses, which have formed

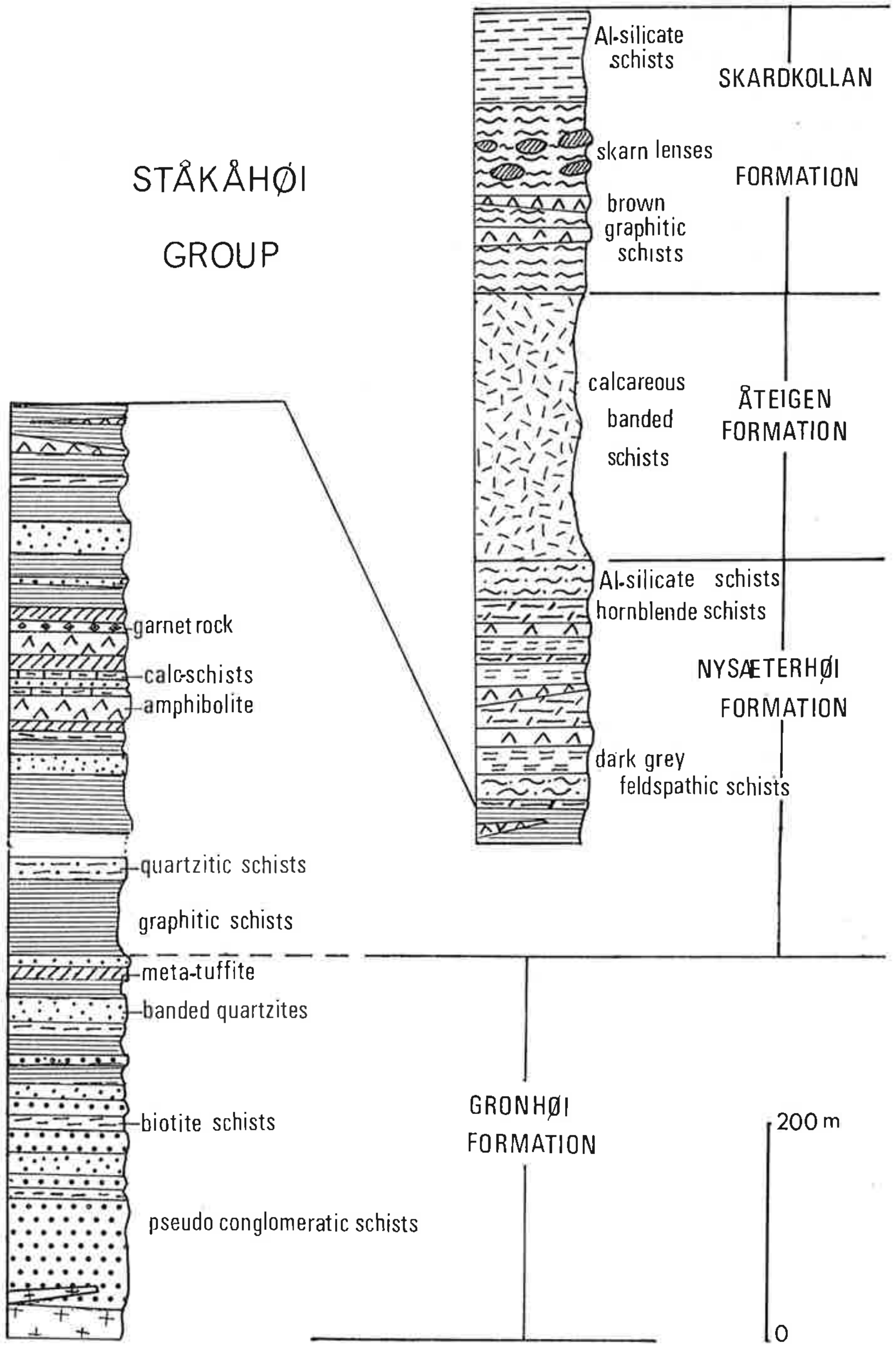


Fig. 3. Lithostratigraphic succession of the Ståkåhøi group (= Gula Group).

from impure calcareous sediments, are typical of the entire Gula Group throughout the Trondheim region.

	VOGT 1945	Hølonda - Horg CHALOUPSKY 1970		Meråker WOLFF 1967		Ålen RUI 1972		Dombås GUEZOU - POITOUT 1972 (This paper)	
Llandoverian	HORG GROUP	sandstones and shales quartzite conglo-merat	UPPER SANDÅ GROUP	sandstone and dark slate	SLÅGAN GROUP	greenschists greenish mica-schists meta sandstone quartzites	HUMMELFJELL FORMATION		
Ashgillian Caradocian	UPPER HOVIN GROUP	dark slate volcanic sandstone limestone conglomerates rhyolite tuffs	LOWER SANDÅ GROUP	quartzite conglo-merate metagreywackes	KJØLHAUG GROUP	graphitic schists quartzite conglo-merate serpentinites graphitic schists grey greenish schists	RØROS GROUP		
Llandeilian Llandvirnian Arenigian	LOWER HOVIN GROUP	green sandstone conglomerates breccia green slate amygdaloïdal greenstones green and dark slates greenstones conglo-merates	KROKSTAD GROUP	metabasite metasandstone conglomerates limestone dark schists conglomerates	SULÅMO GROUP	metabasites conglomerates marble meta sandstones and dark phyllitic schists	KJURUDAL-SOETERSJØ FORMATION	conglomerate metasandstone "garbenschiefer" calcareous and dark schists quartzites and chlorite schists grey quartzitic schists metagreywacks and quartzites greenstones ?	FOKSTUA GROUP
Tremadocian Cambrian ?	STØREN GROUP	Støren greenstones	STØREN GROUP	metabasites and quartz keratophyres	FUNDSJØ GROUP	greenstone greenschists and metakeratophyres	HERSJØ FORMATION	metasediments interbedded within greenstones and keratophyres TYERRAI FORMATION(with the Skardshøi conglomerate)	MUSADAL GROUP
Cambrian ?				various micaschists (Al-silicate schists and migmatites)	SONVATN (GULA) GROUP	dark schists. Al-silicate schists with marble, quartzitic conglomerate greenschists with skarn calcareous psammitic schists graphitic schists and quartzites	GULA GROUP	Al.silicate-bearing schists brown graphitic schists with skarn nodules, dark hornblende, Al-silicate schists graphitic schists banded quartzites pseudo-conglomeratic schists	STÅKÅHØI GROUP

Fig. 4. Lithostratigraphical correlations within the Trondheim Supergroup between the Dombås region and other type-areas in the Trondheim Nappe.

The Skardkollan formation. The rocks of the Skardkollan formation occupy the southernmost outcrop of the Ståkåhøi group. They show a noteworthy constancy of facies from the Dombås area north-eastwards to Folldal. There are two members: (1) Quartzo–graphitic schists with one or more beds containing amphibole–pyroxene nodules. The nodules are 10–50 cm in diameter and are of skarn, as shown by their texture, chemical composition and field occurrence. They probably represent original calcareous or dolomitic nodular deposits. The graphitic schists are cut by some amphibolite sheets. (2) Schists containing Al-silicates and ortho-amphiboles. This member has a rather special chemistry with an abundance of Al, K, Mg and Fe.

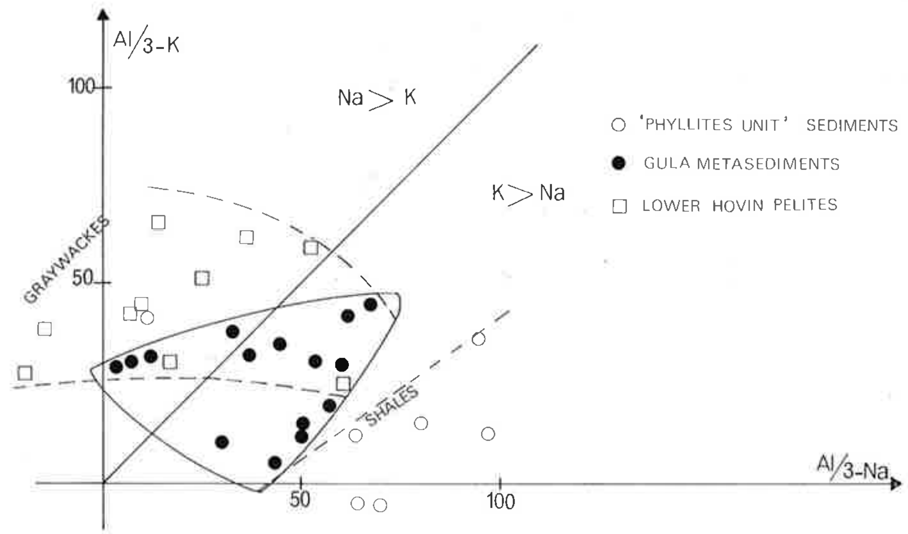


Fig. 5. Al/3–K=f (Al/3–Na) diagram (de la Roche, 1968) illustrating the geochemical trend of the Gula schists.

On the basis of lithology, geochemistry and sedimentological characteristics three distinctive sedimentary sequences can be recognized in the Ståkåhøi group. It is considered that their evolution is fairly typical for the Gula Group sediments in general. The three sequences are: (a) A lower clastic sequence which may represent a transgressive succession as shown by the basal, thin, alternating arkosic and quartzitic beds (pseudo-conglomeratic schists). Upwards, this facies shows a gradual decrease in the coarse detrital elements. (b) An intermediate sequence which marks the end of the main coarse clastic episode and the incoming of graphite-rich sediments with sulphides which are indicative of a reducing (euxinic) environment. The euxinic sedimentation is interrupted by short episodes of volcanic activity (amphibolites and tuffitic rocks) followed or accompanied by clastic deposition (banded quartzites). (c) An upper sequence which shows a clear chemical evolution of its sediments; the pelitic members are rich in Al, Mg and Fe, and the presence of carbonates as a significant mineral phase in the sediments is illustrated by the calcareous banded gneisses. The most distinctive sedimentary feature in this sequence is that of the presence of dolomitic nodules in the upper part of the Skardkollan formation.

These three sequences are representative of epicontinental deposits with a strong indication of a euxinic environment. They are devoid of either turbidites or rhythmic coarse clastic deposits (Guezou 1975a).

Some chemical analyses have been carried out on the Ståkåhøi (Gula) metasediments and comparisons made with geochemical data from two other distinctive lithological sequences, the Lower Hovin Group pelites and the 'phyllite unit' resting on the top of the late Precambrian deposits in the Gudbrandsdal region. The variation of Na and K in relation to Al content discriminate three different fields which correspond to the three main types of sediment (Fig. 5).

Analyses from the Hovin pelites lie within the 'greywacke' field while the phyllites plot in the 'shales' field; the Gula schists are situated between these two fields and display an unquestionable chemical maturity. These features help to separate the Gula schists from the eugeosynclinal sediments of the Lower Hovin Group. Other features independently support the hypothesis that the Gula schists are non-eugeosynclinal deposits; the magmatic characteristics of the trondhjemite suite and the high content of the elements Fe and Mg and low contents of Ti and Al in the basic volcanics of the Gula Group (Nilsen 1974).

It has long been inferred that the Gula schists are of Cambrian age but they show no primary conformable or unconformable relationships with the Eocambrian deposits in any part of the region. Moreover, in spite of previously stated opinions (Wolff 1967, Rui 1972, Olesen et al. 1973), no true primary stratigraphic boundaries are present between the Gula Group and the adjacent greenstones (Støren, Fundsjø, Musadal groups, Hersjø formation); in fact, a tectonic contact exists all along the eastern border as well as along the western margin (Guezou & Poitout 1974, Gale & Roberts 1974). In addition, the Støren/Lower Hovin Group boundary in this southern region is also locally of tectonic character.

The chemical characteristics of the Gula sediments described above suggest that the sediments correspond to epicontinental deposits coming from an internal zone of the Caledonian sedimentary ocean basin. These epicontinental deposits cannot be compared with the Cambrian sediments of the marginal zones (the Baltic or the Greenland Shield margins) even if there were euxinic deposits in upper Cambrian time along the Baltic Shield margin. Two hypotheses can then be envisaged: either the Gula schists illustrate ante-eugeosynclinal deposits within a basin more or less transitional between the margins of the Baltic Shield and the Greenland Shield; or the Gula schists were deposited in a basin in the internal part of the Caledonian sedimentary belt. The evolution of this possible internal basin must have been independent of the evolution of the external marginal zones so that the sedimentary sequence may range from late Precambrian up to Ordovician. Another suggestion, with the Gula Group considered as a miogeosynclinal sequence, has been forwarded by Gale & Roberts (1974).

Structural geology

The four lithological complexes discussed above also represent four individual major tectonic units. This can be demonstrated both in relation to the various deformation sequences recognized and to the different metamorphic histories. The most striking tectonic feature of the investigated area is the presence of tectonic contacts between the several E–W-trending units. These tectonic contacts represent 'troncations' and illustrate tangential shear tectonics as defined by Ellenberger (1967). The tectonic units are non-recumbent thrust nappes. An example of such a tectonic style is demonstrated by the Trondheim Nappe.

From west to east three tectonostratigraphic units overlie the Precambrian orthogneissic basement (Figs. 11 & 12, Plate 1): (1) A parautochthonous sparagmitic cover. This unit, which is involved in complex fold deformation north of Lesja, is now structurally 'mise en accordance' with the gneissic basement. (2) The Andbergshøi Complex. This occurs in an intermediate tectonic position and has basal lithologies which are not completely transposed into parallelism with the underlying units. (3) The Trondheim Nappe. This has a major basal thrust which locally cuts across the underlying units almost at right-angles.

MAIN DEFORMATION EPISODES AND TECTONIC HISTORY

In the Trondheim region it has been accepted, on paleontological evidence, that the major tectonic deformation and metamorphism occurred in about Middle–Upper Silurian time, and this has been confirmed by geochronological studies (Wilson et al. 1973). It is thought that the main deformation episodes of the present area are set in a period which preceeds the main thrusting of the Trondheim Nappe in about Upper Silurian time; however, as Devonian deposits are tectonized east of Røros, the very latest deformations are probably of Middle–Upper Devonian age (Roberts 1974).

Five episodes of deformation have been recognized in the Trondheim Nappe in the present area; in the underlying units only three episodes of deformation can be demonstrated. Each episode will be described below to show how various structures are developed in each tectonic unit. Correlation of the successive deformations in each unit is complicated by the fact that Caledonian deformation events are probably superposed on earlier Precambrian deformations in the underlying units; thus, the sequence of events proposed here is a relative chronology.

F_1 episode

Aplitic dykes in the western basement gneisses are folded on a small scale and show evidence of at least two phases of folding. These dykes have suffered a strong stretching and crushing similar to that in the surrounding gneissic rocks, and have acquired a foliation parallel to the plane of flattening. These deformations are thought to be Precambrian and are related to the structural development of the western orthogneisses. A lineation plunging towards 080° is probably related to this early deformation.

The oldest *Caledonian* deformation recognized in the parautochthonous sparagmitic cover is represented locally by isoclinal folds with strongly extended limbs. This F_1 folding repeats the primary stratigraphic banding; thus the flaggy splitting of these rocks is parallel to the F_1 axial planar schistosity. Linear elements and fold axes plunge towards 080°. A comparable development of F_1 folds is also found in the sparagmitic nappes (Kvitvola–Muen Nappe). According to Prost (1972) this earliest phase of folding was established prior to the major overthrusting.

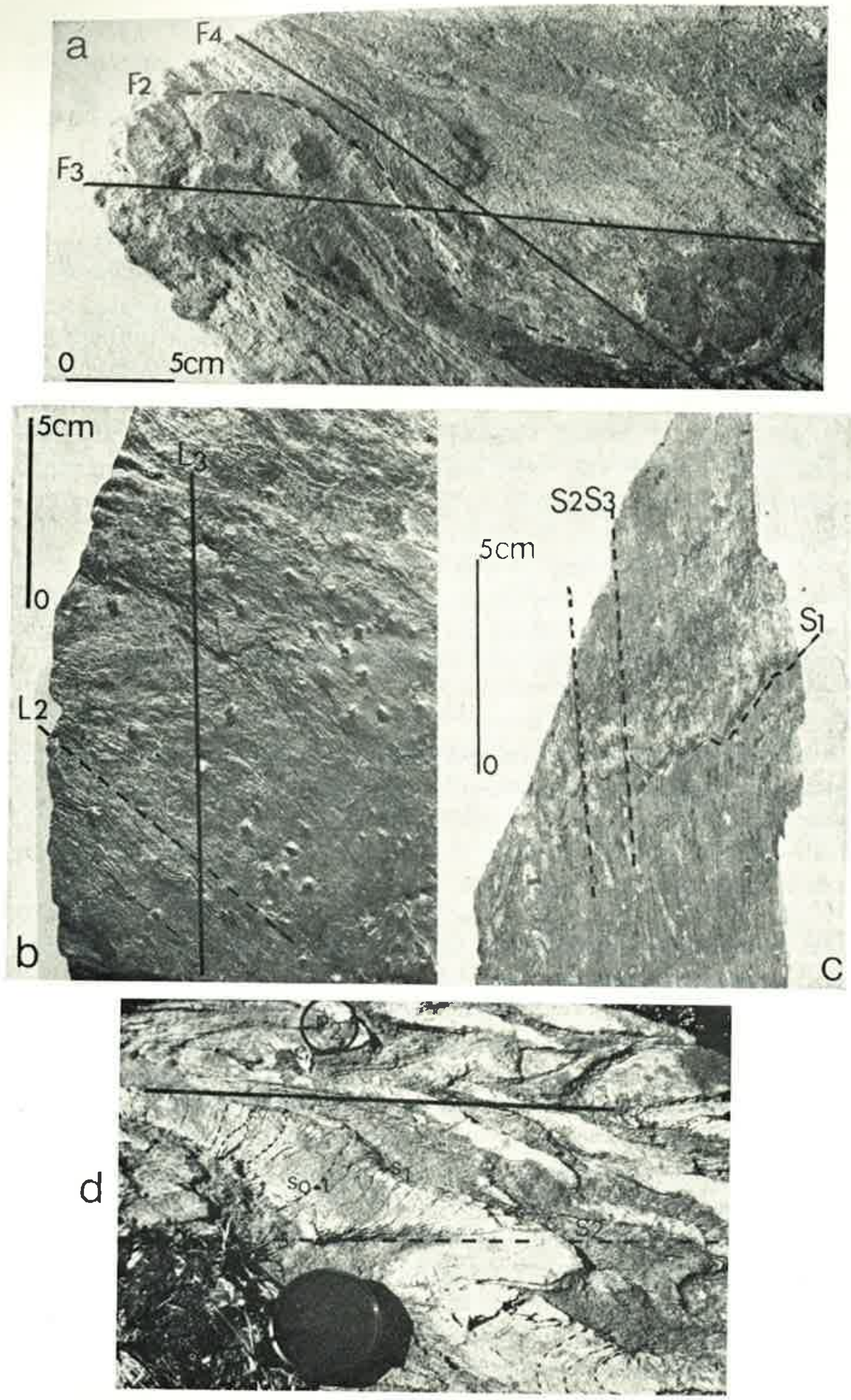
The structure of the Andbergshøi unit is exceedingly complex because of the superposition of two sets of large recumbent folds. F_1 recumbent folds involve quartzitic and gneissic sheets and show steeply plunging axes with an E–W trend. This can be demonstrated on a regional scale (Figs. 11 & 12, Plate 1). On the microscopic scale, it can be shown that some minor thrusts within the banding pre-date the tight to isoclinal folds. The gneissic sheets deformed by F_1 folds were tectonically introduced within the metasedimentary sequence in an earlier event for which no folds have yet been recognized.

The F_1 deformation episode in the Trondheim Nappe was restricted to the Ståkåhøi (Gula) group rocks. F_1 is present as minor folds of the layering which is folded in intrafolial folds with vertical F_1 axes due to later refolding. In the schists of the Åteigen and Nysæterhøi formations, a metamorphic foliation cuts the primary lithological banding of the rocks (Fig. 6d). During mapping within the Ståkåhøi schists, it was observed that lithostratigraphic changes often occur along the strike of the main foliation, which is generally parallel to the axial trend of the major F_3 structures. Such lithostratigraphic changes along strike probably represent a transposition of foliation. The location of the earliest large-scale folds is not possible within the area as only small-scale layering discordance or tight fold hinges are preserved. This early folding event was probably responsible for the development of the pseudo-conglomeratic schists in the Grønhøi formation. Helicitic textures in some biotite and hornblende porphyroblasts (Fig. 8a) are considered to be related to this F_1 episode.

F_2 episode

In the western basement and the sparagmitic cover no deformation structures have been found which can be ascribed to this F_2 episode. A second set of recumbent folds is present in the Andbergshøi Complex and comprises isoclinal folds with axes generally plunging towards 120°. A conspicuous axial planar schistosity is associated with these folds. According to Scott (1967) and Wheeler (1973) in the Sjongsæter and Åmotsdal areas the F_1 folds and F_2 folds have about the same axial direction (E–W). In the present area the most outstanding major F_2 recumbent fold is found in the south-west, where the Andbergshøi unit disappears beneath the Trondheim Nappe (Fig. 11, Plate 1).

In the Trondheim Nappe, folds ascribed to this F_2 episode are tight to isoclinal folds with a conspicuous axial planar schistosity. F_2 mesoscopic folds recognized here are correlated with F_1 folds described by Roberts (1967) and Rui (1972) in the northern and eastern parts of the Trondheim Nappe. The trend of the fold axes and lineations, L_2, shows variations from NE–SW to E–W, a feature due to an important refolding during the F_3 episode. In the central part of the Ståkåhøi group outcrop, large-scale recumbent folds belong to this F_2 episode (Fig. 11). In the southern part of the area, the map pattern of the greenstones indicates the presence of F_2 recumbent folds with an E–W trend (Plate 1). Moreover, some sheets of the Skardkollan formation (Ståkåhøi group) appear as tectonic wedges within the Musadal group. The tectonic origin of these sheets is evident in the Sjøberget area where a tectonic contact exists between the greenstones and the Ståkåhøi schists. Locally, on Storhamnfjell



and Raudberg (Fig. 11), these sheets have been involved in megascopic folds (Fig. 12). These F_2 folds have suffered subsequent deformation during the F_3 episode; thus the thrusting of the Ståkåhøi schists onto the greenstones in this southern area pre-dates the F_2 folding episode. On a small scale within the Ståkåhøi group, F_2 folds overprinted F_1 folds to produce interference patterns of tight domes and basins which were then rotated into alignment with the later F_3 structures (Fig. 6a). The Verket conglomerate also shows superposed folding; pebbles are elongated and flattened, and within the pebbles there is a slight schistosity which appears to be of F_1 age. In conclusion, the F_2 deformation is thought to have produced large-scale recumbent folds; these were overprinted by later F_3 structures.

F_3 episode

In the mapped area the major F_3 folding is responsible for the parallelism of the different formations within the Trondheim Nappe. Folds are present on the mesoscopic scale and generally show tight to isoclinal, similar styles, with an axial planar schistosity often co-planar with the S_2 foliation (Fig 6c). This schistosity is truncated by the basal thrust plane of the Trondheim Nappe. This is clearly seen at the western border of the nappe (Plate 1), indicating that the F_3 episode either preceded or accompanied the emplacement of the Trondheim Nappe.

In the gneissic basement evidence of contemporaneous deformation is rare but a new foliation, outlined by biotite and epidote reflecting 'accordance' processes and developed close to the overlying units, is related to shear zones in the upper part of the basement. These shear zones may reflect a deformation of the basement during the translations of the nappes and illustrate the mechanism of 'mise en accordance' (Santarelli 1972).

In the sparagmitic cover, a well-developed stretching lineation is parallel to small plications along the S_1 cleavage. A strain-slip cleavage (S_3) appears regularly in the thinnest part of the sparagmitic cover and transposes the banding of the rocks into a more steeply dipping attitude. The prominent thinning of the sparagmitic cover from Skjervedal to Lesja could be explained by the earlier translation of the cover over the basement. Evidence of such a translation is found in the wedging out of distinctive conglomeratic layers and coarse clastic beds of arkose along the eastern border of the western basement.

Fig. 6. Some aspects of the small-scale tectonic structures.
a) Ståkåhøi group (brown graphitic schist); F_2 axial trace folded in S_{2-3} foliation. F_3–F_4 lineations also indicated.
b) Strongly flattened S_{2-3} plane with amphibole relics now largely replaced by biotite. L_3 lineation (stretching lineation) and L_4 lineation (rotation of the corn-like relics) indicated.
c) Section perpendicular to S_2–S_3 showing the deformed S_1 foliation (here S_2 and S_3 are parallel).
d) Banded quartzites (Ståkåhøi group) showing So trace (bedding?). The S_1 foliation coincides with the lithological differentiation surfaces. S_2 is developed as an axial plane schistosity of F_2 folds.

In the Andbergshøi Complex, the F_3 deformation is thought to have been restricted to a tightening of the previous F_1 and F_2 folds. Boudinage and stretching within the foliation is a common feature.

In the Trondheim Nappe complex, all the earlier folds, lineations and thrusts are folded together in open to tight F_3 folds. These folds are frequently overturned to the SSE, and show an important element of flattening in the Ståkåhøi schists (Fig. 6a, b). This flattening was coeval with local higher P–T conditions of metamorphism during the F_3 episode. The schistosity produced during this episode has a fan-shaped attitude within the lithologies of the Ståkåhøi and Fokstua groups. Displacements are common along this S_3 foliation, and the boundaries between lithologies are everywhere sharp. There are many mesoscopic antiformal and synformal folds, and it is considered likely that the minor folds were developing contemporaneously with these mesoscopic structures. A good example of an F_3 fold is that of the Fokstua–Nonshøi synform, where the S_3 axial plane foliation is well developed; the minor folds are here developed principally in the vicinity of major hinges, while the limbs show a significant amount of shearing, thus producing sharp contacts between the lithologies (Fig. 6d). To the north of the trondhjemite massif a major F_3 antiform occurs within the Grønhøi formation. A lineation, L_3, parallels the F_3 fold axes and corresponds to a stretching lineation as indicated by amphibole orientation and pebble elongation.

F_4 episode

The Trondheim Nappe had already been transported into its present position before the onset of the F_4 deformation. The deformation involved in this late stage demonstrates the adaptation of the allochthonous cover to a reactivated basement.

The eastern border zone of the gneissic basement shows a rapid steepening of foliation dip to the east, essentially a type of flexural folding (Fig. 11, Plate 1). The axis of this megafold is roughly N–S with a weak plunge to the south. The flexuring was coincident with an updoming of the basement west of the Driva valley in the Åmotsdal region and in the Lesja–Vågå areas. During these movements the allochthonous cover was depressed (Wegmann 1959), such that the axes of the earlier folds have steep plunges all along the western border except in the Snøhetta area.

In the parautochthonous sparagmitic cover, the effects of flexuring appear as a minor folding and slips along the S_3 cleavage which transpose the early foliation. In the Andbergshøi unit, concentric flexural folds with local disharmonic structure were developed at this stage. A weak axial planar cleavage is present and a minor crystallization of biotite occurs locally. Axes of the late folds generally trend NNE–SSW (Fig. 11).

Lithologies within the Trondheim Nappe in the present area were affected by a strain-slip cleavage which developed at a low angle to the S_3 foliation (Fig. 6a, b). This crenulation cleavage produced a crinkling of the S_3 foliation, a new linear element plunging gently to the west. This contrasts with the lineation of the major F_3 episode which plunges irregularly to the east. In the western part of the Trondheim Nappe near the thrust plane the new S_4 cleavage is parallel to the S_3 foliation, and the usually randomly orientated amphibole of the 'garbenschiefer' is here arranged in a conspicuous lineation (Fig. 6b). Generally this latest phase is only seen on a small scale as offsets and crumpling of the S_3 foliation. Many minor thrusts can be observed in the greenstones and in the Tverrâi formation, along the southern border of the trondhjemitic body and close to the contact of the southern part of the Ståkåhøi group (Figs. 11 & 12, Plate 1). In the southern part of the area, the greenstones display gentle arching structures plunging weakly to the NNW. Locally, disharmonic folding and sliding towards the west and east occur on the limbs of these gentle warps; such structures have been observed by Strand (1951) in the Vågå area.

F_5 episode

The F_5 episode consists mainly of faulting and kink-band structures. Reverse and normal faults are known along the western border of the Trondheim Nappe. These faults are locally accompanied by quartz veins and pseudotachylites. In the northern part of the area, along the Jora valley and in the western part of the Fokstua–Nonshøi synform, there are thrust faults with movements towards the north-west. This reverse faulting could represent antithetic movements following the major translation of the nappes to the E–SE. Subvertical faults with only minor displacements are also common. The dominant set has a SSW–NNE strike. A minor set with E–W strike and showing dextral horizontal displacement can be followed westwards into the basement (Plate 1). Kink bands frequently occur in conjugate sets, NW–SE and NE–SW. They are well developed in the Trondheim Nappe lithologies but are less frequent in the underlying units. In the Fokstua–Nonshøi synform, kink bands are generally associated with NW–SE reverse faults.

Metamorphism

Until the last decade the metamorphism of the Trondheim region was known principally through the work of Goldschmidt (1915), which today still represents the most important synthesis. In recent years however, detailed studies have been carried out both in the northern part (Roberts 1968b, Dudek et al. 1973, Olesen et al. 1973) and in southern districts (Mosson & Quesnel 1970, Birkeland & Nilsen 1972, Quenardel 1972b, Bøe 1974, Guezou & Poitout 1974, Pinna 1974). In the present area the metamorphic history has been studied both in the Trondheim Nappe and in the underlying units, by relating the structural history to the successive stages of mineral growth, textural relationships and the inferred thermodynamic conditions.

METAMORPHIC ASSEMBLAGES IN THE UNDERLYING UNITS

The gneissic basement

The Precambrian gneissification of earlier intrusive granitic and aplitic rocks produced the first planar texture with the formation of biotite. Feldspathic augen in the gneisses show in their inner parts relics of plagioclase (oligoclase–andesine) rimmed by K-feldspar. This suggests that granulation most severely affected the outer parts of the augen. A reaction between the two feldspars is shown by the presence of myrmekite structures. The appearance of the S_3 foliation dipping gently to the SE relates to a new crystallization of biotite and epidote. The foliation was deflected around the augen, but was also slightly bent and curved during the F_4 flexural movements. During the F_5 faulting the retrogressive assemblage chlorite + epidote + quartz was developed over wide areas. The basic dykes contain mineral assemblages of the amphibolite facies: hornblende + andesite + biotite + garnet + calcite + quartz.

In summary, the gneissic basement was probably in the upper amphibolite facies during the earlier deformation phases and then dropped to middle greenschist facies during the F_4 and F_5 episodes.

The sparagmitic cover

The quartzo–feldspathic sparagmitic rocks have a restricted mineral assemblage consisting only of quartz, albite, muscovite and K-feldspar. As noted earlier, the flaggy aspect of these rocks relates to the S_1 foliation, and the white micas, both Fe-rich muscovite and phengitic muscovite, define the L_1 lineation. A layer with abundant K-feldspar clasts shows that the rims of the porphyroclasts slightly overgrow the muscovite foliation. It is conceivable that a migration of Na and K occurred during a post-F_1 episode, but was restricted to a narrow zone around the clasts. Farther to the north, where the sparagmites are thinned along their western edge, the F_1 foliation is transposed into a more steeply dipping cleavage. A new growth of white mica occurs within this S_3 cleavage. In some places in this northern area, biotite relics appear among flakes of white mica, thus indicating that a higher grade than upper greenschist facies was probably reached. This pre-F_4 metamorphic grade must be associated with the infra-structural tectonic pattern of the sparagmitic strips north of Lesja. Chlorite is not common in this area and appears to be related to the F_5 episode.

The Andbergshøi Complex

The evolution of the metamorphic parageneses during the successive episodes of deformation in the Andbergshøi unit is somewhat obscure because of the nature of the lithologies and the complex tectonic history.

In the Veslfjell group two metamorphic assemblages can be recognized and these correspond to two foliations. In thin-sections the earlier assemblage is almost obliterated, but relics of labradorite, diopside, K-feldspar, epidote and biotite are preserved in dioritic gneisses. The later F_2 foliation (the regional foliation of the rocks) is defined by the development of biotite, epidote and white mica. In the migmatitic gneisses the growth of the feldspathic augen is related to this stage of metamorphism. In the more mafic rocks, recrystallization of hornblende and garnet was a common feature.

In the Bottheim group, the early metamorphic phase was marked by the growth of biotite, oligoclase, epidote and some garnet in the pelitic rocks, and of dark green hornblende, biotite, andesine and epidote in the greenstones. The metakeratophyres show the assemblage oligoclase, biotite and quartz. The major banding in the rocks was produced during the second episode of deformation which was coeval with the major episode of metamorphism. In the pelitic schists the mineral assemblage is that of oligoclase, white mica, staurolite, kyanite, garnet and biotite. In the amphibolites the assemblage consists of hornblende growing on previous grains, oligoclase, garnet, calcite and epidote. In metakeratophyres, biotite is replaced by muscovite, and garnet and albite are well developed. This second episode of metamorphism was characerised by an increase of both temperature and pressure. In the amphibolites, the occurrence of acid plagioclase with a significant amount of epidote and calcite in association with a blue-green hornblende is equivalent to the staurolite–kyanite zones in the pelitic metasedimentary sequence. Another significant feature of this metamorphic stage is the widespread occurrence of white mica and the growth of albite–oligoclase.

The latest stage of metamorphism is represented by retrogressive conditions in which the previous associations were largely destroyed; biotite and amphibole were chloritized although epidote, calcite, quartz and albite are still quite fresh. Chlorite has also crystallized locally along the late cleavage produced during the F_4 episode of deformation.

Timing and conditions of metamorphism in the Trondheim Nappe

The metamorphic mineral assemblages of the Trondheim Nappe complex are the result of at least five stages of metamorphism. Except for the latest crystallization the delimitation of the successive parageneses is difficult, but in this account an attempt is made to outline the relationship between metamorphism and the several deformation episodes (Figs. 7 & 10). Five metamorphic phases, M_1–M_5, have been distinguished, these corresponding to the deformation episodes F_1–F_5. In addition, an earlier contact-metamorphism event is designated M_0.

The earliest crystallogenic episodes, M_0 and M_1, occur exclusively in the Ståkåhøi (Gula) schist. Relics of andalusite and of staurolite and garnet have been observed in schists in some localities (Figs. 7 — 9c). Both S_1 and S_2 foliations are deflected around these mineral relics. Goldschmidt (1915) and more recently Nilsen & Birkeland (1972), Olesen et al. (1973) and Bøe (1974) have ascribed such mineral relics to contact metamorphism, and gabbroic intrusive complexes are present in association with these occurrences. In the Dombås–Lesja area the schists in question are either several kilometres away from any exposed trondhjemite or gabbro, or they are in tectonic contact with greenstones. If the relics are indeed the result of contact metamorphism, this metamorphic stage pre-dates the earliest F_2 deformation. Considering their spatial distribution it is even more difficult to distinguish M_0 from M_1 in the Gula Group. M_1 is thought to be represented by the paragenesis andesine–labradorite + diopside + orthoamphibole + garnet + biotite in calcareous gneisses and amphibole– pyroxene nodules. M_0 minerals are wrapped around by the S_1–S_2 foliation or scattered within graphitic trails in some amphiboles and biotites

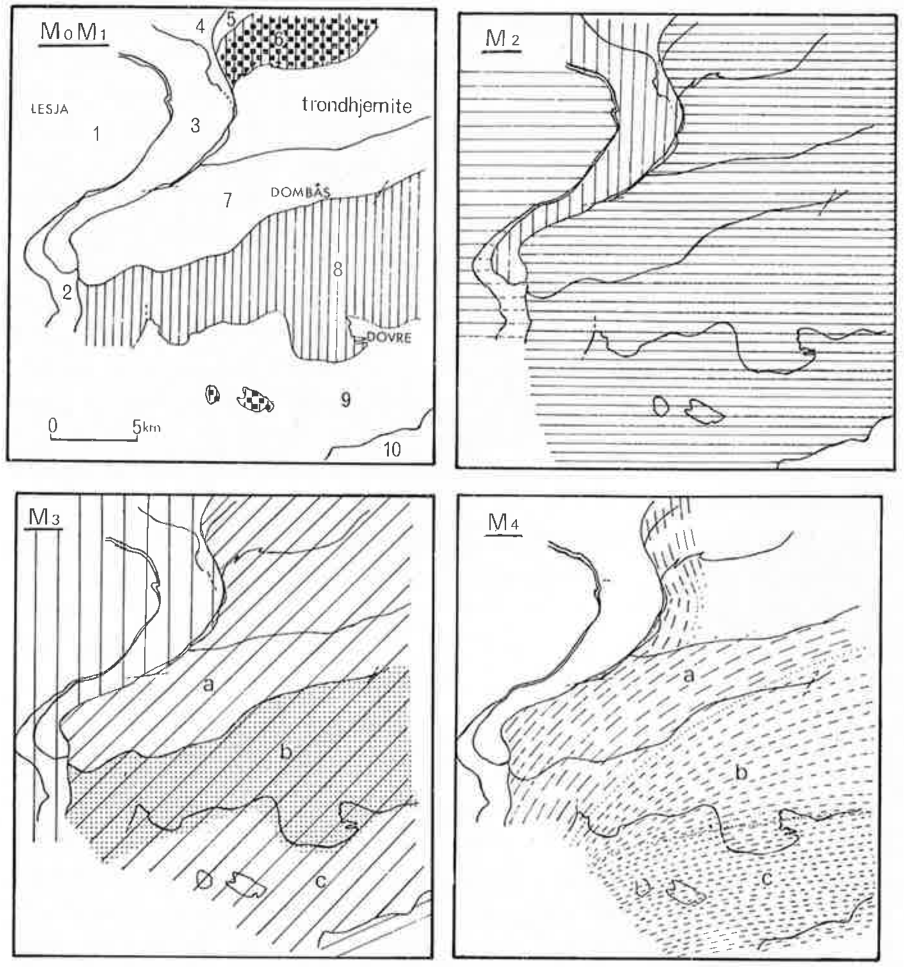


Fig. 7. Successive metamorphic phases (M_0/M_1–M_4) showing their relationship to the major tectono-stratigraphic units.
1) Eastern gneissic basement. 2) Sparagmitic cover. 3) Andbergshøi Complex. 4) Snøhetta unit. 5) Svartdalsætri formation. 6) Grønhøi formation. 7) Nonshøi formation. 8) Ståkåhøi group. 9) Musadal group. 10) South-eastern sparagmitic field.
Ruled lines indicate the main trends of foliations corresponding to the respective metamorphic episodes in the various tectono-stratigraphic units. In M_0/M_1, the black squares in unit 6 indicate the occurrence of M_0 mineral relics. In the M_3 diagram, a = middle greenschist facies, b = middle amphibolite facies, and c = lower greenschist facies. In M_4, a = biotite zone, b = biotite + garnet zone, c = chlorite zone.

(Fig. 8a). These unstable relics indicate either a regional metamorphic event or a contact metamorphism related to magmatic intrusive rocks. Considering the weak effect of the trondhjemite contact metamorphism, and the widespread regional occurrence of primary gabbroic intrusions (Berthomier & Maillot 1971) it is more likely to relate to the latter. However, as the occurrences of these relict minerals in the present area are not visibly related to intrusive rocks, they may conceivably indicate an early regional thermal metamorphism restricted to the Gula schists.

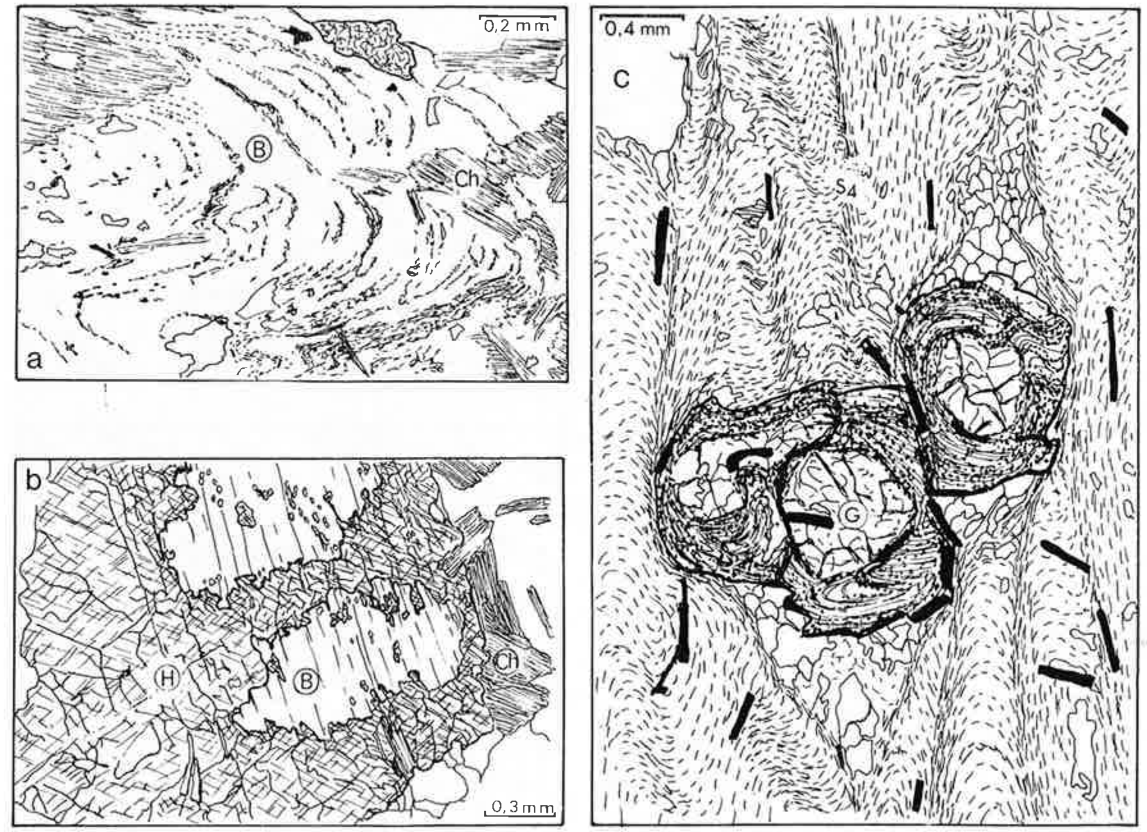


Fig. 8. Metamorphic assemblages and textures.
(a) Ståkåhøi group. Helicitic biotite porphyroblast (B); basal section with graphitic trails (S_0?) and late chlorite growth.
(b) Ståkåhøi group. Relations between hornblende (H), biotite (B) and chlorite (Ch). Cracked hornblende containing fresh biotite with relics of hornblende. The margins of the hornblende porphyroblast are chloritized.
(c) Ståkåhøi group. Late crenulation cleavage (S_4) with successive growth of garnet. A core without inclusions (G) is rimmed by a sigmoidal zone; this outer zone locally seems to be post-S_4 cleavage. Magnetite laths are now mostly parallel to the new cleavage.

The M_2 metamorphic event was widespread throughout the Trondheim Nappe. In the Musadal and Fokstua groups it constituted the first metamorphic phase. The characteristic assemblages are as follows: biotite + sodic plagioclase + tremolite + actinolite + epidote + quartz, with a transition to biotite + garnet + hornblende + plagioclase. Upper amphibolite facies assemblages have not been detected over all the area, especially in the Fokstua group where middle greenschist conditions were dominant. In the Ståkåhøi schists, biotite and hornblende include folded trails of graphite and opaques (F_1 episode). A later development (post-M_2 but pre-M_3) of rutile with sagenite twins in basal sections of M_2 biotite permits the recognition of the S_2 orientation. Moreover, the network of sagenite shows a regular orientation independent of overgrowing M_3 minerals (Fig. 9a).

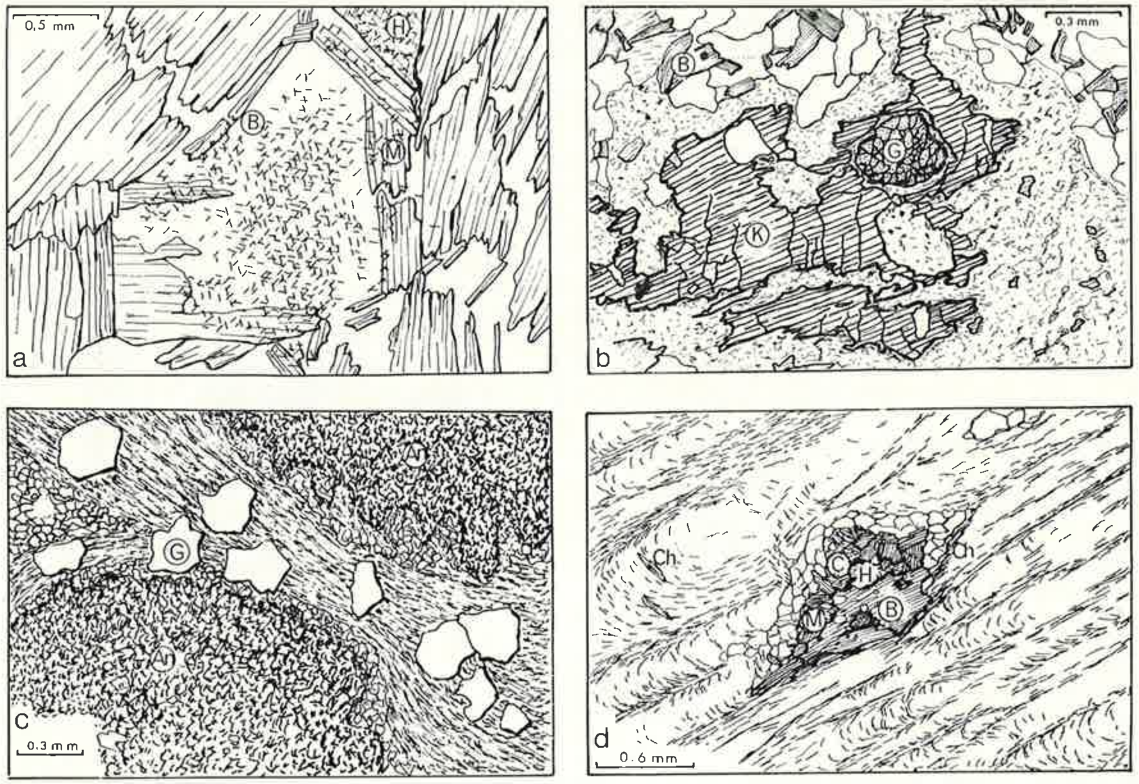


Fig. 9. (a) Ståkåhøi group. Basal section of an M_2 biotite (B) almost completely overgrown by an epitaxial crystallization of rutile (sagenite); muscovite (M) and hornblende (H) porphyroblasts (M_3 episode) discordant to the sagenite network.
(b) Ståkåhøi group; kyanite schist. Kyanite (K) partly retrograded (sericite and quartz alteration products). Late biotite and garnet (G) also present.
(c) Ståkåhøi group; graphitic schists. Retrograded andalusite (An) porhyroblasts (M_0/M_1 phase) with post-tectonic (post-S_2–S_3) growth of garnet (G).
(d) Fokstua group. Lenticular aggregate with enveloping S_4 cleavage. Earlier hornblende porhpyroblast (H) is pseudomorphed by biotite (B), muscovite (M) and calcite (C). Chlorite (Ch) growth is syn- to post-S_4.

The M_3 metamorphic episode contains a typical paragenesis of an intermediate, Barrovian type of metamorphism. The crystallization was probably staggered in two or three successive growth stages (syn- to post-F_3). The S_3 schistosity generally contains the assemblages albite–oligoclase + actinolitic hornblende + phengite + garnet + epidote + quartz in lower greenschist facies, and kyanite + almandine + oligoclase + hornblende + paragonite ± fuchsite ± epidote in middle amphibolite facies (Fig. 9b).

The general aspect of the 'garbenschiefer' is due to syn- to post-S_3 amphibole and white mica crystallization (Fig. 9a). The major mineral growth is post-F_3, but locally syn-F_3 minerals are found (garnet, staurolite, hornblende). This M_3 metamorphic mineral growth occurred at a relatively high pressure as shown by the ubiquitous occurrence of phengite, paragonite or fuchsite in the Ståkåhøi schists and the Musadal group.

Tectonic phases	S Surfaces	Metamorphic episode	TRONDHEIM NAPPE COMPLEX – STÅKÅHØI GROUP – SKARDKOLLAN Form.	TRONDHEIM NAPPE COMPLEX – STÅKÅHØI GROUP – ÅTEIGEN Formation	TRONDHEIM NAPPE COMPLEX – STÅKÅHØI GROUP – GRONHØI Formation	TRONDHEIM NAPPE COMPLEX – Fokstua group	TRONDHEIM NAPPE COMPLEX – Musadal group	ANDBERGSHØI Complex	Western basement Complex
?	So ?	Mo ?	graphitic and opaque trails		andalusite staurolite allanite			? ← ←	?
F_1	S_1	M_1	biotite garnet plagioclase (andesine-labradorite)	biotite diopside ? plagioclase (labradorite ?)	biotite garnet plagioclase (andesine-labradorite)				
F_2	S_2 L_2	M_2	biotite ortho-amphibole oligoclase epidote	biotite tremolite ? épidote-allanite	biotite garnet andésine epidote	biotite garnet oligoclase calcite epidote	biotite garnet oligoclase-andésine épidote	biotite garnet oligoclase potash feldspar epidote	
F_3	S_3 L_3	M_3	white mica (paragonite-phengite) kyanite staurolite actinolitic hornblende	white mica kyanite pargasite	biotite garnet hornblende clinozoïsite	white mica (phengite) hornblende	white mica hornblende ?	white mica kyanite staurolite potash feldspar	biotite K-feldspar epidote
F_4	S_4 L_4 strain slip	M_4	staurolite biotite garnet quartz chlorite epidote →	biotite (garnet) quartz chlorite epidote calcite →	biotite quartz chlorite epidote →	biotite quartz chlorite epidote calcite →	albite ? chlorite garnet quartz chlorite epidote calcite →	? quartz chlorite épidote albite →	quartz chlorite epidote →
F_5	kinks, faults, cataclasis	M_5							

Fig. 10. Correlation of the tectono-metamorphic events in the Dombås–Lesja area.

The M_4 metamorphic episode consists of a late and common crystallization of biotite and is seen both as a static porphyroblastesis and as epigenetic growth on amphibole. Along the southern tectonized edge of the Ståkåhøi group a late crystallization of garnet, staurolite and hornblende has also been noted (Figs. 8c, 9b). A clear example of post-nappe emplacement static growth during the M_4 stage is found in the spatial distribution of biotite porphyroblasts (Fig. 7, M_4). Biotite is generally observed along the western and northern borders of the Trondheim Nappe and around the trondhjemitic body on the northern side of the Fokstua–Nonshøi synform (Fig. 9d).

To the south, biotite + garnet occurs within the tectonic zone along the boundary between the Ståkåhøi and Musadal groups (Fig. 8c). Just to the south of this tectonic zone biotite is almost absent and amphibole is pseudomorphed by chlorite (Figs. 8a, 9d). This low-pressure retrogressive or late thermal event has earlier been noted by Olesen et al. (1973) to account for a late crystallization of sillimanite in their post-D_2 phase (equivalent to post-F_3 in the Dombås area). The present author considers these late crystallizations as dating to the M_4 metamorphic episode.

This low-pressure retrogressive event is followed by the M_5 P–T retrogression, with assemblages of chlorite, sericite, quartz, epidote and albite. This general retromorphic event post-dates the S_4 strain-slip cleavage, and is broadly coeval with the F_5 deformation episode.

CONCLUDING REMARKS ON THE METAMORPHIC DEVELOPMENT

The examination of the metamorphic assemblages and their relationships to the structural episodes provides us with information regarding the time of the nappe thrusting in the tectono–metamorphic development of the area (Fig. 10). The peak of the Barrovian regional metamorphism in this area coincides with the F_3 fold episode. Considering the zonal distribution of the metamorphic assemblages in the southern part of the Trondheim Nappe, one can recognize an early M_0–M_1 episode restricted to the Gula Group and characterized by a regional high-temperature metamorphism. The spatial disjunction of this metamorphism from the heat source must be associated with an early pre-F_2 tectonic episode. The apparent association of this M_0–M_1 thermo-metamorphic episode with eo-Caledonian intrusive basic complexes shows similarities with an important late Cambrian tectonic and metamorphic event reported from the northern Caledonides (Sturt et al. 1967, 1975a, Sturt & Pringle 1969, Bechennec & Hervé 1973) and recently noted in the Bergen area (Sturt & Thon 1975, Sturt et al. 1975b). It is thought that such a metamorphic and magmatic event occurred in the inner parts of the Caledonian orogenic belt.

Mineral assemblages developed in the Fokstua group lithologies during M_2 indicate greenschist facies conditions, whereas upper amphibolite facies prevailed in the Musadal group. M_3 metamorphic isograds, where determinable, are roughly parallel to the F_3 regional structures with ENE–WSW strike. In the north-eastern part of the Trondheim Nappe, Dudek et al. (1973) have shown that the isograds there are slightly discordant to the stratigraphic boundaries. The accurate trend of the isograds has not been traced in the present case, but from the relationships found along the eastern border of the Gula Group, this would indicate an important shortening or narrowing of the metamorphic zoning between the lower greenschist facies and middle amphibolite facies; this would point to a higher P–T gradient within the Gula Group. This narrowing of the metamorphic zones could be explained by a sort of 'effet de socle' (Fonteilles & Guitard 1968) taking into account that the Gula schists suffered a previous medium-grade metamorphism.

The areal distribution of the M_4 mineral growth indicates either a local higher temperature or a slow cooling. The location of this slow cooling in the vicinity of faults, thrust zones and intrusive rocks is interpreted as a result of local heat convection and heat conduction during this late tectonic period. The biotite and garnet isograds on both sides of the Trondheim Nappe, along the north-western and south-eastern borders of the Gula Group, are therefore regarded as relating to a late thermal event post-dating the nappe emplacement.

Conclusions

The Lesja–Dombås area is composed of four separate tectonic complexes each with distinctive lithologies:

1. A western gneissic basement. 2. A sparagmitic cover. 3. The Andbergshøi Complex. 4. The Trondheim Nappe.

Most of the sediments constituting the sparagmitic cover and the Andbergshøi Complex are probably Precambrian in age. The parautochthonous arkosic and quartzitic cover is considered to represent a western extension of the late Precambrian (Varegian or Vendian) deposits. Unfortunately, the continuity of this sparagmitic cover with the well-studied south-eastern region (Kvitvola–Muen Nappes) cannot be demonstrated. The sparagmitic cover disappears along an important fault zone in the Vågå area (Prost 1975). If this sparagmitic unit is of Vendian age, as thought by the author, an important implication is that the complex tectonic pattern shown by this cover along the western border of the Trondheim Nappe represents a Caledonian imprint; thus the underlying gneissic basement has been strongly reworked in Caledonian time.

A second problem is raised by the recognition of the new tectonic unit, the Andbergshøi Complex. Except in the Snøhetta area, where another tectonic sheet of Precambrian rocks has overthrust the Andbergshøi unit (Fig. 11), the continuity of this unit underlying the Trondheim Nappe can be demonstrated up to Åmotsdal (Wheeler, pers. comm. 1972). The lithology of the complex is exceedingly heterogeneous. Precambrian gneissic rocks and quartzites are present as tectonic slices. Various basic and ultrabasic rocks (in the Sjongsæter area) are interlayered with metasediments, The basic rocks (metavolcanics) could possibly be compared with the Paleozoic metavolcanics of the Trondheim Nappe, but they may just as well be of Precambrian age. From a structural point of view and considering the occurrences of ultrabasic rocks and augen gneisses, one may conceivably compare the Andbergshøi Complex with the Seve Nappe in Sweden.

Along the southern border of the Trondheim Nappe, Heim (1972) described a separate tectonic unit, the Grimsa unit, which lies between the Trondheim

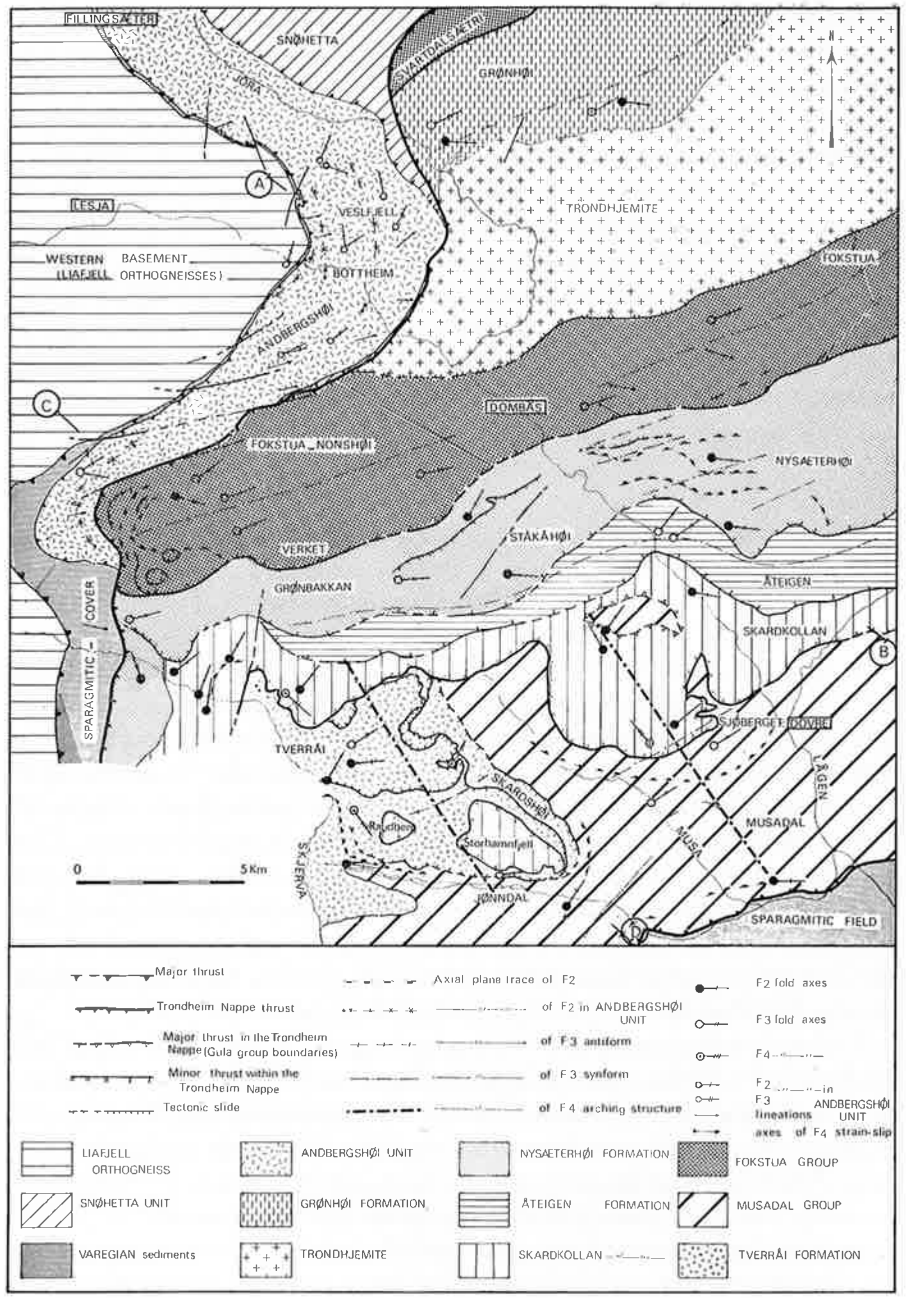


Fig. 11. The principal structures and tectono-stratigraphic units of the Dombås–Lesja area. A–B and C–D—lines of section (see Fig. 12).

Nappe and the Kvitvola–Muen Nappe. The Grimsa unit is made up of the same lithologies as the Andbergshøi Complex (i.e., mica schists, augen gneisses, quartzites and ultrabasic lenses). This unit gradually wedges out against the Trondheim Nappe thrust but continues eastward as thin strips of augen

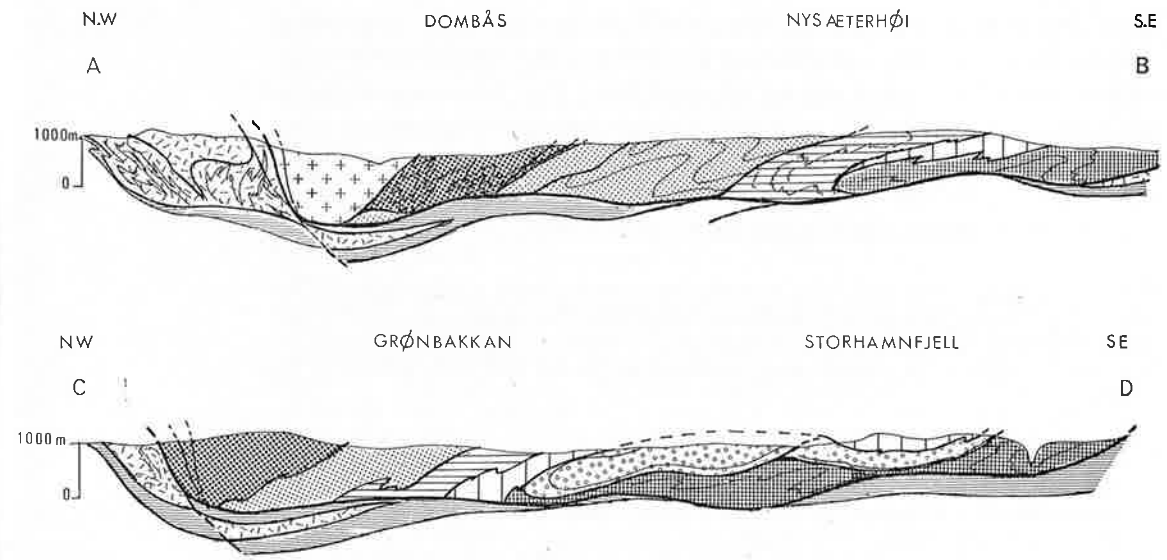


Fig. 12. Geological sections. For legend and section lines, see Fig. 11.

gneisses. Such a structural interpretation was proposed by Törnebohm (1896) (The great Seve Nappe); this hypothesis deserves reconsideration.

The Trondheim Nappe involves mainly Lower Paleozoic rocks. The rock sequence of the Dombås–Lesja area has been divided on a lithostratigraphic basis into three groups: 1. The Ståkåhøi group (= The Gula Group); 2. The Musadal group (= The Fundsjø Group); 3. The Fokstua group (= The Lower Hovin Group). The Ståkåhøi group consists of various schists and psammites with some amphibolites considered as typical for the entire Gula Group. The lithological succession characterizes an epicontinental type of deposition; consequently the Gula schists can no longer be considered as eugeosynclinal deposits. The age of the Gula schists, however, remains an open question. As a tectonic contact exists all along the eastern and western borders of the Gula Group, the largely Ordovician age of the surrounding groups (the Støren/Fundsjø Groups and the Lower Hovin Group) cannot be used to signify a probable Cambrian age for the Gula Group (cf. Gale & Roberts 1974).

The Fokstua group, occupying the core of a synformal structure and correlated with the Lower Hovin Group, is interpreted as an eastern outlier of the western part of the Trondheim Supergroup rock sequence, an hypothesis first proposed by Heim (1972).

The Trondheim Nappe rocks were subjected to five tectonic episodes in the Ståkåhøi group, but only four in the other groups. These are accompanied by metamorphic events. The earliest episode, F_1, is recorded only in the Ståkåhøi group. In the Dombås area, the 'troncation' along the Trondheim Nappe thrust is particularly evident and can be clearly dated as post-F_3/M_3. Other major and minor thrusts are present within the Trondheim Nappe, which could now well be termed the Trondheim Nappe Complex.

The polyphase metamorphism can be dated relative to the nappe emplacement. The peak of the Barrovian metamorphism was in middle amphibolite facies, marked by kyanite crystallization in the Gula schists which have probably suffered an earlier regional thermal metamorphism. This early metamorphism has to be taken into account to explain the convergence of the isograds along the Gula Group margins. The Caledonian metamorphism would appear to have been of an intermediate Barrovian type (Zwart 1969) rather than of an Hercynian type as previously suggested by Dudek et al. (1973).

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