A PRELIMINARY ACCOUNT ON THE GEOLOGY OF THE SELBU-TYDAL AREA, THE TRONDHEIM REGION, CENTRAL NORWEGIAN CALEDONIDES

BY

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ABSTRACT

Sediments and volcanic rocks (ophiolites) all of early Palaeozoic age were metamorphosed, multiply deformed, and intruded by igneous rocks during the Caledonian orogeny. At least six deformation phases including late faults are recognized. There is no simple correlation between deformation phases and tectonic style. The second deformation phase (D_2) is accompanied by Barrovian type metamorphism, ranging from biotite to sillimanite grade, and transposes earlier surfaces into a new foliation, which is itself folded on a regional scale. The transposition foliation varies from crenulation cleavage to schistosity. Basic intrusives are rimmed by contact metamorphic aureoles also of syn-D_2 age. Acid intrusives are of syn- to post-D_2 age. Structural and stratigraphic correlations with nearby areas are attempted. An Ordovician/Silurian age is suggested for the Gula Schist Group.

INTRODUCTION

The Selbu-Tydal area is situated about 75 km ESE of Trondheim (index map, Fig. 1). It is underlain by rocks of early Palaeozoic age, belonging to the Trondheim Nappe (Wolff, 1967, p. 129).

The purpose of this paper is to present some results of a mapping programme, which was initiated in 1968 and is continuing under the direction of Professor Dr. H. J. Zwart, Leiden, the Netherlands.

The Trondheim region has been of geological interest for many years. Since the descriptions of Keilhau (1850) numerous geologists have described rocks and structures of the region, resulting in many different interpretations particularly of the regional structure. The literature has been extensively reviewed by Wolff (1967) and Roberts (1967). A useful review of the geology of the northern Trondheim region has recently been published by Roberts et al. (1970).

Recent mapping programmes in the Meråker area (Chaloupský & Fediuk, 1967; Roberts, 1967, 1968a, 1971; Siedlecka, 1967; Siedlecka & Siedlecki, 1967; Wolff, 1967) and in the Röros district (Nilsen, 1971; Birkeland & Nilsen, 1972; Nilsen & Mukherjee, 1972; Rui, 1972) have dealt with rocks similar to those described here. Kisch (1962) and Torske (1965) described areas immediately adjoining the Selbu-Tydal area.

LITHOLOGY

Fig. 1 is a simplified geological map of the area studied. It comprises a sequence of multiply deformed and metamorphosed sedimentary and volcanic rocks, which are divided into four groups: the Gula Schist Group, the Stören Group, the Fundsjö Group, and the Sulåmo Group (Wolff, 1967), all of which were intruded by syn-orogenic, acid and basic plutonic rocks.

The Gula Schist Group
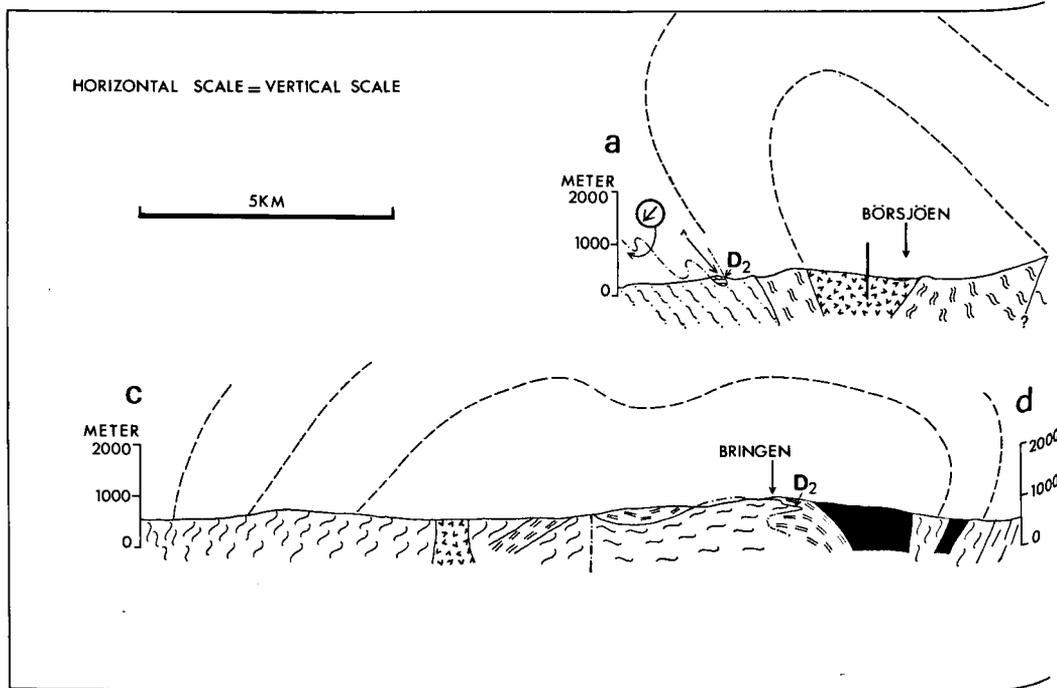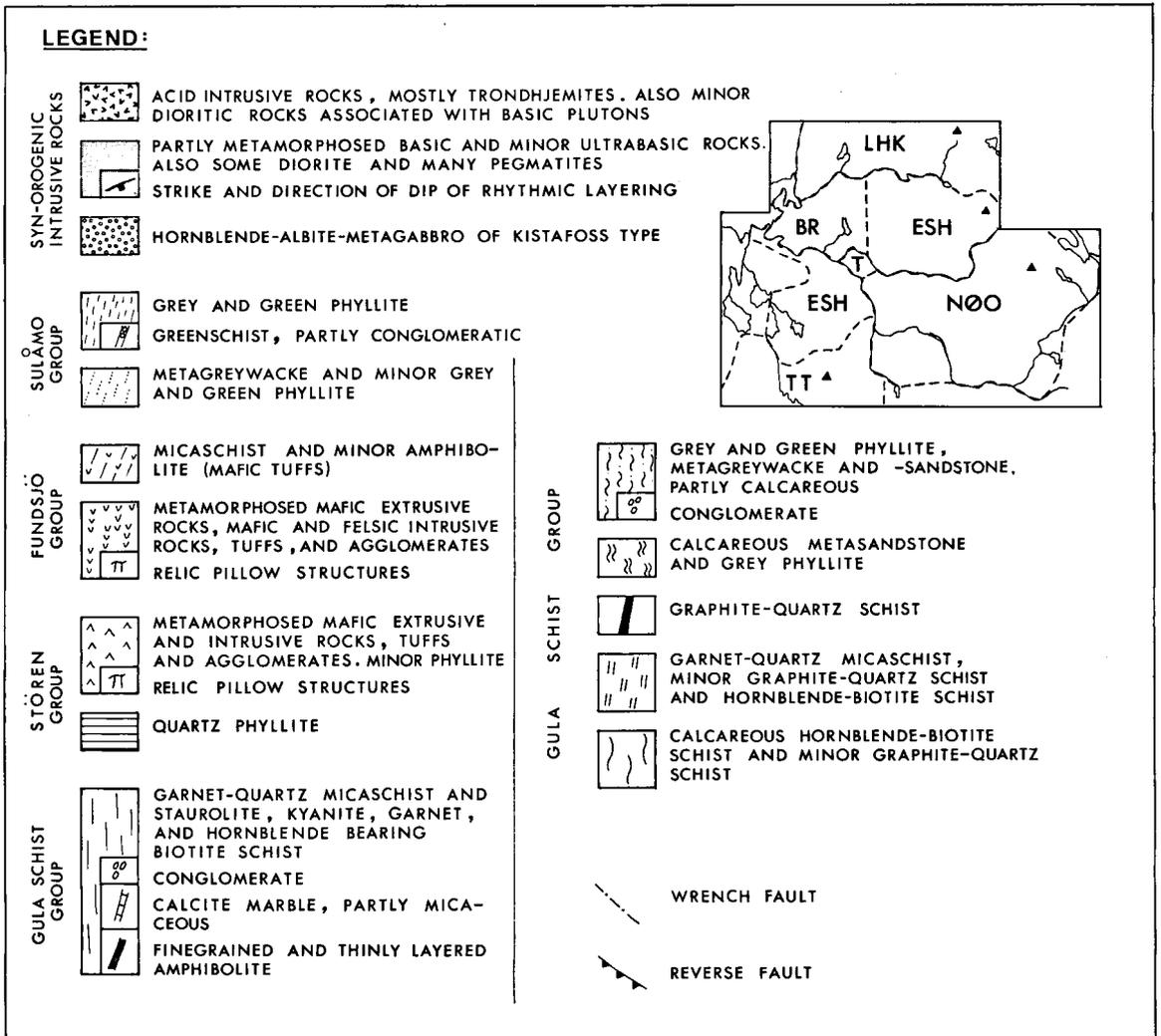The Gula Schist Group occupies the core of a major

Fig. 1. Simplified geological map of the Selbu-Tydal area. Lithological boundaries both certain and uncertain. Strike of S_2 foliation indicated by elongation of lithological symbols. Section-lines refer to Fig. 2.
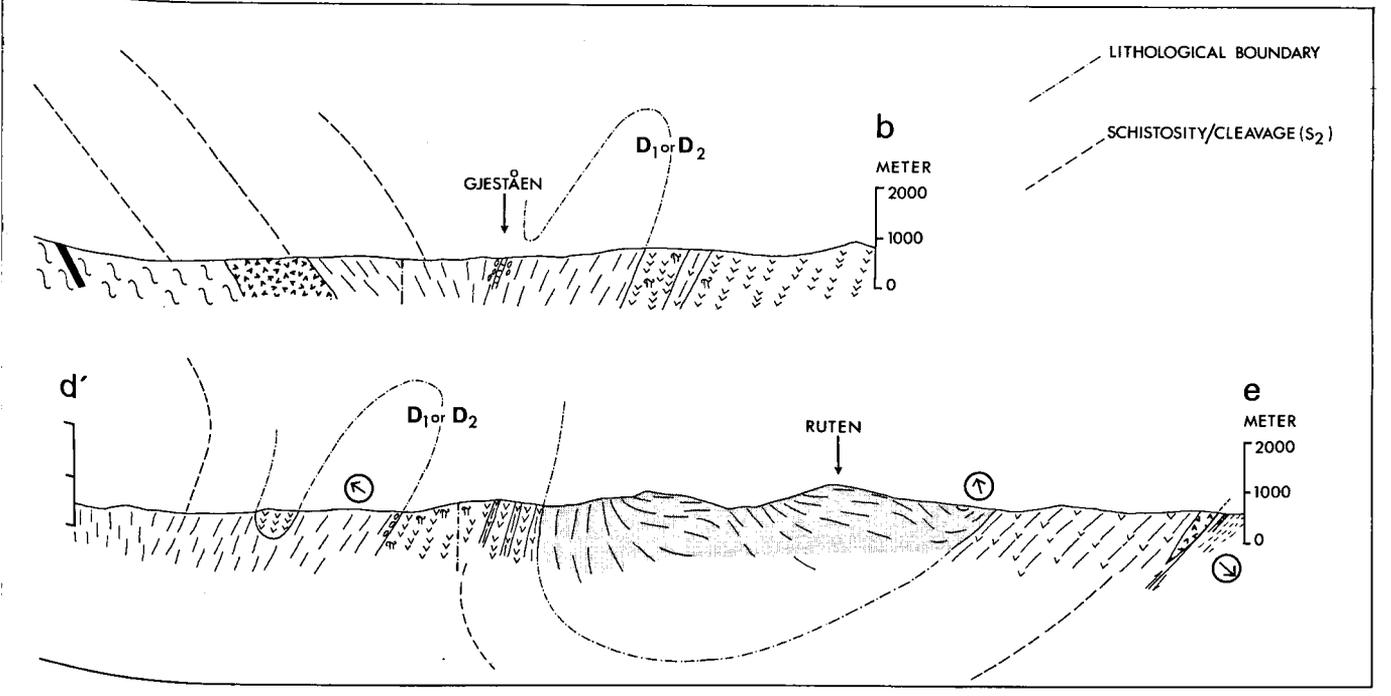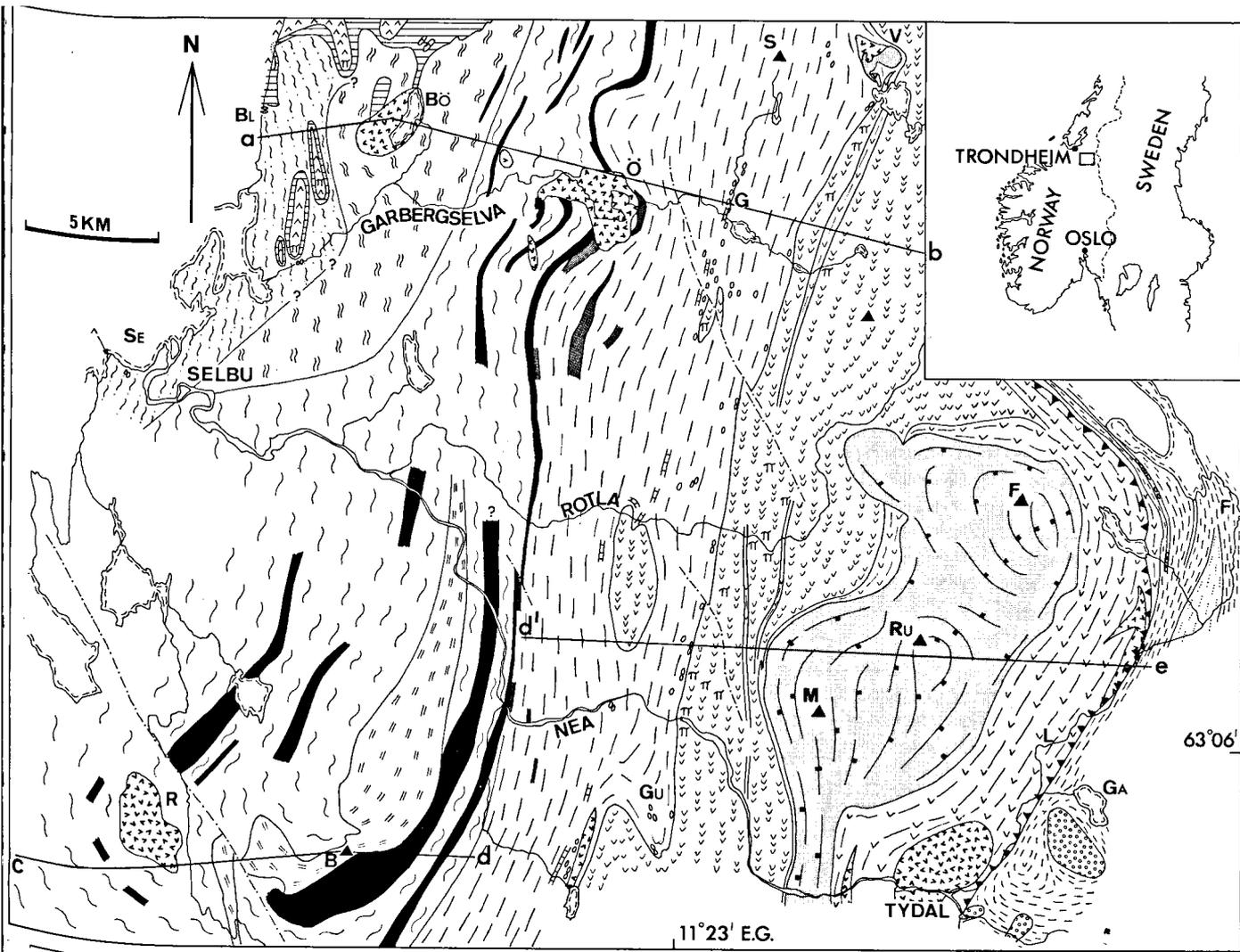Geology by: BR: Børge Rasmussen; ESH: Erik S. Hansen; LHK: Leif H. Kristensen; NØO: Niels Ø. Olesen; TT: Tage Thyrsted; T: traversed.
Names of localities: B: Bringen Mt.; Bl: Blomlia; Bö: Börsjöen; F: Fongen Mt.; Fi: Finnkoihögda; G: Gjeståen; Ga: Gammelvollsjöen; Gu: Gudbrandegga; L: Lödölja; M: Melshogna Mt.; R: Ristjerna; Ru: Ruten Mt.; S: Storskarven Mt.; Se: Selbusjöen; V: Vålåkleppen Mt.; Ö: Öielva.

Fig. 2. Sections through the Selbu-Tydal area. Section-lines indicated in Fig. 1. For identification of lithology, see Fig. 1. Arrow in circle shows direction of younging where indicated by primary structures. Further explanation in the text.

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LEGEND:

SYN-OROGENIC INTRUSIVE ROCKS

ACID INTRUSIVE ROCKS, MOSTLY TRONDHJEMITES. ALSO MINOR DIORITIC ROCKS ASSOCIATED WITH BASIC PLUTONS

PARTLY METAMORPHOSED BASIC AND MINOR ULTRABASIC ROCKS. ALSO SOME DIORITE AND MANY PEGMATITES

STRIKE AND DIRECTION OF DIP OF RHYTHMIC LAYERING

HORNBLENDE-ALBITE-METAGABBRO OF KISTAFOSS TYPE

SULÅMO GROUP

GREY AND GREEN PHYLLITE

GREENSCHIST, PARTLY CONGLOMERATIC

METAGREYWACKE AND MINOR GREY AND GREEN PHYLLITE

FUNDSJÖ GROUP

MICASCHIST AND MINOR AMPHIBOLITE (MAFIC TUFFS)

METAMORPHOSED MAFIC EXTRUSIVE ROCKS, MAFIC AND FELSIC INTRUSIVE ROCKS, TUFFS, AND AGGLOMERATES

RELIC PILLOW STRUCTURES

STÖREN GROUP

METAMORPHOSED MAFIC EXTRUSIVE AND INTRUSIVE ROCKS, TUFFS AND AGGLOMERATES. MINOR PHYLLITE

RELIC PILLOW STRUCTURES

QUARTZ PHYLLITE

GULA SCHIST GROUP

GARNET-QUARTZ MICASCHIST AND STAUROLITE, KYANITE, GARNET, AND HORNBLENDE BEARING BIOTITE SCHIST

CONGLOMERATE

CALCITE MARBLE, PARTLY MICACEOUS

FINEGRAINED AND THINLY LAYERED AMPHIBOLITE

GULA SCHIST GROUP

GREY AND GREEN PHYLLITE, METAGREYWACKE AND -SANDSTONE, PARTLY CALCAREOUS

CONGLOMERATE

CALCAREOUS METASANDSTONE AND GREY PHYLLITE

GRAPHITE-QUARTZ SCHIST

GARNET-QUARTZ MICASCHIST, MINOR GRAPHITE-QUARTZ SCHIST AND HORNBLENDE-BIOTITE SCHIST

CALCAREOUS HORNBLENDE-BIOTITE SCHIST AND MINOR GRAPHITE-QUARTZ SCHIST

WRENCH FAULT

REVERSE FAULT

LHK

BR

ESH

T

ESH

NØO

TT

HORIZONTAL SCALE = VERTICAL SCALE

5 KM

a

METER
2000

1000

0

D_2

BÖRSJÖEN

c

METER
2000

1000

0

BRINGEN

D_2

d

2000

1000

0

N

5 KM

B L
a

BÖ

Ö

G

b

GARBERGSELVA

S

V

TRONDHEIM

NORWAY

SWEDEN

OSLO

S E

SELBU

ROTLA

F

F i

d'

Ru

e

NEA

M

63°06'

Gu

R

B

c   d

TYDAL

L

Ga

11°23' E.G.

LITHOLOGICAL BOUNDARY

SCHISTOSITY/CLEAVAGE (S₂)

b

D₁ or D₂

GJESTÅEN

METER

2000

1000

0

d'

D₁ or D₂

RUTEN

e

METER

2000

1000

0

antiformal structure. The deepest exposed rocks outcrop around Bringen mountain (all names in this paper are indicated on Fig. 1). They are calcareous hornblende-biotite schists and garnet-quartz micaschists, interbedded with graphite-quartz schists, and they occur in a broad zone, which tapers towards the north.

To the northwest and east other pelitic metasediments, in varying grades of metamorphic transformation, structurally overlie the schists described above (Fig. 2). Around Börsjöen and Selbusjöen the common rock types are grey and green phyllites interlayered with metagreywackes and metasandstones, which are often calcareous. In one locality (Blomlia) the phyllite is interbedded with a polymict metaconglomerate, in which quartzite and metabasite pebbles predominate. To the east garnet-quartz micaschist grades into biotite schist, which commonly contains numerous porphyroblasts of staurolite, kyanite, garnet (e.g. the Kvernfjell-horizon, see e.g. Carstens, 1928), and hornblende. The micaschists are commonly interlayered with calc-silicate rocks and quartzitic sandstones, apparently equivalents of the metasandstones and metagreywackes of the western phyllites.

At two localities good graded bedding was observed. One occurrence is in metagreywacke at the outlet of Garbergselva, and the other is in micaschist at Rotla river one km west of the Fundsjö Group. The younging directions at these localities are indicated on Fig. 2.

Several discontinuous layers of fine-grained, thinly layered amphibolite were observed in the eastern Gula Schist Group. They may be equivalent to the Gula greenstone of Nilsen & Mukherjee (1972, p. 160).

Along the entire eastern boundary of the Gula Schist Group there is a zone of conglomerate-bearing micaschist, which can be traced into the Usmadam-Bukhammerfjell metaconglomerate of Kisch (1962, p. 52). These conglomerates should probably be correlated with the Gudå conglomerate to the north (Wolff, 1964). In the area mapped the conglomerate is generally an oligomict quartzite conglomerate with an amphibolitic matrix. However, around Gjeståen it is a polymict conglomerate. Quartzite and metabasite pebbles predominate, and pebbles of blastoporphyritic metadolerite (Fig. 3) and marble also occur (Kristensen, 1972, p. 29).

Calcite marble, sometimes micaceous, occurs locally in the same zone (cf. the Vollfjell limestone, Vogt, 1940, p. 180; Kisch, 1962, p. 18).

The Stören Group

An ophiolitic*) sequence of metabasites (locally with relict pillow structures), mafic metatuffs, meta-agglomerates, and some layers of phyllite is separated from the rocks of the Gula Schist Group by a distinct

*) The term 'ophiolite' is used here in the sense of geosynclinal, mainly mafic, volcanic rocks, not implying that they represent ancient ocean floor.
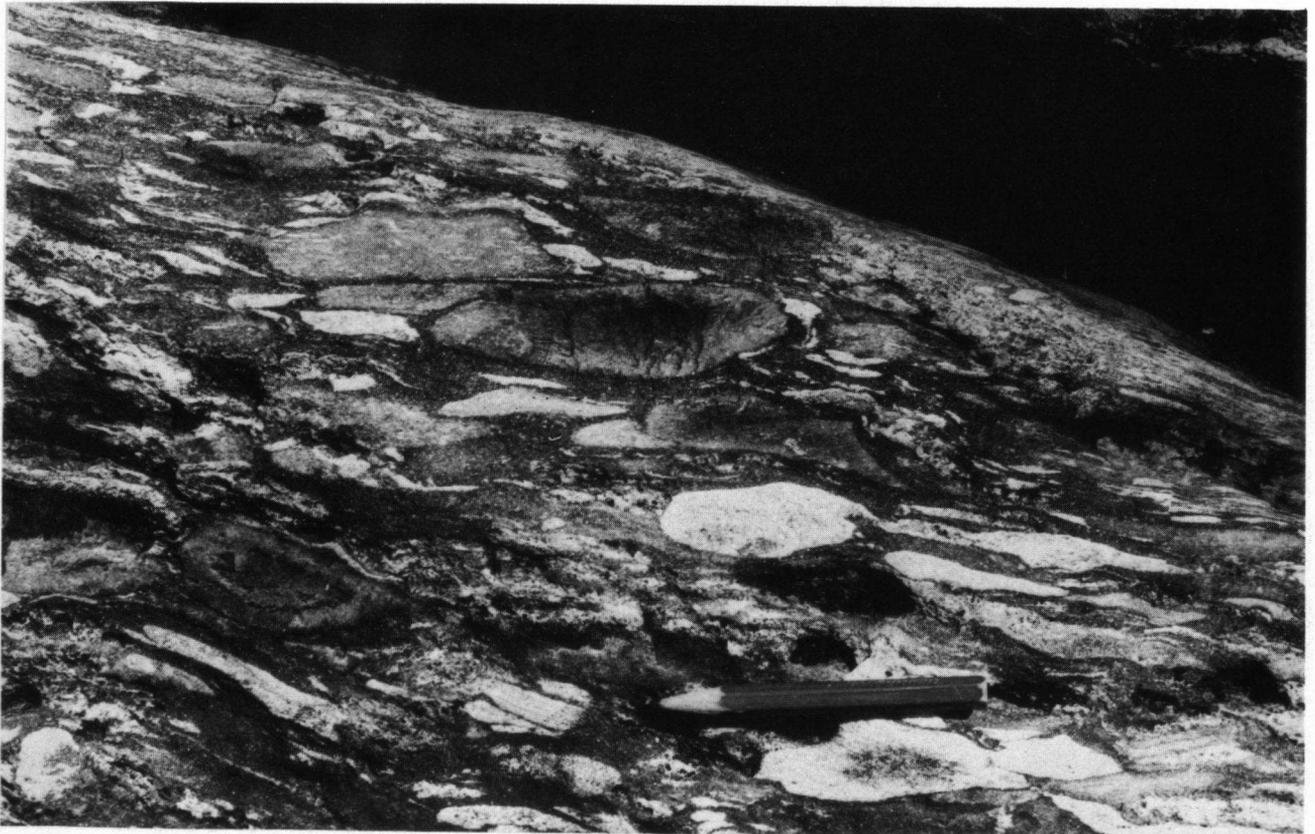

Fig. 3. Polymict metaconglomerate at Gjeståen. Large pebbles in upper left part are deformed blastoporphyritic metadolerite.

sequence of quartz phyllite. The latter is equivalent to the quartz schist of Torske (1965), and typically displays an interlayering on the cm scale of light quartzite and dark phyllite.

The outcrop pattern is dominated by N–S trending synformal structures, the cores of which are occupied by the ophiolites.

The Fundsjö Group

Metabasites, locally with relict pillow structures (Fig. 4), metatuffs, mafic as well as felsic, meta-agglomerates, and some layers of locally graphitic metapelites are the dominant rock types. The only major difference from the rocks of the Stören Group is a higher grade of metamorphism. Intrusive blastoporphyritic metadolerites and metaquartz-keratophyres are locally prominent. By virtue of their association with the pillow lavas they are believed to be syn-depositional, high-level intrusives, with the exception of some metadolerites occurring in the vicinity of the Fongen-Melshogna igneous complex (see p. 264).

These rocks form a major unit, dominating the eastern part of the investigated area. They also outcrop within the Gula Schist Group in isolated occurrences, which probably are the result of large scale folding of early age.

The metamorphosed pillow lavas occur as 'wedges' surrounded by tuffs and pelitic sediments, which commonly grade laterally into one another. This pattern is believed to be of primary origin.

The nature of the Fundsjö Group changes drastically towards the east, pelitic and semi-pelitic metasediments with intercalations of mafic tuffs being the main rock types.

The Sulåmo Group

East of the Fundsjö Group, around Finnkoihögda and Gammelvollsjöen, grey and green phyllites, locally graphitic or calcareous, are intercalated with metagreywackes and metasandstones and some layers of conglomeratic greenschist. The sequence structurally underlies the rocks of the Fundsjö Group.

In one locality south of Finnkoihögda distinct graded beds were observed in metagreywacke, indicating an upside-down disposition of the rocks (Fig. 2).

The conglomerates are polymict, containing pebbles of metabasite, quartz-keratophyre and quartzite, and should probably be correlated with the Lille Fundsjö conglomerate (Chaloupský & Fediuk, 1967, p. 12).

Towards the south the phyllites are porphyroblastic (biotite, garnet, and occasionally Ca-amphibole), resembling the Stuedalsschists of Reusch (1890, p. 31; 1896, p. 24).

Fig. 4. Weakly deformed metabasite with relict pillow structures. Locality from the river Rotla. Looking NW.

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Intrusive Rocks

In addition to the syn-depositional mafic and felsic intrusive rocks of the ophiolites described above, synorogenic igneous activity is evidenced by the presence of acid, intermediate, and basic intrusive rocks. Most of the acid, plutonic rocks are trondhjemitic types (Goldschmidt, 1916, p. 77). They occur partly as large bodies (e.g. at Börsjöen, Öielva, and Ristjerna), and partly as dykes or sills, which in places occur as swarms. In the latter case the trondhjemites may even be the dominant rock type (e.g. at Tydal). They show some petrographic variation (see e.g. Kisch, 1962), as well as varying structural relationships. Some trondhjemites cut across the regional schistosity and have the original igneous fabric throughout. These obviously postdate any penetrative deformations associated with the development of the regional schistosity. Most trondhjemites, however, though they cut across the regional schistosity, are themselves foliated parallel to this surface. Intrusion of these rocks therefore was contemporaneous with the development of the regional schistosity. This establishes the trondhjemitic intrusive activity as syn- to post-metamorphic (see *Timing of metamorphism*).

Basic igneous rocks principally occur in the Fongen-Melshogna igneous complex, which is a layered, sheet-like body, attaining a maximum thickness of at least 5 km. It is apparently thickest towards the west, and thins rapidly towards the east (Fig. 2). It is folded and occupies the core of an asymmetrical synform. The rocks of the complex vary in composition from peridotites, through pyroxene-gabbros, partly olivine-bearing, to diorites, all of which are in places cut by numerous biotite or hornblende pegmatites. A major part of the complex shows a well developed primary, rhythmic layering, which is commonly graded. Occasionally primary structures such as slumping are developed. In one locality on the eastern slope of Fongen mountain an erosional disconformity in the rhythmic layering (Fig. 5) indicates that the body in general lies in a right-side-up disposition (Fig. 2). However, it is inverted locally since it is folded into an overturned s y n c l i n e . Fig. 1 shows that the intrusive body is discordant to the lithological boundaries and it is also discordant to an early schistosity (see *Timing of metamorphism*). The igneous rocks are to a varying extent transformed to hornblende-metagabbros, and locally have attained a secondary foliation concordant with the regional schistosity. An extensive contact metamorphic aureole is developed around the body (see p. 270, and Olesen, 1972).

A large number of sills and dykes of blastoporphyritic metadolerite, showing structural relationships similar to those of the Fongen-Melshogna complex, occur particularly in the rocks of the contact aureole. They are probably contemporaneous with the main body.

A small sheet-like body of pyroxene-gabbro, largely transformed to hornblende-metagabbro, outcrops on
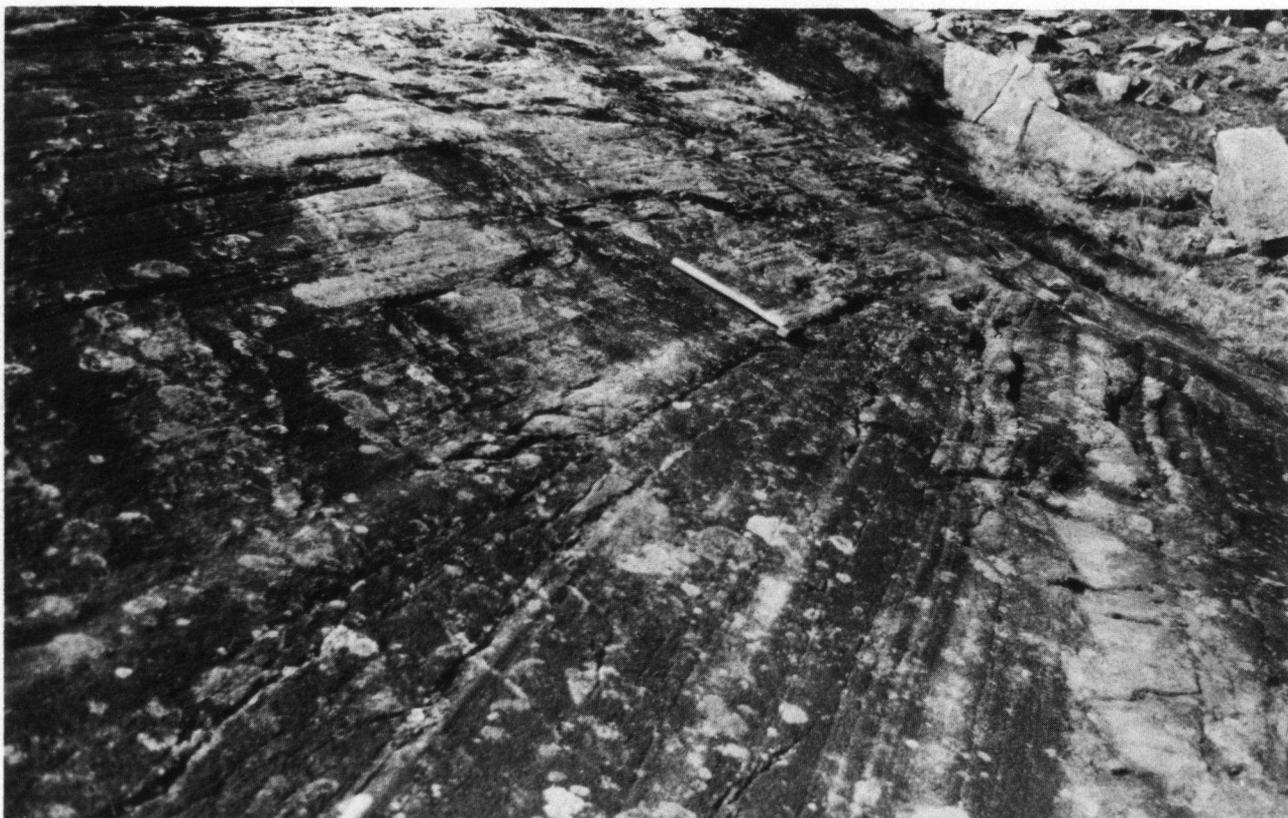

Fig. 5. Erosional disconformity in rhythmic layering of the Fongen-Melshogna igneous complex. Eastern slope of Fongen mountain.

Vålåkleppen mountain (Kristensen, 1972, p. 45). It is also associated with dioritic rock types, is discordant with the country rocks, and has a contact aureole.

Finally a group of hornblende-albite metagabbros outcrop east of Tydal (the Kistafoss metagabbros of Kisch, 1962, p. 56). They occur as major sills in the phyllites. Local cross-cutting relationships with the schistosity were observed in the area mapped, and Kisch (op. cit., p. 57) also reports discordant apophyses. However, the bodies are also locally foliated parallel to the regional schistosity.

All the basic and associated intermediate rocks, described here, thus show identical structural relationships, suggesting contemporaneous intrusion.

STRUCTURAL SEQUENCE

Introduction

Most rocks of the Selbu-Tydal area are metamorphic tectonites. Prominent exceptions are the majority of syn-orogenic intrusive rocks, which, as described above, are only locally deformed penetratively. Also parts of the ophiolitic sequence of the Stören and Fundsjö Groups, particularly the metabasites, were competent enough to avoid penetrative deformation.

The following terminology is used: S denotes an s-surface, e.g. the surface defined by preferred dimensional orientation of minerals, or by a crenulation cleavage. The minerals defining schistosity may concomitantly define a linear fabric. Such a lineation is denoted L. Quartz-rods and elongation direction of deformed pebbles are also denoted by this symbol. Fold axes are denoted by F. Subscript numerals are added to denote relative age relationships, e.g. S_2 overprints S_1, and a group of symbols with a common subscript (e.g. S_2, L_2, and F_2) comprises structural elements of a single deformation phase (D_2).

Basis for proposed structural sequence

The rocks indicate a long sequence of deformations. The many folds, observed in the area, may be subdivided on the basis of tectonic style (Turner & Weiss, 1963, p. 78–79) into four style groups:
s t y l e   g r o u p   1 comprises tight to isoclinal folds with an axial plane schistosity,
s t y l e   g r o u p   2 comprises tight to isoclinal folds with an axial plane crenulation cleavage,
s t y l e   g r o u p   3 comprises open to tight folds with no axial plane foliation,
s t y l e   g r o u p   4 comprises kink-bands, which partly occur as conjugate sets.

Numerous superimposed fold patterns demonstrate that the folds belong to a number of fold generations. It has been possible, however, to demonstrate that there is no straightforward correlation between tectonic style and the fold generations.

Independently of tectonic style the folds and other structures may be subdivided with a high degree of confidence into two major age groups, using as reference surface a prominent foliation, which is recognized throughout the Selbu-Tydal area. The foliation can be observed in most outcrops and can be traced from outcrop to outcrop by similarity in morphology, by orientation, and by a contemporaneous relationship to the main regional metamorphism (see *Timing of metamorphism*). Although similarity exists over short distances, a regional variation in morphology and orientation is apparent (see p. 266 and p. 268). This foliation will be referred to as S_2. Folds and other structures pre- or syndating S_2 are collectively referred to as Group I, while those postdating S_2 are referred to as Group II. Thus Group II structures consistently overprint Group I structures. The groups do not, however, constitute fold generations, as superimposed fold patterns occur within each group. Thus there are folds with S_2 as their axial plane surface folding earlier folds; both by definition are Group I folds (D_1 and D_2 of Table I). Within Group II kink-bands, occurring partly as conjugate sets, form a very distinct style group, which is associated with faults and retrograde metamorphism. These structures consistently overprint other structures of the group. Apart from these late kink-bands and faults, a large number of Group II folds remain, and they have been separated into three sets on the basis of orientation of axial plane and sense of asymmetry. Due to overprinting relationships (of varying confidence) the sets of folds are assigned to separate deformation phases.

Table I shows the structural age sequence and the corresponding style groups. It is evident that with the exception of kinks any individual style group is not restricted to one deformation phase. Nor is a specific deformation phase always characterized by a specific style. Similar discordant relations between tectonic style and fold generations are described by Means (1966) and Williams (1970).

Structural age sequence			Style groups
Group II		Kink-bands & faults	(3)+ 4
	? ?	Selbu-Tydal phase	3
		Finnkoihögda phase	2 + 3
		Gudbrandegga phase	(1)+ 2 + (3)
Group I		D_2	1 + 2
		D_1	1

Table I. () refer to minor occurrences.

Group I

In the lower grade parts of the Selbu-Tydal area a few mesoscopic, isoclinal folds with axial plane schistosity (S_1) have been observed. Most mesoscopic folds, however, are tight to isoclinal with axial plane crenulation cleavage (S_2). The latter folds consistently overprint the former, and S_2 is developed by transposition of the older S_1 schistosity. Thus there are at least two generations of Group I folds, D_1 and D_2 respectively.

Fig. 6. Tight Group I folds with S_2 axial plane schistosity, overprinted by folds and crenulation cleavage (parallel to pencil) of Gudbrandegga phase (lithology: biotite schist). Locality from eastern part of Gula Schist Group at river Rotla. Looking NW.

In the higher grade part of the area tight to isoclinal mesoscopic folds with axial plane schistosity (S_2) abound, particularly in the metasediments and metatuffs (Fig. 6). Microscopic relics of a folded earlier schistosity (S_1) and a few occurrences of superimposed fold patterns, e.g. at Gjeståen (Fig. 7), reveal that two fold generations are again present $(D_1$ and $D_2)$, and that the S_2 is formed by transposition of the older S_1 schistosity. If no superimposed fold pattern is observed it is not always possible to ascribe a given fold to either D_1 or D_2 in the field, because both have the same style and orientation, since the D_1 axial planes (S_1) have been transposed into the S_2 surface. Microscopic relics of a folded S_1 in many of the folds, however, demonstrate that the majority of Group I folds in the higher grade part of the area are of D_2 age.

Because the S_2 schistosity of the higher grade part of the area can be traced continuously into the S_2 crenulation cleavage of the lower grade parts, it is seen that these two S_2 surfaces are equivalent (this is the S_2 used as reference surface as mentioned above), and that D_1 and D_2 in the respective areas are the same. Thus the morphology of the S_2 changes gradually from a crenulation cleavage in the lower grade parts of the area to a medium- to coarse-grained schistosity in the higher grade part (a similar transition is described by e.g. White (1949)).

It should be noted here, that the transposition of S_1 into S_2 is observed, in general, only in the hinge-zones of D_2 folds, whereas in the limbs of these folds only one s-surface can be recognized. It is believed to be parallel to the older S_1, but is progressively rotated towards the S_2 orientation, and has generally been considerably modified by further flattening and recrystallization.

In the higher grade part of the area the S_2 schistosity is lineated. The lineation (L_2) is defined by preferred dimensional orientations of mica, hornblende, kyanite etc. and generally accompanied by a prominent quartz-rodding.

In addition to common mesoscopic examples, Group I folds also occur as macroscopic structures. Thus the outcrop pattern of the Stören Group is dominated by N–S trending synforms (Fig. 2), in the hinge-zones of which a well developed S_2 crenulation cleavage is observed, indicating a D_2 age. On the northern slope of Bringen mountain a major recumbent fold (Fig. 2) is also interpreted as being of D_2 age, because recognizable, mesoscopic D_2 folds on the limbs are congruous with the major structure. The isolated occurrences of the Fundsjö Group in the Gula Schist Group indicate the existence of major isoclinal folds (Fig. 2), which have axial planes parallel to S_2. Many mesoscopic D_2 folds are 'congruous' with the major folds as regards asymmetry. However, the majority of these mesoscopic folds plunge

regional variation in orientation of S_2, which will be described in the following section.

Group II

The structural elements of Group I are commonly observed to be deformed by later folds (Fig. 6), which vary in size from the mesoscopic to the macroscopic scale. Apart from the late kink-bands and faults, three sets of folds are recognized. One deformation phase produces folds of regional scale, which have contributed significantly to the present configuration of lithology, structures, and metamorphic zones. This phase is termed the Selbu-Tydal phase. The other two sets of folds are referred to as the Gudbrandegga and Finnkoihögda phases.

They are of less regional importance and show distinct non-congruous relationships to the major folds of the Selbu-Tydal phase. The age relationships of these two phases to the Selbu-Tydal phase are not fully established due to a lack of mesoscopic overprinting evidence. However, variation in orientation of axial planes of the two phases suggests that they are postdated by the Selbu-Tydal phase (see below). It is because of this uncertainty of age relationships that these phases have been given names of localities in which the folds are most intensively developed rather than labelling them as chronological deformation phases.

Gudbrandegga phase. – This phase is mostly represented by (sub-)angular folds of mesoscopic scale, mostly associated with a crenulation cleavage (Fig. 6), which in a few localities can be traced into a schistosity (post-S_2 schistosity). In the eastern part of the Gula Schist Group the axial directions lie around N–S, the axial planes are mostly steep, and the folds are Z-folds (Fleuty, 1964, p. 476) as viewed towards the north. The folds are most intensely developed at and around Gudbrandegga, where they occur as macroscopic structures, which are clearly outlined by the curving boundary between the Gula Schist Group and the Fundsjö Group. They correspond to the Hilmostöten-Tveraa anticline of Kisch (1962, p. 118) to the south.

Some mesoscopic folds with the same style but different orientation occur in grey and green phyllites in the north-western part of the Gula Schist Group. They are isolated from the Gudbrandegga phase folds sensu stricto. The axial directions are also N–S, the axial planes dip gently to the east, and the folds are also Z-folds as viewed towards the north. These folds are tentatively interpreted as belonging to the Gudbrandegga phase, the difference in orientation of axial planes being due to later folding by the Selbu-Tydal phase.

Finnkoihögda phase. – This phase is also represented by (sub-)angular folds of mesoscopic scale, mostly associated with a crenulation cleavage. The axial directions lie in the NW–SE quadrants, the axial planes are sub-horizontal or dipping moderately towards NE or SW, and the folds are S-folds as viewed towards NW. They are observed only in the eastern half of the investigated
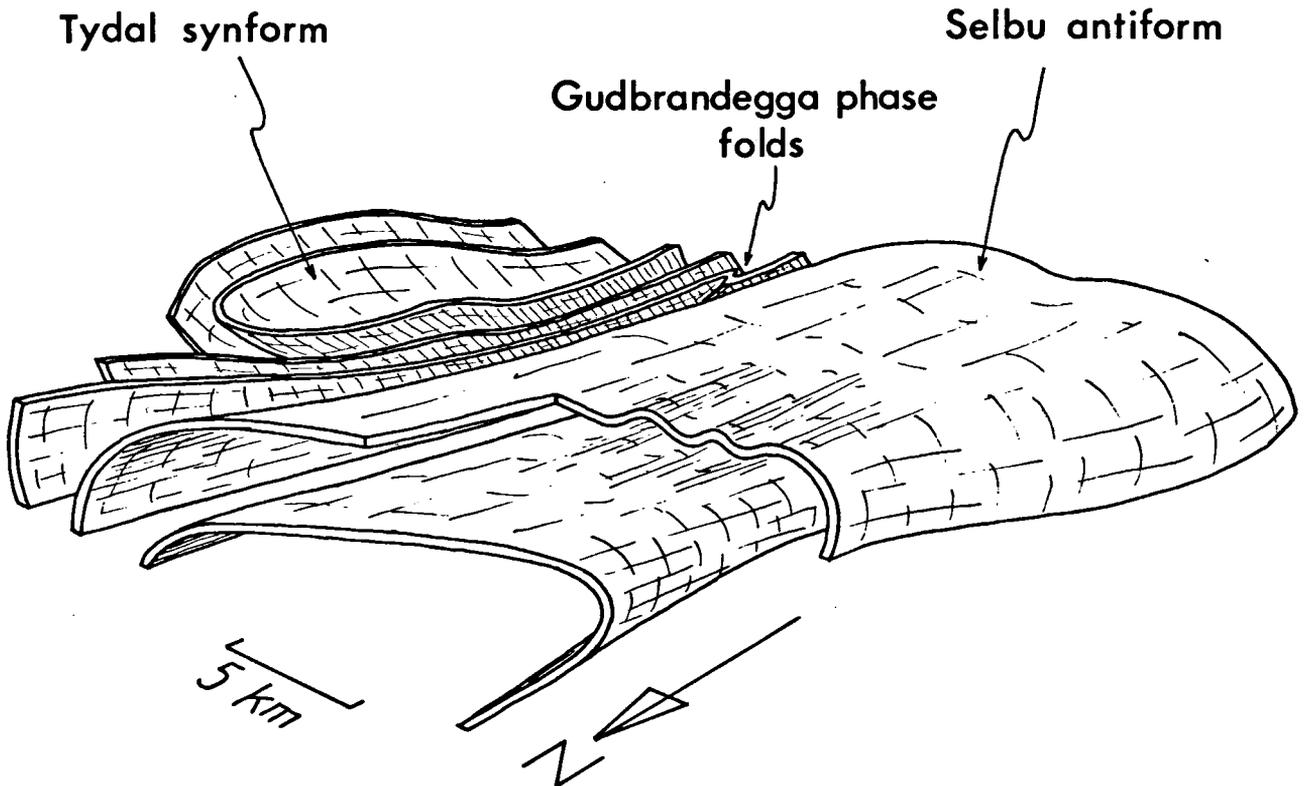

Fig. 7. D_2 folds overprinting D_1 folds at Gjestäen (lithology: layered psammitic and pelitic schist). The latter folds are exceptionally well preserved, as the D_2 folds are unusually open. Looking SW.

moderately to steep towards SSW (see below), while the fold axes of the major folds are sub-horizontal, as deduced from the geological map. Due to this discrepancy the age of these major Group I folds is still a matter of dispute.

The geometrical pattern of the fold axes, the schistosity/cleavages, and the lineations is altered by later folding (see *Group II*). The direction of F_2 axes varies grossly like the L_2 lineation, the latter being N–S with low plunge in the west, gradually swinging through SW to W and NW with increasing plunge in the east. It should be noted, however, that this similar geometry between F_2 and L_2 is only statistical, as large as well as small angles between F_2 and L_2 are commonly observed, when the rocks are studied closely. In addition it is also possible within a single outcrop to observe D_2 folds of identical shape and orientation of axial plane, but with axes differing in orientation up to 90°. A possible explanation for this is that the D_2 folds in fact constitute more than one generation.

The regional variation of L_2 is accompanied by a

Tydal synform

Gudbrandegga phase
folds

Selbu antiform

Fig. 8. Interpreted three-dimensional shape of major folds of Selbu-Tydal phase. The folded surface is the S_2 foliation. Major folds of Gudbrandegga phase are also shown in south-central part.

area, and superimposed fold patterns indicate that they postdate the Gudbrandegga phase. Variation in orientation of the axial planes is interpreted as being due to later folding by the Selbu-Tydal phase.

Selbu-Tydal phase. — As mentioned above this set of folds is of major importance. E—W sections through the investigated area (Fig. 2) show the variation in attitude of lithological boundaries and the S_2 foliation. Considering S_2, two major structures are apparent, an antiform to the west (Selbu antiform) and a synform to the east (Tydal synform). The folds trend roughly N—S, and they show considerable variation in profile. Fig. 8 shows the interpreted shape of the folds.

To the south the Selbu antiform is a broad, flat-topped structure with a sub-vertical western flank and an overturned eastern flank. The flat 'top' has minor undulations but is generally dipping gently towards the west. Towards the north the 'top' consists of several smaller macroscopic folds with a sub-horizontal enveloping surface. In the extreme north the 'top' dips towards the east, and both flanks are overturned.

The Tydal synform is overturned towards the east. The shape of the structure is strongly influenced by the presence of the Fongen-Melshogna igneous complex. Close to the intrusion the fold remains 'open', apparently due to the presence of the competent igneous body, and it is believed to become tighter towards the north, where no gabbro sheet is present, and to the south,

where the gabbro sheet apparently occupies only the western, overturned limb of the synform.

Mesoscopic folds of this phase seem to be scarce. North and north-east of Bringen mountain a few open folds with N—S axial direction and steep axial planes are interpreted as belonging to this phase. North of Fongen mountain some mesoscopic open folds are also interpreted as belonging to this phase.

Assuming a flexural slip fold mechanism an unfolding of the Selbu-Tydal phase folds reveals a more simple geometrical pattern of the Group I structural elements. E.g. L_2 remains N—S to the west and gradually swings to NW—SE in the east. At least a part of this variation could be primary. Furthermore this unfolding also rotates the axial planes of the folds of the Gudbrandegga phase into a higher degree of parallelism. This also applies for the folds of the Finnkoihögda phase, supporting the age relationships given above.

Kink-bands and faults. — Kink-bands, partly in conjugate sets, are extensively developed particularly in the vicinity of late faults.

A number of faults with sub-vertical fault planes striking NNW—SSE, are interpreted as wrench faults because of the geometry of the associated conjugate kinks. The apparent magnitude of a dextral horizontal shift is known in some cases, the maximum determined being 0.5 km.
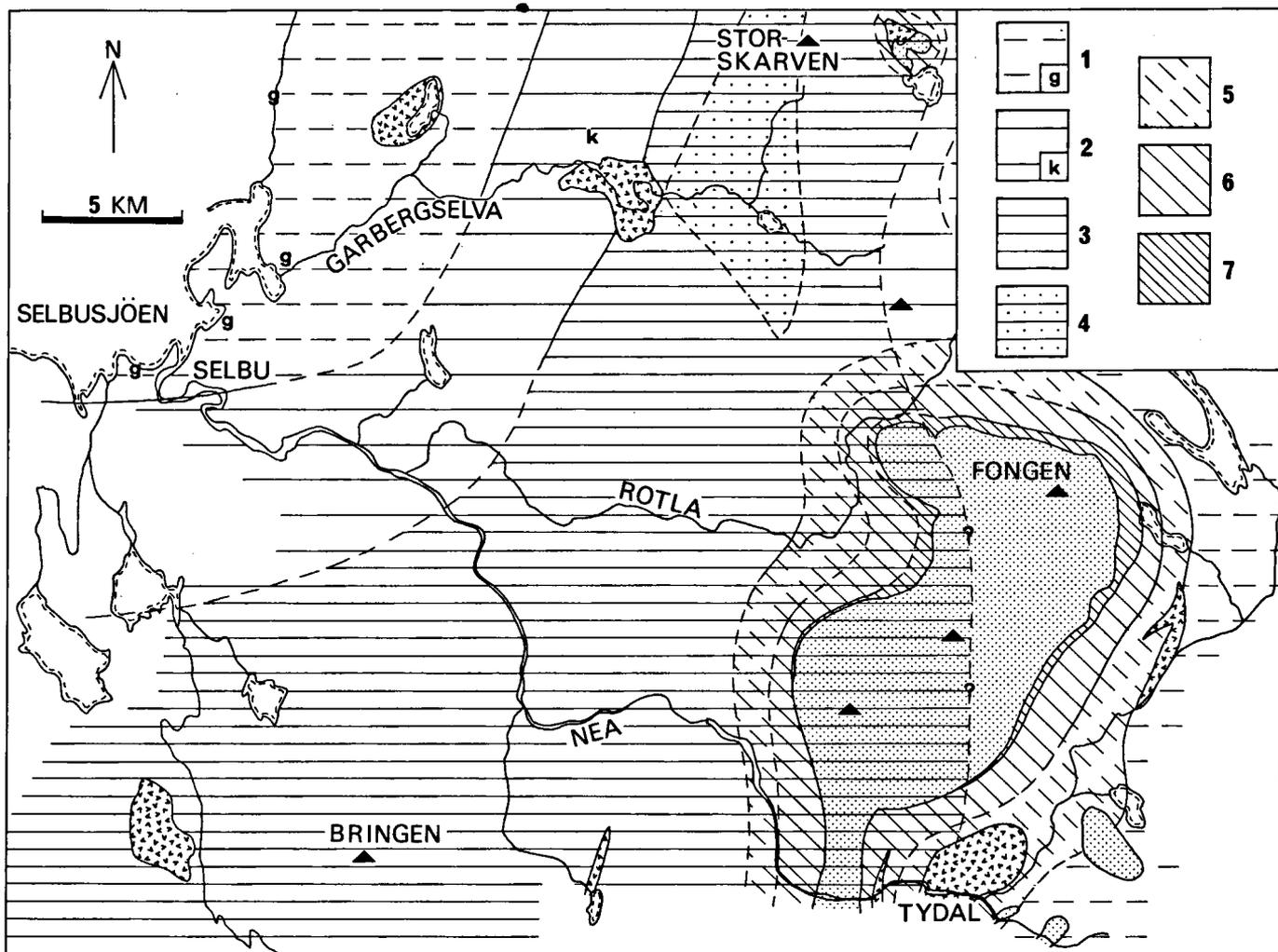
A fault can be followed from north and east of Fongen

Fig. 9. Map of metamorphic zones of the Selbu-Tydal area.
Regional metamorphism: 1: biotite zone (g: isolated occurrence of garnet); 2: garnet-hornblende zone (k: isolated occurrence of kyanite); 3: staurolite-kyanite zone; 4: sillimanite zone.
Contact metamorphism: 5: andalusite zone; 6: sillimanite zone; 7: cordierite zone.
Unbroken lines are isograds determined with reasonable precision, while broken lines refer to uncertainty due to transitional nature or unconvenient lithology.
Major syn-orogenic intrusives are indicated (see Fig. 1). Further explanation in the text.

Mt. to Tydal, where it joins up with the Heina zone of Kisch (1962, p. 44) and the 'western thrust fault' of Rui (1972, p. 8). The fault plane is dipping towards the west. It is interpreted as a reverse fault, also because of the geometry of the associated conjugate kinks. It is probably of minor displacement, as it does not, apparently, offset the previously established metamorphic pattern.

Brecciation and retrograde metamorphism accompany the faults, and in the case of the reverse fault pseudotachylites cut across the schistosity of the country rocks.

METAMORPHISM

Areal distribution
The regional metamorphism of the investigated area is of the Barrovian type. Fig. 9 shows the distribution of metamorphic zones. The isograds have been drawn to delineate areas, where given index-minerals are of common occurrence in appropriate lithologies. Isolated mineral occurrences outside corresponding zones are indicated by letter symbols.

1) The biotite zone. Garnet occurs locally.
2) The garnet-hornblende zone. In the north-western Gula Schist Group the lower limit of the zone is delineated mainly on the basis of the occurrence of hornblende.
3) The staurolite-kyanite zone. In addition to staurolite and kyanite, garnet and hornblende are of widespread occurrence. Diopside and grossular-rich garnet occur in some calc-silicate rocks.
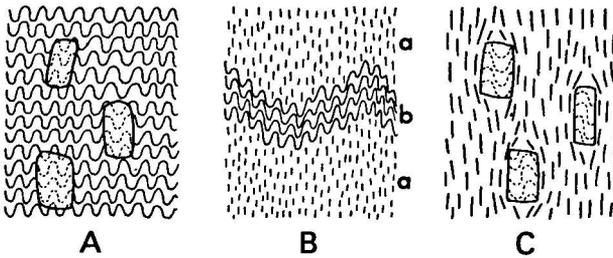
Fig. 10. Schematic illustration of some microstructural changes involved in the transition from lower to higher grade rocks.

A: S_1 with D_2 crenulations are typical of the biotite zones. Biotite porphyroblasts overgrow the D_2 crenulations.
B: Gradual transitions from rocks containing S_1 to rocks containing an S_2 schistosity are common particularly in or close to the garnet-hornblende zones. Hand-specimens may contain both schistosities:
a: an S_2 schistosity develops preferentially in layers relatively poor in micas.
b: in layers rich in white mica and/or graphite an S_1 schistosity with or without D_2 crenulations may persist into the higher grade zones.
C: In the higher grade zones the schistosity is mostly of D_2 age. Relics of S_1 may be preserved in e.g. biotite porphyroblasts.

4) T h e s i l l i m a n i t e z o n e . Scattered formation of white mica + sillimanite. Kyanite, staurolite, garnet, and hornblende are of widespread occurrence. The zone occurs in spatial association with a swarm of trondhjemitic dykes.

It is noted that the regional metamorphism is asymmetrically related to the regional, large-scale structures, e.g. the eastern flank of the Selbu antiform is of higher grade than the western flank. This is due to the fact that the folds of the Selbu-Tydal phase deform a pile of rocks, in which a metamorphic zonation with discordant relations to lithological boundaries and regional schistosity was already established (see *Timing of metamorphism*).

The regional metamorphic zonation pattern here described does not differ essentially from that established by Goldschmidt (1915).

The eastern transition from higher- to lower-grade metamorphism is substantially influenced by contact metamorphism around the Fongen-Melshogna igneous complex.

The following contact metamorphic zones are present:

5) T h e a n d a l u s i t e z o n e . Garnet is of widespread occurrence. Staurolite occurs locally. The rocks are mostly well foliated (schists, amphibolites). The andalusite and garnet isograds coincide in the northeastern part of the area. To the south-east the zone is defined by the occurrence of garnet, as andalusite is lacking.
6) T h e s i l l i m a n i t e z o n e . Garnet is of widespread occurrence. Staurolite occurs locally. Unstable relics of andalusite are locally present. Orthoclase occurs innermost in the zone, where also sillimanite occurs as prismatic crystals up to 5 cm long (see also
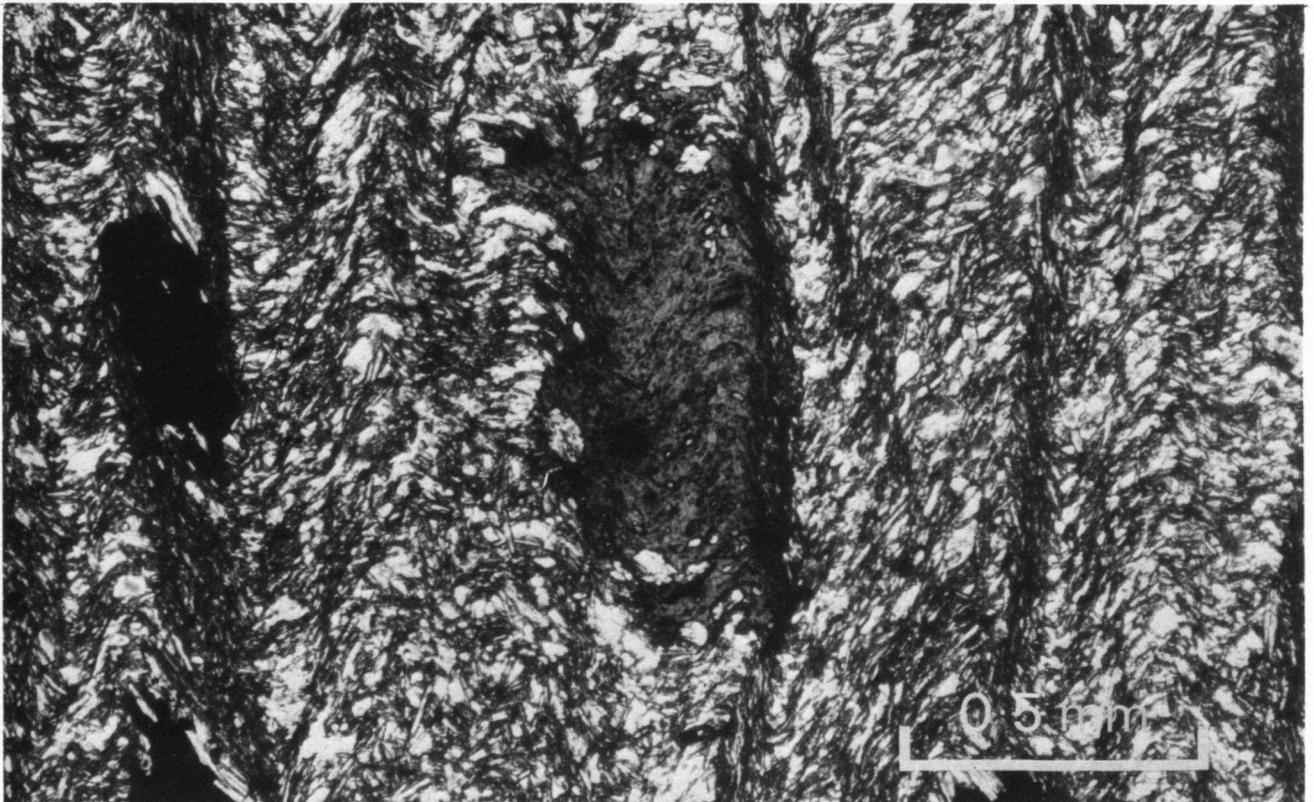

Fig. 11. A fine-grained white mica schistosity (S_1) with D_2 crenulations, overgrown by biotite porphyroblast. One nicol. From locality in western part of Gula Schist Group in the river Garbergselva (spec. LHK 69–358). The western biotite zone.

Kisch, 1962, p. 53, and Nilsen, 1971, p. 339). In the outer parts of the zone sillimanite occurs as fibrous pods resembling those described by Roberts (1968a, p. 172). The rocks are mostly foliated (schists and amphibolites) and commonly show migmatitic structures.

7) The cordierite zone. Garnet is of widespread occurrence. The rocks are commonly rich in enstatite/hypersthene, anthophyllite/gedrite, or cummingtonite/grunerite. Sillimanite, orthoclase, and staurolite are also present. The rocks of the zone are mostly massive hornfelses and commonly show migmatitic structures. Hornfelsic rocks of similar mineralogy occur as xenoliths within the complex.

A possible outermost biotite zone is not traceable, partly because the contact metamorphism overprinted rocks already regionally metamorphosed, and partly because the regional metamorphism continued after the intrusive event (see p. 274).

Around the intrusive complex of Vålåkleppen cordierite and sillimanite zones are developed, but the andalusite zone is missing. The cordierite zone is only a few meters wide, and is not shown in Fig. 9.

Some of the bigger trondhjemite intrusions show contact metamorphic effects, such as a change of fabric to more isotropic and coarse-grained rocks, as well as a change of mineralogy. Hornfelses containing grossulargarnet, tremolite/actinolite, clinozoisite, and zoisite are developed around the Börsjöen trondhjemite, and diopside in the vicinity of the Öielva trondhjemite is also believed to be of contact metamorphic origin.

Timing of metamorphism

The growth of metamorphic minerals can be dated relative to the schistosities and cleavages of the rocks (see e.g. Zwart, 1963). As described above two schistosities (of D_1 and D_2 age respectively) are present in the Selbu-Tydal area. It is possible with the aid of microstructural investigations to follow a gradual transition from a predominance of a crenulation cleavage type S_2 in the peripheral and lower grade areas to the west and east (Fig. 10A, and Fig. 11), through transitional stages (Fig. 10B, and Fig. 12), to the central higher grade areas, where the regional well developed schistosity is of D_2 age (Fig. 10C), and where relics of S_1 are only preserved as inclusions in porphyroblasts (Fig. 10C, and Fig. 13), and in graphite-rich schists, in which the microstructures did not readjust so much during the following progressive metamorphism.

The phyllites of the western biotite zone characteristically contain many biotite porphyroblasts, which overgrow both a fine-grained schistosity, defined by white mica and minor biotite (S_1), and the crenulations of D_2 age (Fig. 10A, and Fig. 11).

The eastern biotite zone is almost confined to the Sulåmo Group. The phyllites are biotite-porphyroblastic towards the south. The porphyroblasts exhibit planar inclusion trails, and the schistosity of the rocks deflects around the porphyroblasts. Due to a lack of D_2 folds the relative age of the porphyroblasts is not well established. Comparisons with neighbouring areas suggest that the included schistosity is an S_1 or an early S_2. The porphyroblasts are spatially related to the hornblende-albite metagabbros, suggesting that they are of a contact metamorphic origin.

Moving into the higher grade zones many schists also contain biotite porphyroblasts. They commonly include relics of S_1, occasionally with helicitic crenulations (as defined by e.g. Spry, 1969, p. 257), and the S_2 deflects around the porphyroblasts (Fig. 10C, and Fig. 13). The same applies to garnet and hornblende in the garnet-hornblende zone. In the highest grade zones garnet, hornblende, staurolite, and kyanite have also been observed with relics of S_1 with or without helicitic crenulations. Garnet, hornblende, staurolite, and kyanite
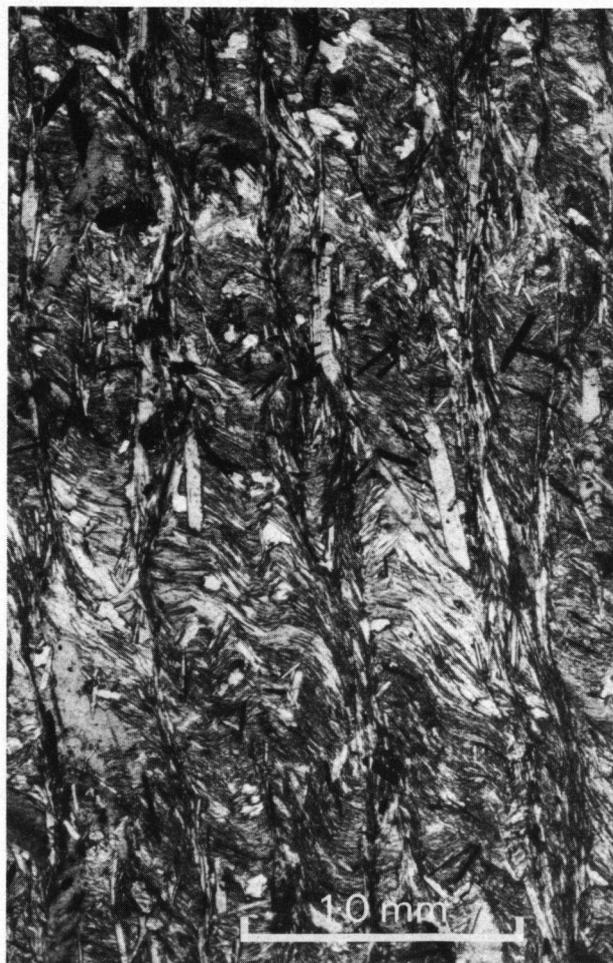

Fig. 12. A fine-grained white mica schistosity (S_1) with D_2 crenulations. New micas (larger grains: biotite, smaller grains: white mica) grow parallel to the planes of crenulation cleavage (S_2). Transitional stage between crenulation cleavage type S_2 and schistosity type S_2. The figure illustrates that two mechanisms seem to be active in the process of transposition: (a) a bodily rotation of S_1 grains into the S_2 planes, and (b) nucleation and growth of new grains of mica oriented parallel to S_2. One nicol. From locality in western part of Gula Schist Group ca. 5 km ESE of Selbu (spec. BR 68–23). The western garnet-hornblende zone.
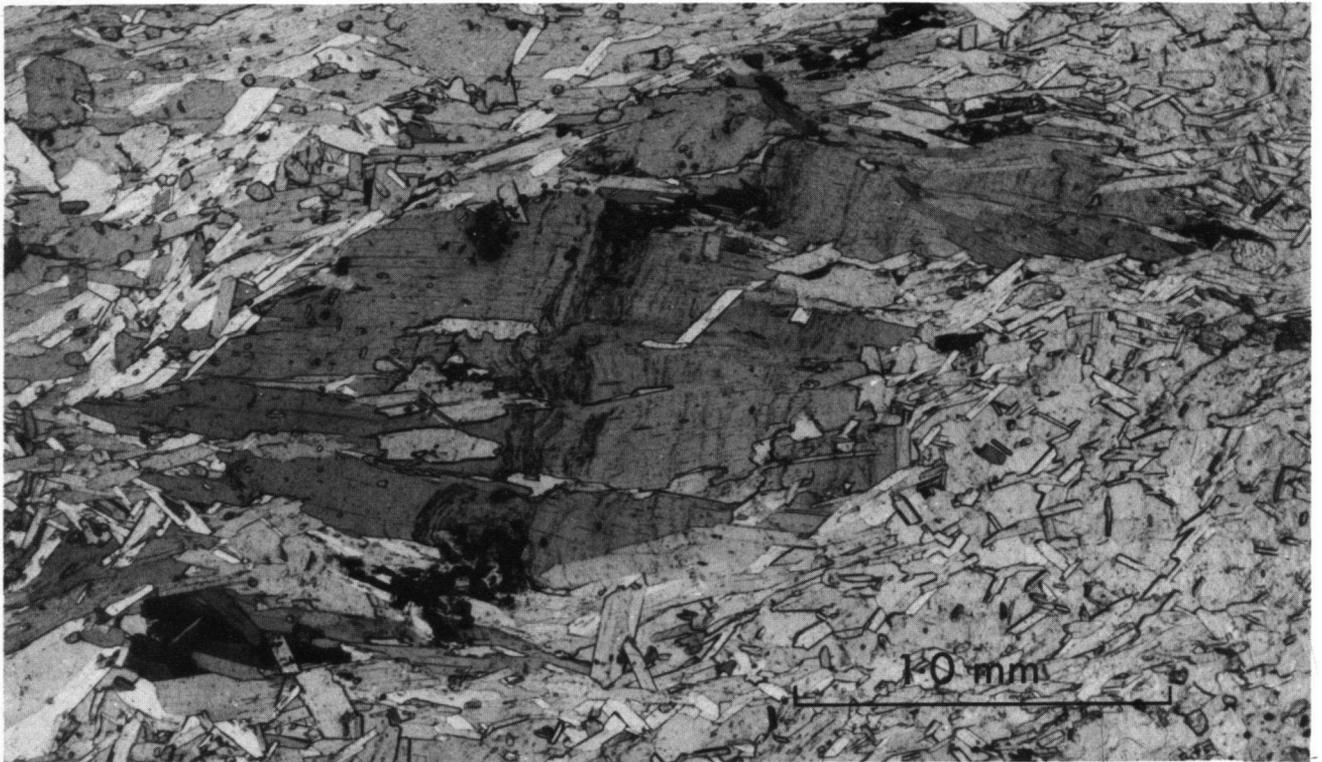
Fig. 13. A medium-grained white mica schistosity of D_2 age (section perpendicular to L_2; S_2 parallel to long dimension of figure). Biotite porphyroblast is partly recrystallized (during D_2), and includes relics of an S_1 with D_2 crenulations (indicated by graphite trails). One nicol. From locality in eastern part of Gula Schist Group west of Gudbrandegga (spec. NØO 69–446). The staurolite-kyanite zone.
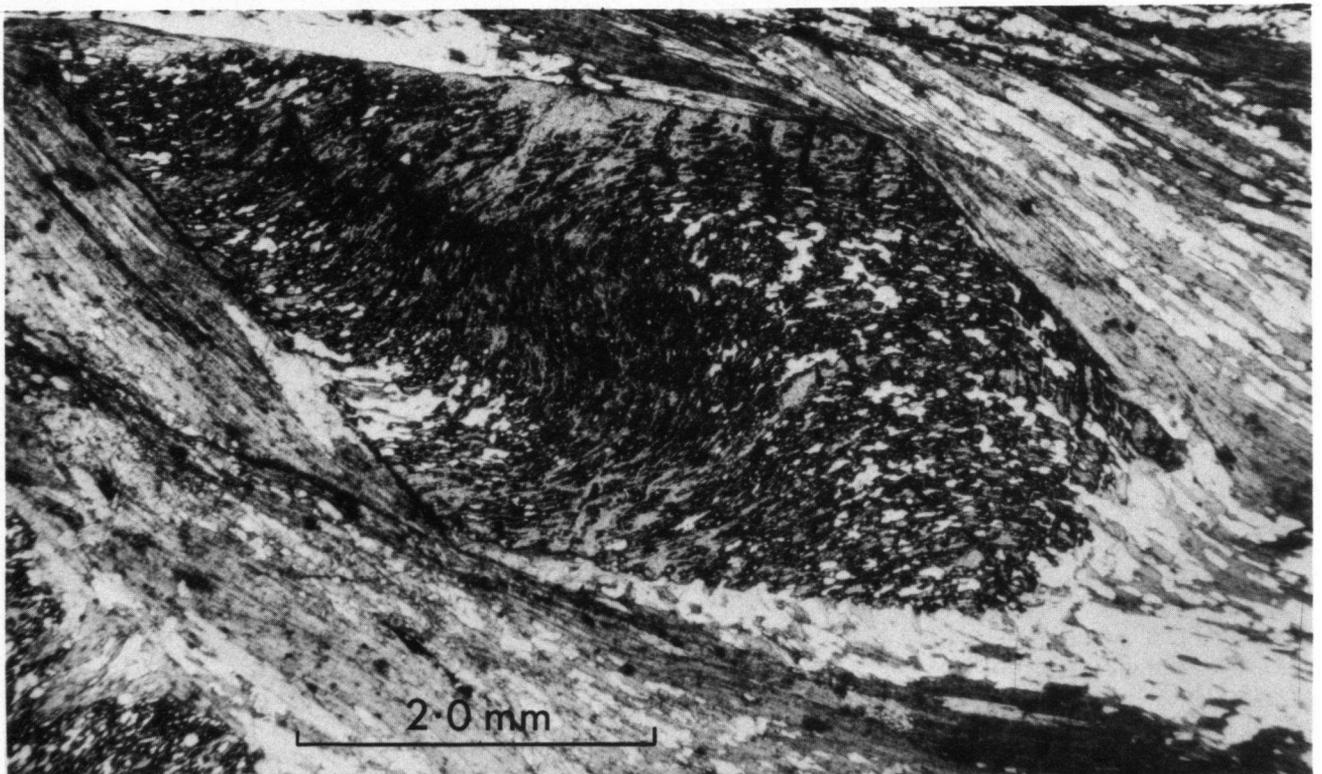

Fig. 14. Staurolite porphyroblast with S-shaped inclusion trails, indicative of syn-kinematic growth. Continuity between inclusion trails and the external medium-grained biotite schistosity of D_2 age (section parallel to L_2). Angle of rotation exceeds $130°$. One nicol. From locality in eastern part of Gula Schist Group at river Rotla (spec. NØO 68–286). The staurolite-kyanite zone.
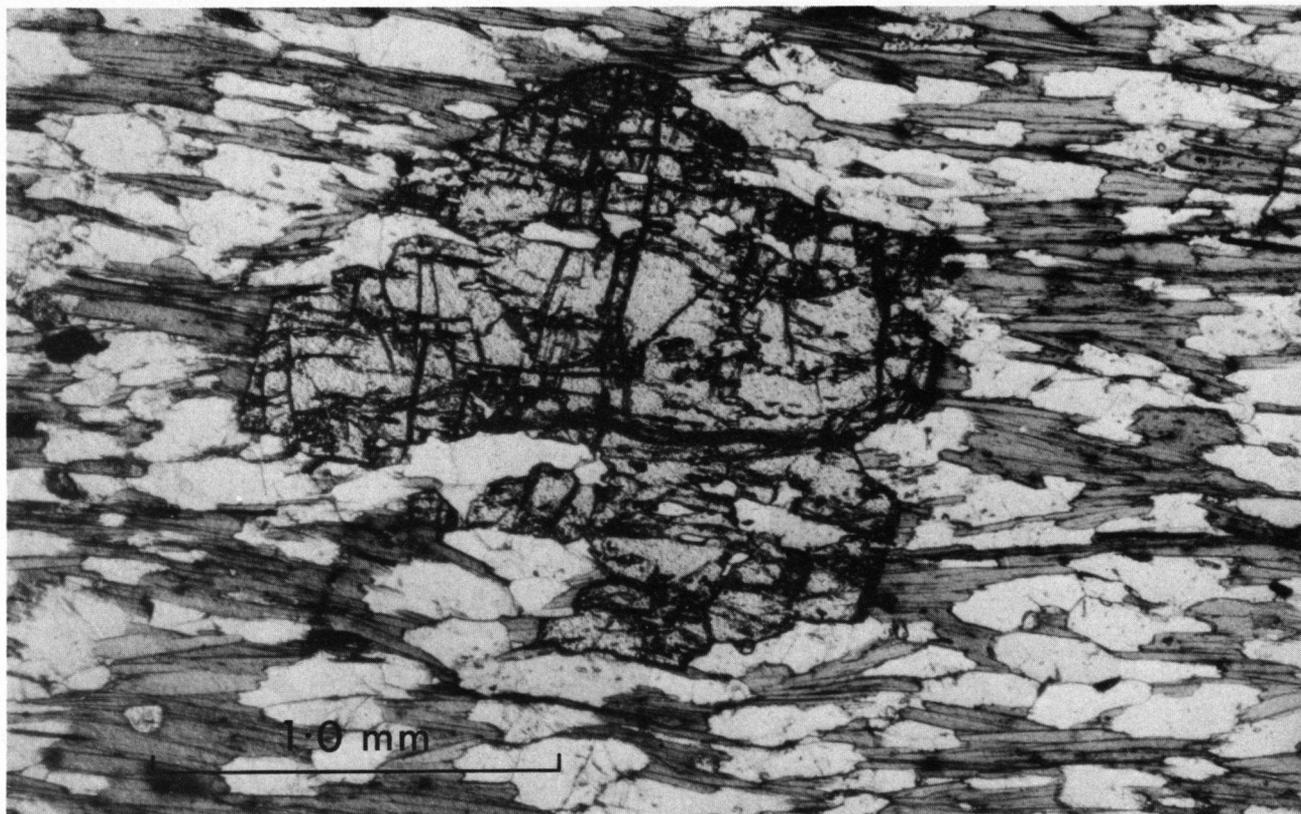
Fig. 15. Garnet porphyroblast postdating a medium-grained biotite schistosity of D2 age. One nicol. From locality in eastern part of Gula Schist Group ca. 2 km N of river Nea (spec. NØO 68–156). The staurolite-kyanite zone.

also overgrow S_2 during flattening, commonly involving rotation of the growing porphyroblasts (Fig. 14). Finally it is commonly observed that rims or occasionally whole porphyroblasts of these minerals post-kinematically overgrow S_2 (Fig. 15).

The formation of regional metamorphic sillimanite is of relatively late age. Aggregates of coarse-grained white mica containing sheaves of fibrolitic sillimanite and occasionally grains of partly resorbed kyanite lie as lenses in the schistosity. Though generally unaffected, staurolite was observed in one thin section to be replaced by white mica + sillimanite. The rims of the aggregates overgrow and postdate S_2, while a weak deflection may be observed around the central part of the aggregates. This deflection may reflect flattening around preexisting porphyroblasts.

In the higher grade zones the peak of regional metamorphism thus coincides with and postdates the movements, responsible for the formation of S_2. The higher grade minerals, staurolite, kyanite, and white mica + sillimanite, are deformed by the Group II structures, although in one thin section kyanite is observed to overgrow a crenulation of the Gudbrandegga phase.*)

*) Recent microstructural observations indicate, that there is an at least partial contemporaneity between the formation of white mica + sillimanite and an e a r l y s t a g e of the Gudbrandegga phase folding.

Retrograde white mica and chlorite porphyroblasts are locally plentiful in the higher grade zones, where these minerals commonly form at the expense of staurolite and kyanite.

It is emphasized here that the investigations indicate that the higher grade rocks are the result of a temporal progression of metamorphism, which is directly comparable with the present zonal progression, e.g. the sillimanite postdates staurolite and kyanite, which in turn include garnet and replace biotite.

In the south-eastern part of the area most porphyroblasts are believed to be of contact metamorphic origin. The relative age of intrusion of the Fongen-Melshogna igneous complex can thus be established, using identical techniques. E.g. andalusites and garnets of the outer aureole are observed in their cores to include an S_1 partly with incipient crenulations of D_2 age, so that the intrusion must postdate an early stage of D_2. However, the intrusion was followed by a continued development of S_2, still under contact metamorphic conditions, and the igneous body and the hornfelses were transformed in part to amphibolites and schists, respectively.

Thus there seems to be partial contemporaneity between the kyanite-bearing regional metamorphism and the andalusite-bearing contact metamorphism. However, the peak of regional metamorphism postdates the time of intrusion of the Fongen-Melshogna complex (Fig. 16).
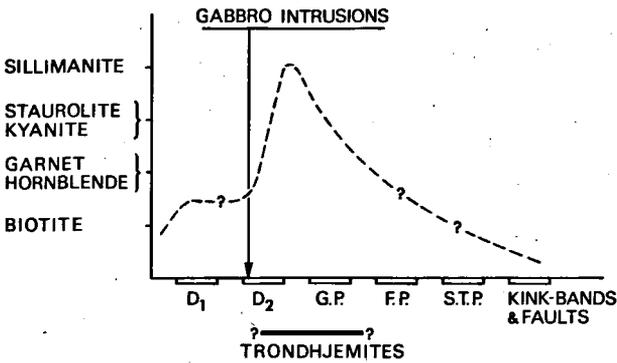
Fig. 16. Schematic correlation of structural, metamorphic, and syn-orogenic igneous events in the Selbu-Tydal area.

In the eastern part of the aureole the contact metamorphism was throughout the cooling history of higher grade than the regional metamorphism, which explains the absence of overprinting of contact metamorphic mineral assemblages by regional assemblages. In contrast, in the western part of the aureole, conditions of higher grade regional metamorphism outlasted the contact metamorphism, resulting in replacement textures, such as andalusite → kyanite, and andalusite → white mica + staurolite. Birkeland & Nilsen (1972, p. 19) noted similar textures at the Hyllingen gabbro (the southern continuation of the Fongen-Melshogna igneous complex).

The contact metamorphism around the Vålåkleppen metagabbro is likewise overprinted by the regional metamorphism (Kristensen, 1972, p. 53).

Thus in the north-eastern part of the Selbu-Tydal area two generations of sillimanite have been recognized, (a) an 'older' contact metamorphic, and (b) a 'younger' regional metamorphic generation, which are separated in time by a period of kyanite-staurolite grade regional metamorphism.

Fig. 16 is an attempt to show schematically the structural, metamorphic, and igneous relationships described above. Fig. 17 shows tentative P–T trends of regional and contact metamorphic rocks during the main metamorphism of syn- to post-D_2 age.

DISCUSSION

The results described above are in some respects in conflict with previously published results from the northern Trondheim region. A few points of major interest are briefly discussed below.

Recent structural interpretations of the regional structure of the Trondheim region (Roberts et al., 1970) were based particularly on a study of the Stjördalen profile (Roberts, 1967, 1968b). According to Roberts a central anticline of F_1 age (Stjördalen anticline), containing rocks of the Gula Schist Group, is flanked by partly overturned synclines/synforms of F_2 age. The axial plane trace of the Stjördalen anticline is indicated by Roberts et al. (1970, Fig. 2) to continue towards the

SSW, where it apparently joins up with the axial plane trace of the Selbu antiform. As described above, however, the Selbu antiform is a late structure deforming the regional schistosity and the axial planes of D_1 and D_2 folds, suggesting a misinterpretation of the Stjördalen anticline.

Apart from these discrepancies in the correlation of major structures, problems in the correlation of mesoscopic structures abound. Dealing with the higher grade zone of the Stjördalen profile a comparison of tectonic style suggests that the mesoscopic F_1 structures of Roberts (1967, p. 96) correlate with the Group I structures of the Selbu-Tydal area (despite the above mentioned correlation of macroscopic structures), and particularly it is believed that his F_1 structural elements (schistosity, mineral-lineation) correspond to S_2 and L_2 of the higher grade parts of the Selbu-Tydal area. This is supported by a microstructural study of a few thin sections from the Gula Schist Group of the Stjördalen profile (Zwart, pers. comm.), showing the schistosity of these rocks also to be an S_2.

In the lower grade zones the correlation may be the straightforward $F_1 = D_1$, and $F_2 = D_2$ (Roberts, 1967, p. 71; Roberts et al., 1970, p. 138).

Fig. 2 demonstrates that the rocks of the Fundsjö Group occupy the core of the Tydal synform. A similar structure is not described to the north, but to the south Rui (1972, Fig. 11) in his profile indicates a comparable structure at Holtsjöen (note, however, that his stratigraphy is not comparable with that of the Selbu-Tydal area. Rui (op. cit.) and Nilsen (1971) interpret the schists around the Hyllingen gabbro as belonging to the Gula Schist Group, while in this paper these rocks are considered as part of the Fundsjö Group). Fig. 2 obviously points to a correlation of the Gula Schist Group (or parts of it) with the Sulåmo Group, and indeed the lithology of the structurally higher parts of the Gula Schist Group is not essentially different from the lithology of the Sulåmo Group as described in this paper, and by Chaloupský & Fediuk (1967), and Siedlecka & Siedlecki (1967), when the different grades of metamorphism are neglected. Such a correlation appears to be a paradox, as the Gula Schist Group is considered to be of Cambrian age, and the Sulåmo Group of Middle Ordovician age (see e.g. Wolff, 1967).

Considering, however, the available evidences within the Selbu-Tydal area of the tectono-stratigraphic position of the Gula Schist Group, namely younging directions as indicated in Fig. 2 (note, however, that the locality in the eastern Gula Schist Group is of no significance, as it lies in the core of a major Group I fold), and the occurrences of metabasite pebbles in conglomerates, structurally underlying the ophiolitic sequences, a major stratigraphic inversion might be suggested. This is supported by Morton (1972, p. 314), who on the basis of the sulphide ore sequence at Rödhammeren Mine (west of Hyllingen gabbro, the southern continuation of the Fongen-Melshogna igneous
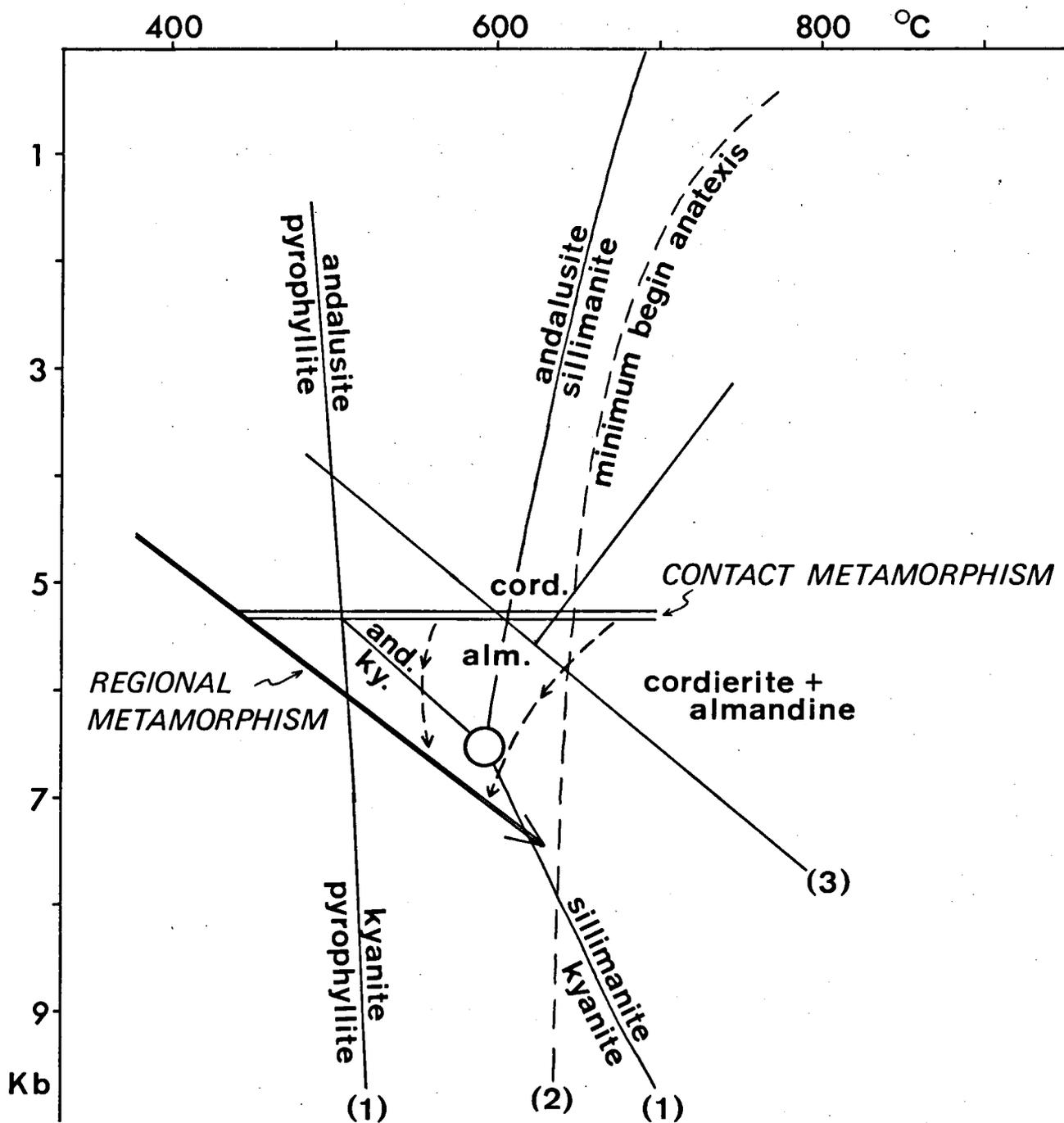
Fig. 17. Tentative P–T trends of regional and contact metamorphic rocks of central higher grade part of Selbu-Tydal area. Dotted arrows show possible post-intrusive trends of contact metamorphic rocks, due to regional metamorphic overprinting. Experimental data from: (1) Althaus (1969); (2) Luth et al. (1964); (3) Hirschberg & Winkler (1968). (Note that the observed contact metamorphic zonation does not correlate fully with that inferred from the experimental data, as a garnet-free cordierite zone is not observed).

complex) considers it most probable that these rocks are younging towards the west. As seen from Nilsen (1971, Fig. 2), the rocks at Rödhammeren Mine appear to correlate stratigraphically with the *Dictyonema* locality (Vogt, 1889). It is therefore suggested that the rock sequence west of these localities — including the Gula Schist Group — is actually of Ordovician/Silurian age. By this interpretation the above mentioned discrepancy in age between the Gula Schist Group and the Sulåmo Group would be eliminated.

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