Polyphase deformation in the Hattfjelldal Nappe, internal zone of the Scandinavian Caledonides, North-Central Norway

WINFRIED K. DALLMANN


This paper presents a structural investigation of the Hattfjelldal Nappe (part of the Storfjället Nappe Complex), Nordland, Norway, leading to a tentative model for the sequence of deformational events within the nappe and its bordering thrust zones. The investigated area belongs to the internal zone of the Caledonian fold-and-thrust belt. The rocks have been subjected to multiple deformational phases. The deformational sequence comprises at least two generations of isoclinal folds, as well as younger transverse and longitudinal folds. The phases can be correlated with movements in the bordering thrust zones. Finally, some aspects of correlation of fold phases in neighbouring nappes are discussed by comparing the Hattfjelldal Nappe with the underlying Jofjället Nappe.


Published literature concerning the Hattfjelldal Nappe is sparse compared with that elsewhere in the Seve-Köli Nappe Complex in the Scandinavian Caledonides. The first lithological descriptions appeared in the work of Holmsen (1912). Regional mapping of the Hattfjelldal district on the scale 1:250,000 was first presented in 1924, together with a description of the map (Rekstad 1924). More detailed work was started in 1950, in connection with prospecting for sulphide deposits, but was restricted to the area around Mikkeljord (Færden 1953). Until this date, it was known that the upper boundary of the Hattfjelldal rocks was defined by a major thrust zone, which could be followed northward from the Grong district to the Hattfjelldal area (Foslie 1923, 1924). Strand (1953, 1955) published his results of mapping and stratigraphical investigations in the area between Rössvatnet (Fig. 1) and Tunnsjøen (Grong district), and made a first attempt at lithostratigraphical correlation. Furthermore, he recognized the minor thrust zone at the base of the rocks around Hattfjelldal and introduced the term 'Hattfjelldal Nappe'.

The mapping in the Köli Nappes since the 1960’s has significantly increased our knowledge of the structure and stratigraphy in this nappe complex. The area north and west of the Borgefjellet Window (Fig. 1), however, was not investigated in detail. In the 1970’s, L. A. Barkey compiled a series of lithological maps on the scale 1:50,000, which remained unpublished. Though these maps were still rather general and lacked structural elements, they have provided a valuable base for further investigations. Finally, the initiation of the IGCP Nordland project led by I. B. Ramberg (University of Oslo) has increased our understanding of the regional geological situation (Mörk 1979, Ramberg 1981, Ramberg & Stephens 1981, Stephens et al. 1985, Stølen 1985, Sverdrup 1985). Fig. 1 shows the present knowledge of the tectonostratigraphy in this area.

The aim of this paper is to present a structural analysis of the Hattfjelldal Nappe, which is the uppermost nappe of the Seve-Köli Nappe Complex in the area between Rössvatnet and Borgefjellet. A detailed description of the structural elements is followed by a discussion of the deformational events, which leads to a tentative model for the structural development of the nappe.

Regional context

In the western part of Central Scandinavia, both continental margins of the early Paleozoic Iapetus Ocean (or a segment of it) are thought to be exposed, the eastern margin being the Baltic Shield, the western margin probably being the uppermost thrust nappes (Helgeland and Rödingsfjället Nappe Complexes; Stephens et al. 1985). The whole nappe pile in between reflects different settings of miogeoclinal and eugeoclinal character (Table 1).
Helgeland Nappe Complex

<table>
<thead>
<tr>
<th>Upper: Hattfjelldal and Akfjellet Nappes</th>
<th>Rödingsfjället Nappe Complex</th>
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<tr>
<td>Jofjältal Nappe</td>
<td></td>
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<tr>
<td>Krutfjellet Nappe</td>
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<tr>
<td>Middle: Gjersvik Nappe</td>
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<tr>
<td>Leipikvattnet Nappe</td>
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<tr>
<td>Gelvenäske Nappe</td>
<td></td>
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<tr>
<td>Stikke, Atofjället or Laxfjället Nappe</td>
<td></td>
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<tr>
<td>Lower: Björkvattnet Nappe</td>
<td></td>
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<tr>
<td>Seve unit</td>
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<tr>
<td>Kölí unit</td>
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<td>Baltic Shield</td>
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Table 1. Tectonostratigraphic table of the Caledonian Nappes in Southern Västerbotten (Swedish side) and Southern Nordland (Norwegian side).

The Baltic Shield is overlain by an autochthonous cover sequence, succeeded by a series of nappes (Lower and Middle Allochthon) derived from areas on or adjacent to the Baltoscandian continent (Gee 1975, Gustavson 1978, Roberts 1978, Ramberg & Stephens 1981, Stephens et al. 1985, Stephens & Gee 1984). Above them occurs the Seve-Kölí Nappe Complex (Upper Allochthon) derived from distal continental, oceanic and volcanic arc-related settings (Gee 1975, Stephens & Gee 1985), which is succeeded by nappes thought to be derived from a western continental margin (Uppermost Allochthon).

Based on earlier work, Stephens & Gee (1985) interpret the Upper Kölí Nappes as being derived from a fore-arc related setting, and the Middle Kölí Nappes from volcanic arc and back-arc related settings. Assuming a time relationship between these complexes, these authors suggest an eastward dipping subduction zone during the early Ordovician. After the collision of the western continental margin with the volcanic arc complex, the sense of vergence was considered to have changed to allow the final thrusting eastward onto the Baltic Shield.

Fig. 1 shows the location and tectonostratigraphic position of the Hattfjelldal Nappe that here forms the highest thrust unit within the Seve-Kölí Nappe Complex. Due to this position, it is thought to represent sediments derived from a tectonic setting situated between the volcanic arc (represented in the underlying Middle and Upper Kölí Nappes) and the presumed western continental margin (represented in the overlying Helgeland Nappe Complex) — before, during or after the collision of the two units.

This interpretation requires a Lower Paleozoic age of the rocks of the Hattfjelldal Nappe. This is discussed in detail in Dallman (in prep.), where an Ordovician to Silurian age can be envisaged via lithostratigraphical correlation with other Kölí Nappes.

The metamorphism in the investigated Kölí lithologies is low-grade. The Helgeland Nappe Complex, however, where it overlies the Hattfjelldal Nappe, shows transition from medium- to high-grade metamorphism towards the south.

Concerning the terminology on Table 1 and Fig. 1, one should note that Häggbom (1980) defined the term ‘Jofjältal Nappe’ for all the Kölí rocks between the Krutfjellet Nappe and the Rödingsfjället Nappe Complex. This was modified by Ramberg (1981), who had mapped out the ‘Akfjellet Nappe’ as an isolated unit with the higher metamorphic Brakfjellet Tectonic Lens at its base. As a result of field work in this area (Theisen & Dallmann 1984), I consider it more appropriate to follow the terminology of Ramberg, as a tectonic break of the same order can be observed at the base of both the Akfjellet and Jofjältal Nappes. Furthermore, the Akfjellet Nappe has a similar regional importance to that of the Hattfjelldal Nappe. To follow the first published work by Häggbom would mean to increase the complexity of the terminology of the Kölí Nappes by finding new terms and building up a more complicated system of overlapping collective names and subunits.

Outline of the stratigraphy

The reconstruction of the lithostratigraphy of the Hattfjelldal Nappe is difficult because of strong deformation and comparatively low degree of exposure in many areas. Obvious primary rock boundaries are restricted to those between rocks that are weakly foliated (some marbles, conglomerates, quartzites). The lithostratigraphic reconstruction is mostly based on frequently observed
repetitions or bed sequences in tectonically different positions and way-up indications from conglomerate pebbles.

The establishment of the stratigraphy will be explained in detail in Dallmann (in prep.), and only the main division is introduced here. It consists mainly of two groups (Fig. 2):

1. A lower marble group, mostly consisting of the so-called ‘Hattfjelldal limestone’ (Strand 1955), which is referred to as the ‘Hattfjelldal Group’;
2. An upper phyllitic, quartzitic and conglomeratic group showing many similarities with the ‘Limingen Group’ of the Gjersvik Nappe (Lutro 1979), with which it has been correlated (Dallmann 1984).

General characteristics of deformation

The Hattfjelldal Nappe provides an example of structural development in the internal zone of the Caledonian thrust-and-fold belt. It is characterized by syn-sedimentary tectonics (Dallmann, in prep.) and by later, strongly compressive deformation resulting in polyphase folding combined with thrust and shear movements. The structures of the whole nappe are easterly vergent.

Fig. 3 shows a structural map of the Hattfjelldal Nappe. The main map-scale repetitions of the stratigraphy are interpreted as early isoclines, because alternating upright and inverted stratigraphical sequences can often be observed.

in the presumed limbs (Dallmann, in prep.). Minor shear zones and imbrication related to the early phases of isoclinal folding are abundant, but are mostly not mapped because of poor exposure and because of the lack of macroscopical evidence in many phyllitic rocks. A regional, penetrative foliation is associated with the isoclinal folds. These early features are overprinted by younger folds with both Caledonian and transverse axial trend.

This structural style differs from other Köli

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**Fig. 2.** Generalized lithostratigraphical succession of the Hattfjelldal Nappe. The formation names of the Limigen Group are taken from the Gjersvik Nappe (Lutro 1979).

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**Fig. 3.** Structural map of the Hattfjelldal Nappe, showing main stratigraphic groups, thrust zones, trend of main foliation and traces of fold axes correlated with different phases. The cross-section A-B is approximately representative for the middle and northern part of the area, whereas the southern part is represented by small subareas on Fig. 9 and 10 (position indicated on the map).
STRUCTURAL MAP OF THE HATTFJELLDAL NAPPE
(NORDLAND, NORWAY)

LEGEND:

HELGELAND NAPPE FRONT:
- mylonitic foliation traces and shear zones (generalized)
- carbonate mylonite zone
- boudined amphibolite layers
- thrust fault
- minor tectonic boundary, supposed thrusting

HATTFJELLDAL NAPPE FRONT:
- thrust fault
- broad high-strain zone

OTHER FAULTS:
- normal fault, or unknown sense of displacement
- suggested strike-slip fault
- minor thrust fault

FOLDS (axial surface traces)
- antiform
- synform
- plunge of axis
- early isocline
- fold
- fold
Table 2. Deformation sequence of the Hattfjelldal Nappe and its suggested generating events.

<table>
<thead>
<tr>
<th>Def. Phase</th>
<th>Main Structural Elements</th>
<th>Conditions of Deformation, Suggested Generating Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>D5</td>
<td>Conjugate fracture sets, reactivation of planar features</td>
<td>Remaining stress fields after decreased ductility</td>
</tr>
<tr>
<td>D4</td>
<td>F₄ longitudinal folding with increasing intensity towards the Helgeland Thrust, &quot;flow folding&quot; close to the thrust, kink folding and fracture cleavage at late stages</td>
<td>Transition from ductile to brittle deformation</td>
</tr>
<tr>
<td>D3</td>
<td>F₃ transverse folding with varying intensity and orientation, &quot;flow folding&quot; close to the thrust</td>
<td>Further thrusting of the HNC, possibly due to gravity collapse stretching, viscous flow in calcite marbles, brittle deformation in siliceous rocks at late stages, transition from transverse to longitudinal folding by changing strain ratios</td>
</tr>
<tr>
<td>D2</td>
<td>F₂ isoclinal folding, S₂ regional penetrative foliation, intensity increasing towards the Helgeland Thrust</td>
<td>Thrusting of the Helgeland Nappe Complex, totally ductile deformation, subsequent to continent-continent collision, peak of low-grade metamorphism</td>
</tr>
<tr>
<td>D1</td>
<td>F₁, S₁, isoclinal folding causing repetition of the stratigraphy, probably more than one deformational event</td>
<td>Thrusting of the Hattfjelldal Nappe</td>
</tr>
</tbody>
</table>

Nappes immediately below, which - at map scale - are less intensively folded. The deformation style of the Akfjellet Nappe, however, is comparable with that of the Hattfjelldal Nappe. Both nappes lie in the same tectonic position beneath the Uppermost Allochthon and represent a similar zone of intense polyphase folding and thrusting.

To permit later attempts at correlation, some data from the underlying Jofjallet Nappe are taken into account in the following sections.

Analysis of the structural elements

The deformation events are referred to as D₁ (oldest) to D₅ (Youngest), the corresponding folds as F₁ etc., and planar features (foliations, axial planes) as S₁ etc.

Folds and foliations

D₁ structures. – Those structures that are older than and cut by the regional, penetrative foliation S₂ are collectively referred to as D₁ structures. They do not necessarily belong to only one event of deformation. Due to the strongly superposed D₂ structures in most of the area, no age relationship between the individual D₁ structures could be observed.

The most frequent D₁ elements are relic foliation planes (S₁; Fig. 4a, b, c) that are not entirely transposed by S₂. They are normally preserved in quartz-rich phyllites, preferably in the hinge zones of F₁ isoclines.

The S₁ foliation is defined by the orientation of white mica and chlorite. In calcite marbles, some recrystallization results in a distinct banding or lamination. Furthermore, calcite, quartz and mixed calcite-quartz veins occur parallel to the S₁ foliation. The foliation is parallel to the lithologic
layering (Fig. 4e). However, small-scale isoclinal folds (F₁), e.g. preserved in the pressure shadow of quartz veins folded by F₂, have been observed at a few localities (Fig. 4d). In addition, it is proposed that even the major map-scale isoclines (compare Fig. 3) are F₁ folds, as the D₁ Hattfjelldal Thrust cuts these folds, and is not repeated by isoclinal folding.

**D₂ structures.** – The D₂ phase gave rise to the strongest deformation structures that are preserved. It caused intense isoclinal folding (F₁) and a penetrative axial surface cleavage (S₂), which is the dominant foliation throughout the Hattfjelldal Nappe, except for a narrow zone along the Helgeland Thrust, where the younger

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**Fig. 4.** D₁ structures – a and e thin sections; b, c, and d field sketches (vertical W-E sections, approximately down-plunge).

a: Relict S₁ foliation and S₂ crenulation cleavage. Graphitic quartz phyllite, Susendalen.
b: S₁ foliation, folded by F₁ during development of an S₂ axial plane foliation. Quartz phyllite, N of Ivarrud.
c: Penetrative S₁ foliation, cut by S₂ shear foliation. Calcareous quartz phyllite, Pantdalsfjellet, Jofjøllet Nappe.
d: F₁ isoclinal folds in pressure shadow of quartz vein, refolded by F₂. Calcareous quartz phyllite, Unkerdalen.
e: S₂ foliation parallel to lithologic boundary, obliquely cut by S₂ shear foliation. Quartz phyllite, Susendalen.

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**Fig. 5.** D₂ structures – a, b, and c field sketches (vertical W-E sections, approximately down-plunge)- d and e thin sections.

a: F₂ isoclinal shear fold. Graphitic phyllite, Sommedjellet.
b: F₂ shear fold. Quartz vein in a fine-banded greenstone, Sandskarfjellet.
c: D₂ shearing of layers of different competence. Quartz phyllite, Ørjedalen, Jofjøllet Nappe.
d: Micro-scale F₂ shear fold. Dolomite marble, Kvalpskaret.
e: Rotated rock fragment. Calcareous conglomerate, Sandskarfjellet.

S₂ foliation may dominate. It is remarkable that, within the underlying Jofjøllet Nappe, the intensity of D₂ deformation decreases rapidly toward the east. Finally, it occurs only in local shear zones, which deform a penetrative S₁ schistosity. On the other hand, D₂ structures are increasingly superposed by younger deformation (D₃₋₄) towards the Helgeland Thrust.

The S₂ foliation is defined by the parallel orientation of white mica, chlorite and biotite, and sometimes elongate recrystallized grains of carbonates and quartz. There is often a distinct enrichment of graphite and micas along the foliation. Growth of low-grade metamorphic minerals (clinozoisite, biotite, actinolite etc.) occurred pre- to syn-D₂, and never across the S₂ foliation.

Mica-rich rocks show mostly an S₂ transposition foliation, whereas mica-poor rocks (quart-
zites, some marbles) may still show primary bedding or other sedimentary structures.

\( F_2 \) folds are defined by the bending (quartzites, dolomites) or shearing (phylmites etc.) of the \( S_1 \) foliation and/or the lithologic layering. They occur mainly as medium- and small-scale structures, but also some of the map-scale isoclines may belong to \( D_2 \). Fig. 5 shows \( F_2 \) fold shapes and shear structures from different lithologies (see also Fig. 4).

**\( D_3 \) structures** – The folds are defined in that they fold the regional \( S_3 \) foliation, and that their axial surfaces are refolded by the only rarely occurring younger folds observed in the field, \( F_4 \) (Fig. 6a). Field criteria to recognize \( F_3 \) folds are essentially restricted to the style of folding and geometrical parameters described below, which are primarily observed at outcrops showing a clear relationship (Fig. 6).

The \( F_3 \) fold axes and crenulations plunge westward (230°–295°) at low angles between 0° and 35°. Axial surfaces are steep (normally > 75°), but there are local exceptions with almost recumbent folds. The inter-limb angle of the folds varies considerably at different localities; the folds may be close to tight, mainly in the Unkerdal and Kvalpskaret regions (subareas III and V on Fig. 8) or open to gentle elsewhere.

Generally, \( F_3 \) and \( F_4 \) folds can be distinguished by their characteristic directions of axes, though this distinctive feature vanishes in the calcite marbles in the vicinity of the Helgeland Thrust. There, deformation grades into 'flow folding' and

![Diagram](attachment:diagram.png)
finally into a persistent transpositional banding, disturbed by ‘flow’ structures around boudins of more competent amphibolite (Fig. 6e, 7e).

(The term ‘flow folding’ here and in the following sections is used for commonly non-cylindrical folds with curving axes and axial surfaces, as a result of non-affine, probably viscous flow, as described by Carey (1954)).

The S3 axial surface foliation, if present, is indicated by the recrystallization of white mica. Where phyllitic rocks underlie the Helgeland Thrust, S2 and S3 superpose each other at moderate angles, giving rise to a ‘pencil’ cleavage with rhomboidal cross sections.

$D_4$ structures – The $F_4$ folds are defined by folding of the $S_2$ and the $S_3$ (if present) axial surface foliations, the $S_4$ axial surfaces are not refolded. The determination of $F_4$ folds in the field is restricted to the recognition of the style of folding and the geometrical parameters, which are characterized below (Fig. 7).

The fold axes, measured on $S_2$ planes, are generally directed subhorizontally N-S, but sometimes plot into two distinctly separated areas on the stereo net, due to rotation by the previous folding of $S_2$ by $F_3$ (compare Fig. 8, subareas III and IV).

$S_4$ axial surfaces of megascopic folds dip 40–50°W on average. Field observations at mesoscopic folds provided dip values between 0 and 75°W. Low dip values appear preferably in the vicinity of the Helgeland Thrust. In several places, $S_4$ is developed as a fracture cleavage (Fig. 7 a, b) with a weak displacement.

The style of folding changes from gentle flexures in the east to tight shear folds towards the Helgeland Thrust. Marbles are increasingly deformed by ‘flow folding’ towards the Helgeland Thrust, as described above. Intercalated amphibolitic layers are boudined. At the uppermost levels of the Hattfjelldal Nappe (the uppermost tens of meters), a strong transposition banding is developed, and this zone is designed as the ‘carbonate mylonite zone’ on Fig. 3. There appears to be a gradual transition from the $S_4$ axial surfaces at lower levels to the transposition banding, which is subparallel to the thrust plane.

In mica-rich rocks at moderate distances from the thrust, i.e. the central zone of the Hattfjelldal Nappe, $F_4$ folds are kink-like, occasionally with parasitic folds on the limbs of larger ones (Fig. 7 c, d).

The Hattfjelldal Thrust
The lower boundary of the Hattfjelldal Nappe is often developed as a discrete thrust plane, though it often forms a broad zone of high-strain. As it is difficult to recognize thrusting in phyllitic rocks, there is no continuous evidence for thrusting along this zone. The following observations, however, may confirm the assumption of a thrust:

1. There is a stratigraphic discordance along the supposed thrust zone.
2. The discordance has in many places a tectonic origin, and is marked by the occurrence of strongly deformed marbles with transposition banding and ‘flow’ structures, zones with strongly elongate pebbles in conglomerates, or thin bands of usually graphitic phyllite between the two supposed nappe units.

$F_4$ folds and $S_4$ foliation are well developed in the thrust zone, the latter often as a crenulation cleavage. A thrust that could be dated as $D_2$ would be supposed to contain zones in which $D_1$ structures are destroyed and replaced by a strong $S_4$ shear foliation. In areas where the Hattfjelldal Thrust is well exposed (e.g. top region of Sommerfjellet), such zones could not be found. Both conglomerates and phyllites here preserve the $S_1$ relic foliation between $S_4$ foliation planes and similar features have been observed in many other places along the thrust zone.

These observations indicate that thrusting of the Hattfjelldal Nappe was pre-$D_2$, and the Hattfjelldal Thrust is therefore regarded as a $D_1$ feature.

The Helgeland Thrust
The upper boundary of the Hattfjelldal Nappe is the basal thrust zone of the Helgeland Nappe Complex (HNC). This complex is built up of more competent lithologies. In the vicinity of the thrust zone, these are essentially quartz dioritic and meta-gabbroic intrusions, mica gneisses, migmatic or granite-intruded quartzo-feldspathic gneisses and banded gneisses with amphibolitic layers. The lithologic break with the marbles and phyllites of the Hattfjelldal Nappe leads to a clearly visible escarpment along the thrust front.

The thrust planes dip generally at 25–30°W, but exceptionally up to 90° between Nellifjellet and Skinnfjellet (Fig. 3). The thrust plane often
Fig. 8. Stereographic representation of post-D3 structures for eight subareas within the Hattfeldal Nappe. Equal-areal projection. Interpretation in the text.
splits up into two or more thrust faults and forms imbricate structures with slices of mylonite-bounded quartz diorite sheared off the HNC.

Rocks of both nappes are affected by mylonitization. Within the Hattfjelldal Nappe, the mylonite zone lies mostly within the calcite marbles of the Hattfjelldal Formation. Most of these carbonate mylonites are totally recrystallized, but show a well-developed thin transposition banding parallel to the thrust planes, which grades downwards into the irregular 'flow folds' described above. The banding and 'flow folding' is supposed to be an interference feature of several deformational events.

A number of tectonically emplaced amphibolitic layers with partly mylonitic boundaries occur exclusively within or close to this zone. They are mostly sheared and boudined, and their origin is unknown. Occasionally, boudins of other material are found in the marbles of the thrust zone, e.g. quartz diorite and siliceous mylonite of the type found at the base of the HNC.

A consideration of the geometry and spatial distribution of the $D_2$ and $D_4$ folds in the Hattfjelldal Nappe in addition to the observations at the thrust front provides several arguments for polyphasic thrusting (note that the term 'phase' here is used descriptively and means a period of uniform mode of transport with a uniform style of developing structures; there is no evidence for a cessation of movement between these phases):

1. Rotated fragments of siliceous mylonite in a carbonate matrix indicate one phase of ductile flow in silicates (± carbonates), and a second phase of ductile flow only in calcitic carbonates.
2. In parts, the HNC lies without a silicious mylonite zone upon the mylonitic 'Hattfjelldal Limestone'. A continuous siliceous mylonite zone, however, must be considered to have developed initially when the Helgeland Nappe was sheared off underlying rocks. Consequently, these mylonites must have been cut off later in several places. Further nappe transport did not form any siliceous mylonites. As no cataclastic deformation occurred, the movement is considered to have been entirely within the marbles, which reacted by ductile flow.

Thus, there were at least two phases of thrusting: an initial ductile phase, and a later phase, when only calcite marbles were ductily deformed, and silicate rocks were deformed in a brittle fashion or not at all.

3. Both the $D_2$ and $D_4$ folds are orientated with axial surfaces at an acute angle to the thrust, and axial traces subparallel to the thrust front, as the stress distribution during thrusting demands (compare Fig. 11). The inter-limb angle of folds of both phases, and the degree of transposition of older structures increases toward the thrust both during $D_2$ and $D_4$.

The sum of these observations suggests that thrusting of the HNC was a continuous event during $D_2$ and $D_4$. The initial thrusting, however, may have even been older. The stretching lineations and small scale transverse folds in the mylonites indicate a thrust direction between NNE and ESE.

**Faults and fractures**

Throughout the Hattfjelldal Nappe, a conjugate fracture pattern is readily mapped on air photos. The fractures cut the $D_4$ folds. The acute angles are oriented in an E-W direction indicating the unchanged orientation of the axis of highest stress during that late, brittle deformation. Some of the fractures show a minor displacement. In addition, there is evidence for older faults of possibly syn-$D_4$ origin.

**The regional refolding pattern**

**General structural analysis.** – To permit analysis of the regional post-$D_2$ deformation the Hattfjelldal Nappe was divided into seven subareas. Each subarea represents a region with a fairly uniform style of $F_3$ and $F_4$ folding, although transitions between those styles are gradual. $S_2$ foliation poles (and occasionally $S_3$ and $S_4$ foliation poles) and $F_3$ and $F_4$ fold axes from each subarea were plotted in equal area Schmidt nets (Fig. 8).

The scattering of the $S_2$ poles along the $F_3$ circles is due to $F_3$ folding, whereas scattering away from the circles is generally due to $F_4$ folding (compare orientation of folds!).

On average, the $F_3$ fold axes plunge ca. 260°/30°. In subarea II, they plunge more southerly (230°/37°), and in subarea III and VII more northerly (280°/35° and 285°/15°). Subarea V and VII show distinctly two maxima of $S_2$ poles belonging to each one limb of the $F_3$ folds.

The $F_4$ folds are sometimes defined by two fold axis maxima, which appear to be the result of interference between $F_3$ and $F_4$ folds (subarea II, III and IV): For measurements of all fold axes, $S_2$ had to be used as a reference plane. The two maxima of $F_4$ fold axes may thus reflect meas-
urements on the two limbs of F₃ folds, because the probability of measuring on an F₃ limb is much higher than in the hinge zone.

The F₃ axes do not show this phenomenon in the same way, because the F₃ fold limbs dip less regularly. They become more regular in smaller subareas (Fig. 9 d, 10 d). Consequently, F₃ may also show two maxima.

Another possible explanation of this phenomenon is the presence of conjugate folds. These were observed at only one place in the Jofjället Nappe near subarea II. In this subarea, the two maxima of F₄ fold axes plot on the same side of the field of F₃ axes. Consequently, the explanation by conjugate folds may be applicable in this case.

The S₄ axial surfaces dip 20–30° in subarea VI, 10–25° in subarea VII, and 5–45° in subarea IV. The general strike direction is N–S, and the axes are, on average, subhorizontal.

The subareas II, III, IV and VI, where most of the S₂ values were taken in the eastern (lithologically more heterogeneous) parts, show the highest deviation of S₂ poles from the F₁ π-circles. This is due to the more open shape of F₃ folds with increasing distance from the Helgeland Thrust. Near the thrust, the F₃ folds are close to tight, and the S₂ poles on the limbs plot closer to each other.

Subarea Va was regarded separately because of its close relationship to a slice of rocks of the HNC emplaced along a fault at Kvalpskaret. The F₃ axis is rotated into ENE direction (ca. 250/0°), and can be explained as a local effect caused by the emplacement of the slice within the marbles of the Hattfjelldal Nappe.

To illustrate the relation between these stereographic considerations and the real situation in the field, two small areas with a different tectonic style were mapped in detail (1:5.000). They were chosen, because they are relatively well exposed, provide a variety of structural elements on a small area, and exhibit heterogeneous and easily distinguishable lithologies. The area ‘Nyhaugen-Trangbergan’ (Fig. 9) shows predominantly the late F₃ and F₄ folds, whereas the area ‘Tjönnlaenget’ (Fig. 10) shows mainly early isoclinal folds.

The ‘Nyhaugen-Trangbergan’ area, Ivarrud, Susendalen (Fig. 9). – This area is situated adjacent to the Hattfjelldal Thrust. The structure is dominated by interfering F₃ and F₄ folds. Evidence for major F₁ and F₂ isoclinal folds is absent. Note that the minor deviations from the expected axial surface trace directions in Fig. 9 b are due to the rough topography, especially along the river banks, which could not be indicated on the map for technical reasons.

In the stereogram (Fig. 9 d), the rotation of S₂ poles by F₃ is of higher degree than the rotation by F₄. The reason can be seen in the cross sections through the area (Fig. 9 c): F₄ folds are close to tight and overturned, and the difference between the dip values of the two respective limbs is therefore less than that of most of the more open F₃ folds. The equivalent importance of both fold sets, however, is indicated by dome structures generated by the interference of F₃ and F₄ folds. Dome structures (partly overturned) are shown both by the meta-gabbroic sill (middle of map, Fig. 9 a, b), and by the thrust plane (top of map, Fig. 9 a, b.; compare Fig. 3). Two maxima of F₃ fold axes, each related to one possible position of the F₃ π-circle, are indicated in the stereogram (Fig. 9 d). Fig 9 e shows the reconstructed lithostratigraphy to facilitate the understanding of deformation in Fig. 9 a, b, c.

The ‘Tjönnlaenget’ area, Sommerfjellet, Susendalen (Fig. 10). – Here, the map-scale structure is dominated by F₁ or F₂ isoclinal folds, on which F₃ and F₄ are superposed to a minor extent. The isoclinal fold axes are indicated by dotted lines on Fig. 10 b. F₁ folds form a main open antiform with smaller, hardly reconstructable folds on the limbs. F₄ fold axes have distinctly different directions on both limbs of the antiform (Fig. 10 b),

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Fig. 9. Structural analysis of the Nyhaugen-Trangbergan area, N of Ivarrud, Susendalen. Position of area indicated on Fig. 3. Interpretation in the text.

a: Geological map. Lithologic boundaries are based on topography in addition to the observed outcrops.

b: Structural interpretation map. Some lithologic layers are shaded to indicate fold traces. Lithologic boundaries are parallel to S₁ foliation.

c: Cross-sections: A-A’ amd B-B’ show mainly F₄ folds, C-C’ mainly F₃ folds.

d: Equal-area stereogram representing post-D₃ structures.

e: Reconstructed lithology with collective information from the entire map area. Position of the Jofjället Nappe’s calcareous quartz phyllite on top of the sequence is taken from Dallmann (in prep.).
Quaternary cover
phyllite
conglomerate
meta-gabbro
marble (w. intraclasts)
calcite qtz. phyllite
contact metam. zone
Hattfjelldal thrust
observed outcrop

- 62° strike and dip (dip value) of S₂ foliation
Hattfjelldal thrust
axial trace of fold, direction of plunge
anticline
F₃: syncline
anticline
F₄: syncline
Hattfjelldal Nappe
Jofjället Nappe
legend and scale see Fig. a.
which points at an $F_4$ axial surface with low westward dip. The rotation of both $F_3$ axes by $F_4$, and $F_4$ axes by $F_3$ is indicated by the stereogram (Fig. 10 d). Although there are very few fold axis observations, the necessary information is obtained by tracing of the fold axes on the map (Fig. 10 b).

Fig. 10 e shows the generalized, reconstructed lithostratigraphy of the area to facilitate the understanding of the deformation pattern on Fig. 10 a, b, c. The cross sections (Fig. 10 c) were chosen to demonstrate $F_4$ folds on the northern limb of the main antiform (A-A'), $F_4$ folds on the southern limb of the main antiform (B-B'), and the twice refolding of the early isoclinal folds by both $F_3$ and $F_4$ (C-C').

Discussion

The deformation sequence

Early isoclinal folds. – It has been suggested that the large-scale isoclinal folds are mainly $D_1$ features, which had been superposed and reoriented by the $D_2$ phase to a great extent, so that it is no longer possible to reconstruct orientation, trends of increase of intensity, etc. of these folds. Furthermore, the features related to $D_1$ deformation may belong to several phases of deformation, which cannot be discriminated. However, it has been stated above that thrusting of the Hattfjelldal Nappe over the underlying Jofjället Nappe occurred and ceased during the $D_1$ deformation. The thrust was not reactivated during the later $D_2$-$D_3$ thrusting of the HNC. This suggests that the Hattfjelldal Thrust was already fixed at an early time in the deformational history of the Koli rocks.

The $D_2$ phase gave rise to the most penetrative deformational structures in a wide zone underlying the basal thrust of the HNC. The intensity of $D_2$ deformation increases toward the thrust and is considered as relating to it. Furthermore, the fold geometries suggest an upwards increasing portion of simple shear directed from the west to the east (Fig. 11 a). The illustration is idealized, i.e. it does not take into account the influence of different lithologies, which makes the fold pattern more irregular in nature.

Although it cannot be excluded that at least some of the $D_1$ structures are the result of early HNC thrusting, the $D_3$ phase is considered to have been one particular event of thrusting of the HNC onto the Koli nappe pile.

Later events. – $D_4$ is a phase of transverse folding, i.e. the fold axes are orientated W–E, i.e. sub-parallel to the direction of nappe transport.

The development of transverse folds in thrust regimes has been discussed since Balk (1936). He stated that transverse folds may be generated under thrusting due to inhomogeneities in both the underlying and the thrusting substratum. In the Scandinavian Caledonides, transverse folds are common. They may refold an earlier set of longitudinal folds (Foslie 1941, Kulling 1950), or both sets may develop contemporaneously (Kautsky & Tenengren 1952, Kautsky 1953, Ramberg 1967). In recent times, the significance of rotation of fold axes into the X-direction of the strain ellipsoid due to stretching within the axial plane of the folds has been emphasized (Sanderson 1973, Escher & Watterson 1974, Rhodes & Gayer 1977). Such fold axis rotation is thought to be due to strongly increased X/Y strain ratio under strong shear stress.

In the Hattfjelldal Nappe, $F_3$ and $F_4$ folds were not totally simultaneous, as the $F_3$ axial planes may be refolded by $F_4$ (Fig. 6a), though such refolded structures are infrequent. Areas with tight and many transverse folds lack intensive longitudinal folding ($F_4$). ‘Flow folding’ and transposition in the thrust zone of the HNC grade into both $F_3$ and $F_4$ folds at lower levels. A certain dependence of both fold sets upon each other may thus be suggested. They are supposed to be generally contemporaneous events, due to different strain orientations in different areas. Changing strain ratio in a certain area could give rise to refolding of the transverse by longitudinal folds, whereas transverse folding may have continued elsewhere. Inhomogeneities of regional or local nature may have been responsible for the concentration of transverse folds in certain areas. Those of regional nature may be basement culmination like the Borgefjellet Window (Fig. 1) or minor culminations eventually underlying the Koli rocks. Pinch-and-swell structures like those of the Kruffjellet Nappe (Häggbom 1980, Ramberg 1981) also come into question. Local inhomogeneities are present within the strata of the Hattfjelldal Nappe, e.g. quartzite bodies, which form embayments into neighbouring phyllites or calcite marbles. Those were less competent and consequently easily compressed. A previously mentioned example for fold axis rotation into the supposed direction of nappe transport due to local inhomogeneities is the subarea Va (Fig. 8),
Fig. 10. Structural analysis of the Tjønnlaengen area, Sommerfjellet, Susendalen. Position indicated on Fig. 3. Interpretation in the text.

a: Geological map. Lithologic boundaries are based on vegetation on topography in addition to the observed outcrops.
b: Structural interpretation map. The Limingen Group’s lithologies are shaded to indicate fold traces.
c: Cross-sections, showing early isoclinal folds refolded by $F_4$ (A-A' and B-B') and by both $F_3$ and $F_4$ (C-C').
d: Equal-area stereogram representing post-$D_3$ structures.
e: Reconstructed lithology with collective information from the entire map area.
where a slice of quartz diorite has been emplaced within the marbles of the Hattfjelldal Nappe.

Minor transverse folds in thrust or shear zones – as well as some observed westward plunging stretching lineations – are thought to be due to strongly increased shear movement in the sense of Sanderson (1973), without the necessity of an inhomogeneous substratum.

Longitudinal folding (F₄) follows transverse folding (F₃) in those areas, where refolding has been observed. Also kinking and fracture cleavage are related to F₄, but not F₃ folds, which supports the supposition that the F₄ folds include the latest folds observed in the field. Fig. 11 b shows the changing style of D₄ deformation dependant on the upward increasing portion of simple shear deformation in an idealized manner. In nature, this pattern is complicated by the influence of different lithologies and by the superposition of deformation phases.

Aspects of correlation with the underlying Jofjället Nappe

The only previous publication giving a detailed structural analysis of the Jofjället Nappe is that of Sandwall (1981) from the Swedish Jofjället area ('low-grade part of the Storfjället Nappe'). This area is situated between 20 and 45 km east of Rössvatnet, outside of the map (Fig. 1). There, the Jofjället Nappe underlies a thin wedge of the Akfjället Nappe (a tectonostratigraphic equivalent of the Hattfjelldal Nappe). The Uppermost Allochthon in this area is represented by the Rödingsfjället Nappe Complex (RNC).

Repetitions of the stratigraphy within the Jofjället Nappe are interpreted as resulting from imbrication (Sandwall 1981). In the Hattfjelldal Nappe, however, stratigraphic repetitions usually show symmetric successions (A-B-C-B-A) and are therefore regarded as being caused by isoclinal folding. Nevertheless, D₃ thrust zones of minor importance occur.

Sandwall correlates the thrusting of the Jofjället Nappe and the underlying nappes with his D₂ phase because of the increasing transposition of D₁ by D₂ structures toward the thrusts, resulting in the mylonitic foliations of the thrust zones. He assumes that the nappe emplacement was contemporaneous for all nappes and correlates the D₂ phase of each nappe on the basis of this assumption, involving the possibility of a small diachronity (p. 89).

The non-contemporaneous emplacement of the Hattfjelldal and Helgeland Nappes onto the respective underlying units, and the downward decreasing intensity of thrust-related deformation (Fig. 11, Sandwall p. 67) put this assumption to question. The mylonitic foliation of a thrust zone may correspond to S₁ in the overlying, but to S₂ in the underlying nappe. Discrimination may be difficult, as both foliations tend to turn parallel to the thrust plane, transposing all earlier structures to such an extent that age relationships can no longer be recognized. Indeed, both Sandwall and I consider the D₂ phase as a composite one, which may hide the record of the respective earlier episodes because of the strong superposition of D₃ structures (Fig. 12).

Sandwall's D₃ phase can most likely be correlated with the D₃₊₄ phase in the Hattfjelldal
Nappe, and his $D_4$ phase with the late kink folds, which I was unable to discriminate from my $D_4$ phase. Sandwall explains these folds with gravity-controlled disturbance after thrusting. The Hattfjelldal Nappe, however, reveals evidence for continuous thrust movement of the HNC during these phases (Fig. 11 b). A synthesis of both explanations can be made by adopting the model of Gee (1978), where the Caledonian Nappes are considered to have suffered a gravity-controlled collapse after emplacement. This generates stretching tectonics causing further eastward displacement. The presence of a similar interfering system of transverse and longitudinal folds in the HNC (Johnsen 1979) and RNC (Ramberg 1967) fits well with this hypothesis. The Köli Nappes might have suffered this process earlier (e.g. pinch-and-swell structures of the Krutfjellet Nappe; Häggbom 1980, Ramberg 1981).

Conclusions

The established sequence of deformation of the Hattfjelldal Nappe and the suggested generating events are summarized in Table 2. The following conclusions of more general character can be drawn:

The thrusting of the Hattfjelldal Nappe over the Jofjållet Nappe ceased considerably earlier ($D_1$) than the thrusting of the Helgeland Nappe Complex over the Hattfjelldal Nappe ($D_{2-4}$). The $D_2$ to $D_4$ phases of folding are related to thrusting of the Helgeland Nappe Complex under changing strain and ductility conditions (Fig. 11).

The $D_1$ and $D_2$ phases are dominated by isoclinal folding of the strata. Nappe imbrication, e.g. observed by Sandwall (1981) in the Jofjållet Nappe (Jofjållet area), is of minor importance here. That the early phases of isoclinal folding in neighbouring nappes can be correlated with each other is uncertain, because of the possible step-
wise translation of the deformation phases from one nappe to the next (Fig. 12).

The D₃ transverse and D₄ longitudinal folds seem to have developed more or less simultaneously, with a tendency toward the longitudinal trend. Transverse folding is mostly considered to relate to lithologic inhomogeneities of the substratum.

**Fig. 12.** Idealized sketch to demonstrate the resulting foliations by a stepwise emplacement of nappes. Explanation in the text.

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