THREE FOLD PHASES IN THE NORTHERN PART OF TROLLHEIMEN IN THE NORWEGIAN CALEDONIDES*

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Løset, F.: Three fold phases in the northern part of Trollheimen in the Norwegian Caledonides. *Norsk Geologisk Tidsskrift,* Vol. 57, pp. 121–131. Oslo 1977.

The northern border of Trollheimen towards Surnadalen has a complex geology with Cambro-Silurian, Eo-Cambrian (?) and Precambrian rocks folded three times during the Caledonian orogeny. The first recognizable folds, F_1, are isoclinal slip folds associated with a pervasive axial plane schistosity and lineation.

The Surnadal syncline and other major recumbent folds in the northern part of the area belong to the first phase of folding.

The second folds, F_2, are rather tight flexural-slip folds, while the third folds, F_3, are open flexural-slip structures.

A regional dome structure with Precambrian granitic gneisses in the core occurs in the south-western part of the area.

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Trollheimen is the mountainous region between Oppdal and Surnadal in north-western Norway. In the central part of Trollheimen there are mostly basal gneisses of Precambrian age. In the Oppdal district there are flagstones, micaschists, and some volcanic rocks of presumably Eo-Cambrian to Cambro-Silurian age above the gneisses. In the Surnadal district a wedge of Cambro-Silurian rocks has been folded down into the basal gneisses. This is the Surnadal syncline.

The geology of Trollheimen has been investigated by several geologists. Strand (1953) described the rocks in the Surnadal syncline. He mapped a zone of quartzite in the boundary zone between the basal gneisses and the overlying micaschists. This quartzite was therefore regarded to be of Eo-Cambrian age, belonging to the Tingvoll Group of Hernes (1956a). Sr/Rb-dating from the basal gneisses in this district gave 1600–1800 mill. years (Priem 1967). It is, however, not established that the boundary between the Precambrian and the Cambro-Silurian follows the quartzite zone, and the Eo-Cambrian age of the quartzite is uncertain.

In his papers, Hernes (1956a, b) gave several profiles across the Surnadal syncline, describing the syncline as a large isoclinal, recumbent fold. Large recumbent folds have also been described from this region by other geologists. Muret (1959) distinguished four tectonic phases here:

The piling up of several recumbent folds or nappes.

Subsequent folding of these nappes.

Formation of a large culmination which gave rise to local folds by downward gliding from the culmination.
Formation of N-S fractures.

In the Oppdal district, large recumbent folds were described by Holtedahl (1950), and in the Lesja area Scott (*in* Strand & Kulling 1971) described two phases of folding. From the central part of Trollheimen, Hansen (1967, 1971) made detailed investigations. The rocks here have been deformed into a large scale recumbent nappe, which has later been deformed into broad upright domal antiforms and tight basins.

The object of the present paper is to describe the folds of the different fold phases and to discuss the folding history of the area.

General geology

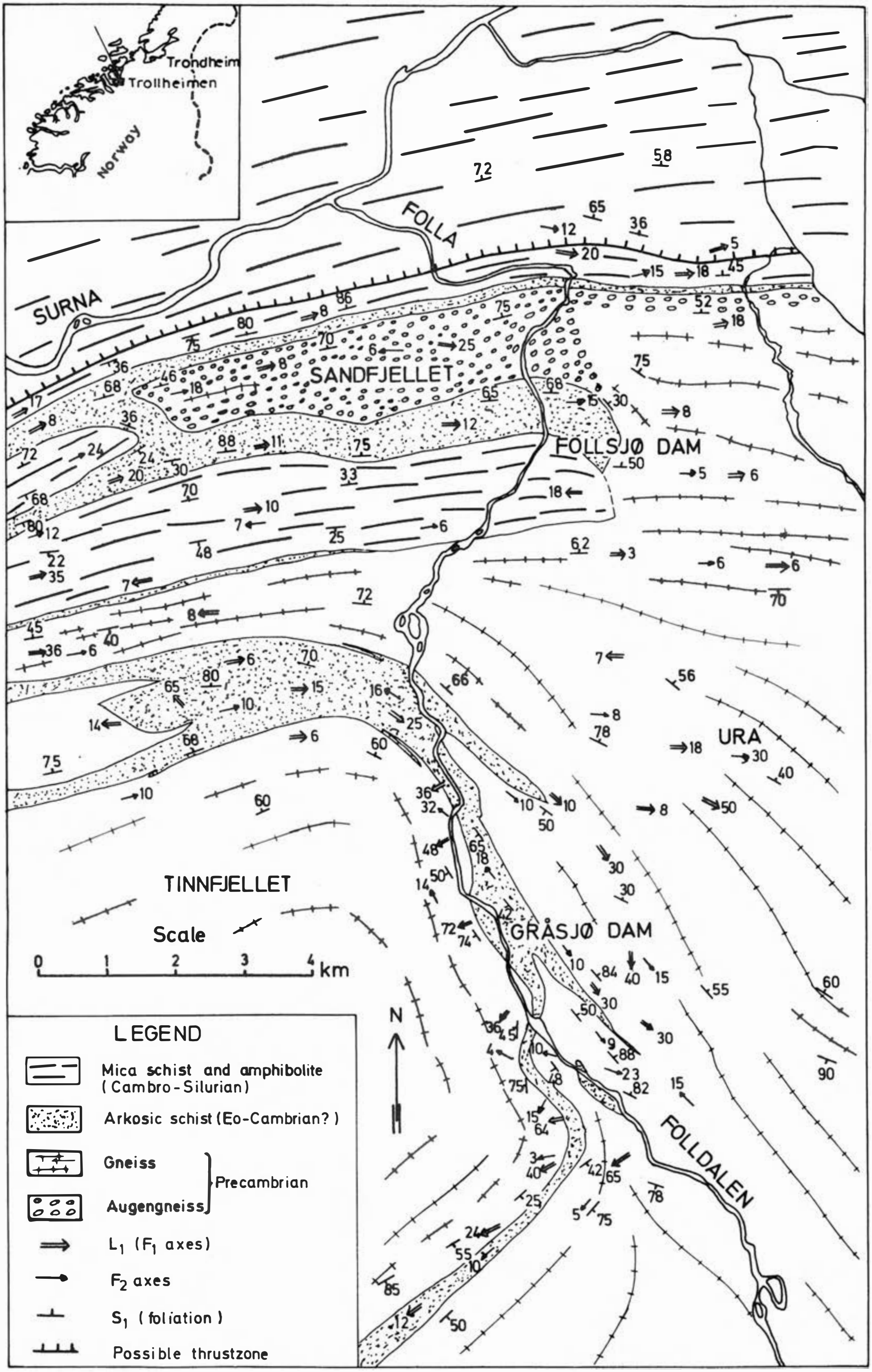
The investigated area is in the northern part of Folldalen, which is a hanging valley from south to Surnadalen. Fig. 1 is a geological map of the area. The youngest rocks are a series of micaschists and amphibolites. The northernmost zone of these rocks belongs to the Surnadal syncline and is therefore probably of Cambro-Silurian age, and the rocks are probably similar to the Gula Group. Rocks of the same type further to the south in the area are estimated to be of the same age. Most of the amphibolite is probably supracrustal but numerous thin beds may be sills.

In the northern zone of micaschists and amphibolite, there is a zone of augengneiss with mylonitic groundmass and augen of microcline. This may be a thrust-zone. Above this zone there occur thick beds of amphibolite with numerous trondhjemitic intrusions, but below there are only thin amphibolite beds, and trondhjemite seems to be missing.

At the base of the Cambro-Silurian sequence there is an arkosic to quartzitic schist which varies in thickness due to isoclinal folding. This rock is lithologically similar to the light sparagmites of Oppdal, Gudbrandsdalen etc. for which an Eo-Cambrian age has been suggested. In the underlying gneiss there are numerous sills and dykes of granite which are not observed in the arkosic schist. The arkosic schist therefore seems to be younger than the gneiss.

The basal gneiss is of Precambrian age as the Sr/Rb-dating gives 1600–1800 mill. years (Priem 1967). In the northern part of the area the composition of the gneiss is mostly granitic and at the boundary to the arkosic schist there is a zone of augengneiss. This augengneiss has a granitic to granodioritic composition but not a mylonitic groundmass as the augengneiss in the Cambro-Silurian rocks. In the southern part of the area the gneiss usually has a dioritic to quartz-dioritic composition, but in Tinnfjellet there is a rather homogeneous granitic gneiss. In the gneiss there are numerous intru-

Fig. 1. Geological map of the northern part of Trollheimen.


Trondheim
Trollheimen
Norway
SURNA
FOLLA
SANDFJELLET
FOLLSJØ DAM
URA
TINNFJELLET
GRÅSJØ DAM
FOLLDALEN
Scale
0 1 2 3 4 km
N
LEGEND
Mica schist and amphibolite (Cambro-Silurian)
Arkosic schist (Eo-Cambrian?)
Gneiss
Augengneiss
Precambrian
L1 (F1 axes)
F2 axes
S1 (foliation)
Possible thrustzone

sions of different character. There are at least two generations of granitic intrusions and basic intrusions of different compositions.

All the rocks are metamorphosed to the almandine-amphibolite facies.

Three phases of folding

Structurally the area is divided in two parts. The northern half belongs to the Surnadal syncline and similar ENE-WSW or E-W structures. The southern part Tinnfjellet forms a dome surrounded by arkosic schist. At least three phases of folding can be distinguished. In the northern part of the area all fold axes have a direction about E-W. In Tinnfjellet the axial direction varies (Fig. 1). The small structures are best preserved in the arkosic schist.

First folds (F_1)

The oldest planar structure is a lithological banding S_0 which has been deformed into isoclinal folds, F_1. The F_1 fold amplitudes are much longer than their wave-lengths (Fig. 2). These are typical similar-type folds with tight closures and a pervasive axial-plane schistosity, S_1, which is the main schistosity in this area. The main schistosity is therefore not folded by F_1. A lineation L_1 is of F_1 age and is defined as the line of intersection of S_0 and S_1. The F_1 axes (and L_1) have a direction about E-W in the northern part of the

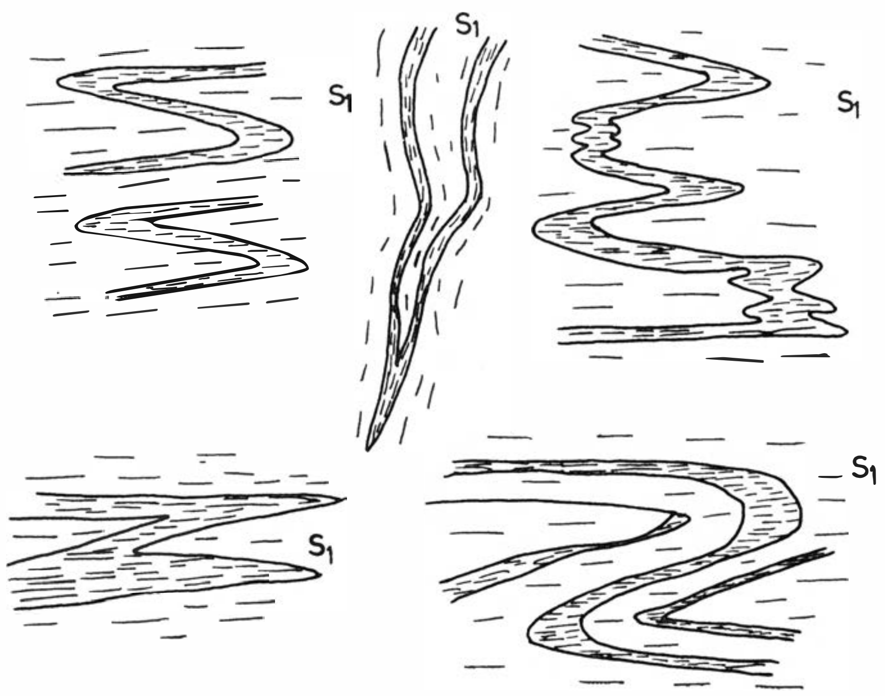


Fig. 2. Profiles of F_1 folds.

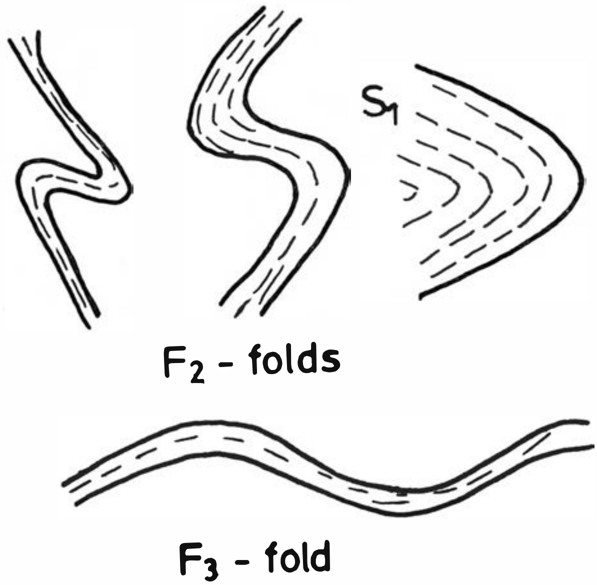


Fig. 3. Profiles of F_2 and F_3 folds.

area. In the southern part of the area the F_1 linear structures have variable orientations.

Second folds (F_2)

The schistosity S_1 is laid in folds where the limbs have almost the same orthogonal thickness, e.g. essential flexural-slip folds. These are termed F_2 folds. Slight thinning of the fold limbs has taken place locally, and in some localities a weak axial plane schistosity (S_2) can be observed. The F_2 folds are rather tight, but usually not isoclinal; the closures are rounded and the fold amplitudes are of the same length as the wave-lengths (Fig. 3). In the northern part of the area the F_2 axial direction is about E-W, parallel to the F_1 axes. In the southern part of the area the F_2 axes are tangential to the dome structure and usually different from the F_1 axial direction. The axial planes of the F_2 folds vary in attitude due to late F_3 folding. A lineation L_2 occurs sometimes, in part defined as the axes of the microfolds; and mullions and boudinage structures may belong to the same phase of folding.

Third folds (F_3)

The youngest folds, F_3, are open flexural-slip folds with amplitudes slightly less than their wave-lengths (Fig. 3). They are only rarely associated with lineation and the axial directions are always approximately E-W with axial plane nearly vertical.

The three types of folds here described are not identical with the three fold types described by Hansen from the central part of Trollheimen (Hansen 1971). The 'sahlfolds' and 'norfolds' of Hansen are both similar type

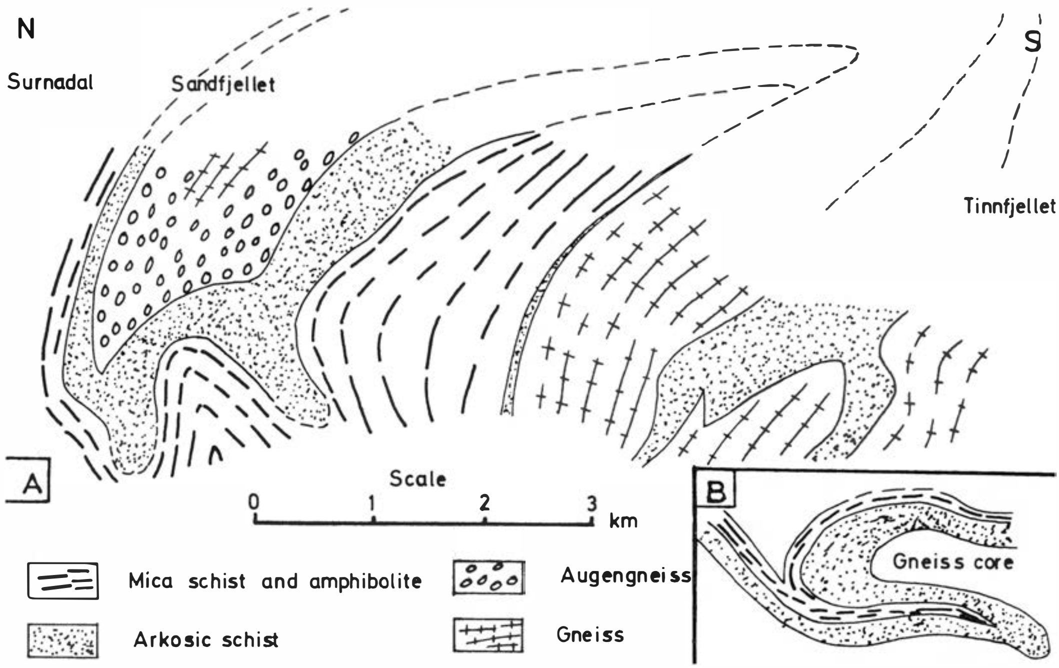


Fig. 4. A) Projection of the geological structures into a vertical N-S-striking plane.
B) Profile of the Surnadal syncline (after Hernes 1956a).

folds, but they do not seem to be identical to the F_1 folds in the northern part of Trollheimen. The F_1 folds may be older than Hansen's folds. Hansen also mentions some still older folds but gives no description of them. Hansen's 'discfolds' have a parallel type of geometry and may be identical to the F_2 folds.

Major recumbent folds

The northern part of the area is dominated by the Surnadal syncline. The syncline is nearly recumbent and isoclinal (Hernes 1956a, b). Above the recumbent syncline there seems to be another recumbent fold with closure to the north and with gneiss in the core (Figs. 4 and 5). Most of the rocks in the northern part of Folldalen belong to the upper limb of the syncline; the overlying recumbent fold and the succession are therefore inverted. This is, however, a simplified picture. The recumbent folds are probably of F_1 age, and they are refolded by F_2 and F_3. Fig. 4A is a projection of the major structures into a N-S striking vertical plane. The two southern areas with Cambro-Silurian rocks apparently belong to the core of the Surnadal syncline being folded up by F_2. Fig. 6 shows the structural plots from different localities in the investigated area. In the northern part (subarea A), the fold-axes of all the three phases usually plunge slightly to the E or ENE (Fig. 6 A_2). The original L_1 direction was probably about E-W, parallel to

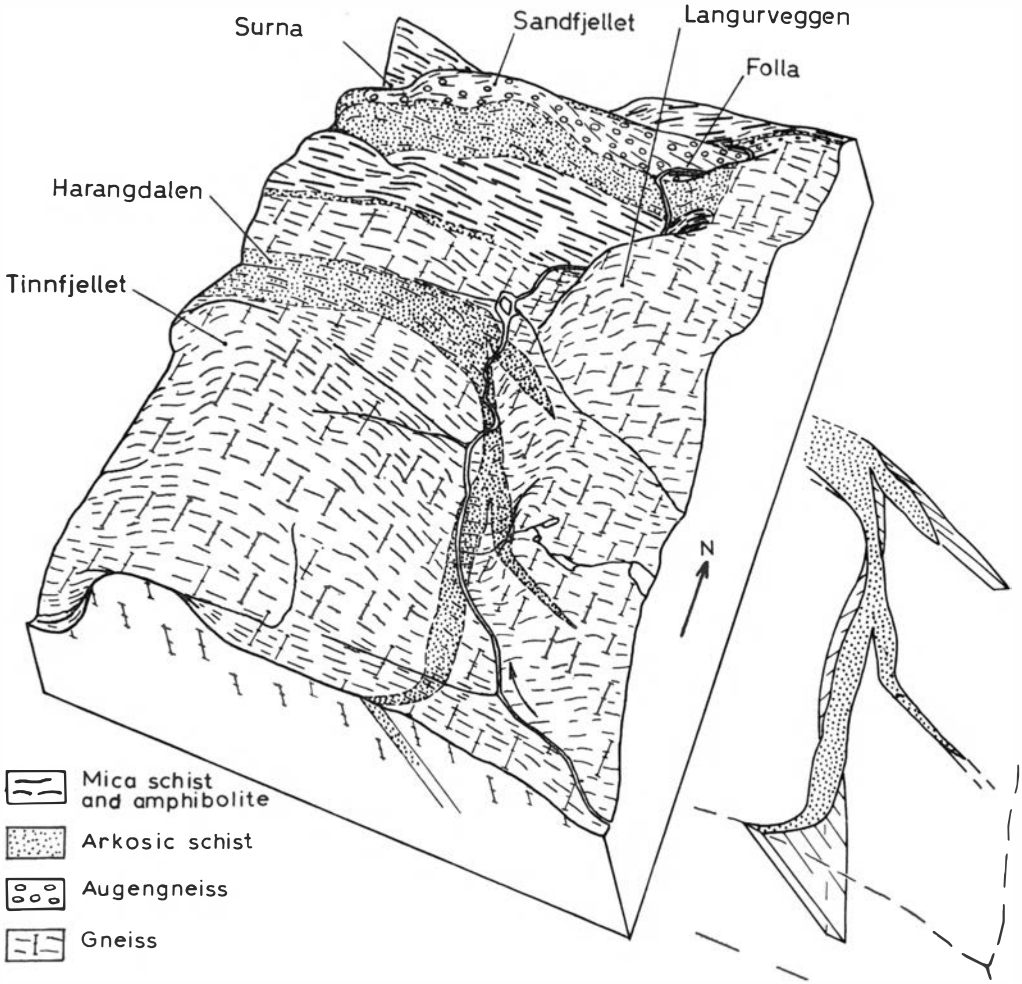
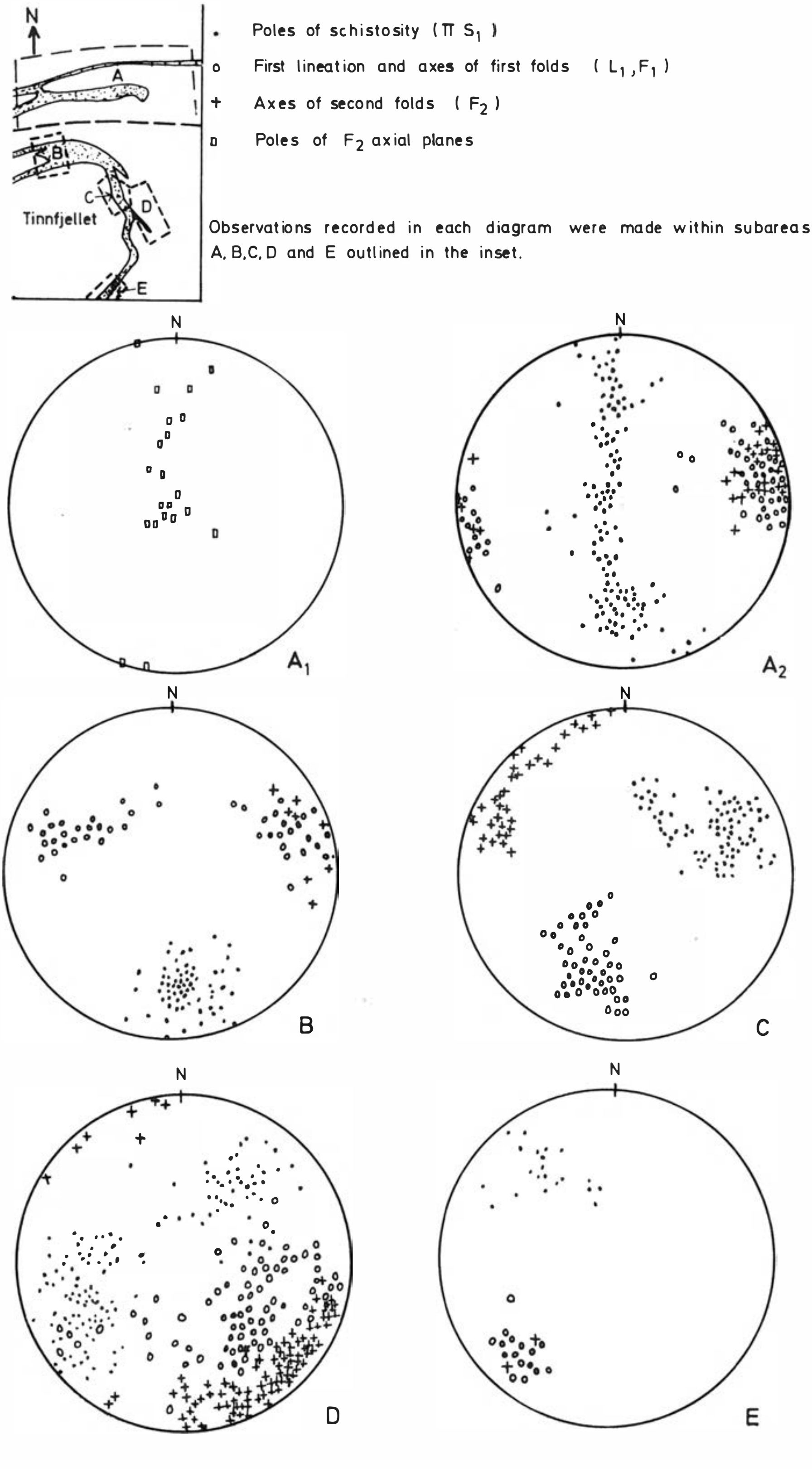


Fig. 5. Block diagram of the area. The arkosic schist surrounding Tinnfjellet is drawn to the right.

the F_2 axial direction, and L_1 was therefore only slightly rotated by F_2. The F_2 axial planes, however, have various orientations probably caused by later F_3 folding (Fig. 6 A_1).

Tinnfjellet dome

The Tinnfjellet dome is the main structure in the southern part of the area. A homogeneous granitic gneiss is here surrounded by arkosic schist. It is, however, not a normal dome, because on the eastern side the schist dips below the gneiss. This is probably caused by local F_2 folds which here have an almost horizontal axial plane. Some wedges of the schist pinching out in the gneiss on the eastern side are probably closures of F_1 folds (Fig. 5).


N
A
Bi
C
D
E
Tinnfjellet
Poles of schistosity (πS_1)
First lineation and axes of first folds (L_1, F_1)
Axes of second folds (F_2)
Poles of F_2 axial planes
Observations recorded in each diagram were made within subareas A, B, C, D and E outlined in the inset.
A_1
A_2
B
C
D
E

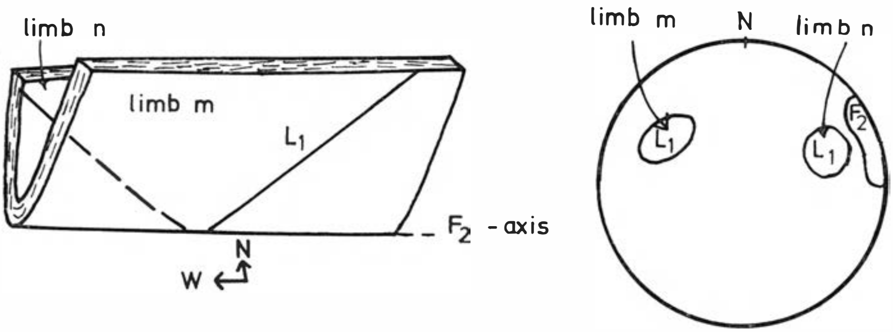


Fig. 7. Deformation of L_1 by F_2 folding in subarea B.

The original L_1 direction was also here probably E-W, and since the axial direction of the F_2 folds is tangential to the dome structure, the angle between the original L_1 direction and the F_2 axial direction changes in different parts of the dome structure. The L_1 was rotated by F_2 according to the angle between the original L_1 direction and the F_2 axial direction. A lineation deformed by flexural-slip folding will ideally describe a cone surface. This cone surface will describe a small circle in the stereo diagram. In this way it is possible to construct a probable path of L_1 in different localities.

In subarea B on the northern side of the dome structure, the arkosic schist dips to the north above the gneisses of Tinnfjellet. Lineation L_1 plots in two areas within a girdle in the stereo diagram (Fig. 6 B), while the F_2 axes plunge gently to the north-eastern quadrant. The L_1 seems here to define a great circle, indicating slip deformation of L_1. The L_1 orientation may be explained by nearly isoclinal F_2 folds. L_1 refolded in this way will have a different orientation on the two opposite limbs on a F_2 fold (Fig. 7). The rather thick sequence of arkosic schist may be explained by such near isoclinal F_2 folds.

On the eastern side of the dome (subarea C, Fig. 6 C) the arkosic schist dips below the gneisses in Tinnfjellet. The F_2 fold axes plunge gently to the north-western quadrant while the L_1 lineation plunges to the south-west. The F_2 axial planes and both the limbs of the F_2 folds dip to the south-west. The L_1 direction seems to be explained by F_2 folding of an original L_1 direction E-W. Fig. 8 shows a F_2 fold and the L_1 orientation on the two limbs from this area.

In subarea D (Fig. 6 D) the S_1 poles are distributed in a diffuse girdle. The F_2 axes usually plunge gently to the south-east. The regional dip of the layers is here about vertical, but since the F_2 axial planes are about horizontal, the two limbs of a F_2 fold have opposite dip directions and S_1 therefore defines a girdle in the stereo diagram. The L_1 has different orientation

Fig. 6. Structural plots in the stereo diagram.

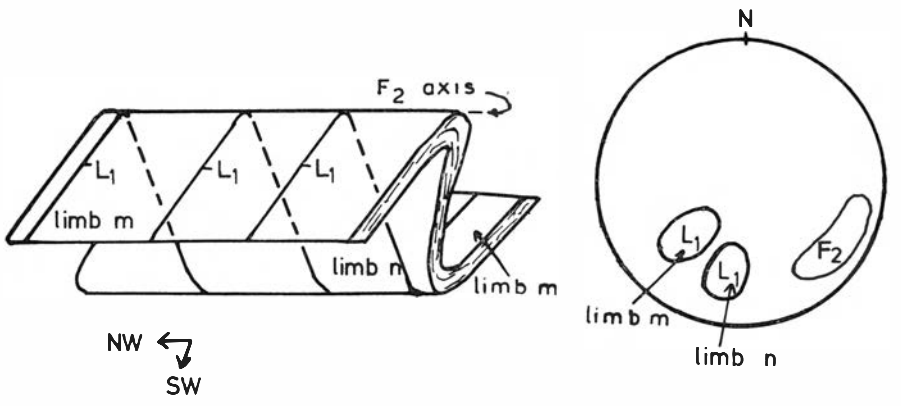


Fig. 8. Deformation of L_1 by F_2 folding in subarea C.

but plunges essentially to the southeastern quadrant. The L_1 orientation seems to be explained by F_2 deformation as for subarea C, but since S_1 orientation in subarea D is more random, the L_1 is also more random.

In subarea E on the southern side of the dome, the arkosic schist is again above the gneiss in Tinnfjellet and dips to the south-east, while L_1 plunges gently to the south-west. Only a few F_2 folds are observed here. The L_1 orientation seems to be explained by a slight rotation during the dome formation.

The dome formation probably started during the F_2 period, and local stresses may have formed the F_2 folds with axial orientation tangential to the dome structure. The dome formation may also have continued after the formation of the smaller F_2 folds had finished.

Reconstruction of the folding history

The three fold phases have deformed all the rock groups and must therefore be of Caledonian age. The strongest metamorphism seems to have taken place during the F_1 period when all rocks (except some gabbro intrusions) were recrystallized in the almandine-amphibolite facies. The main schistosity, S_1, was formed during this period. S_1 is an axial plane schistosity in the F_1 folds. F_2 microfolds are often observed in the mica layeres and the longest axes of quartz and feldspar grains are often orientated in the F_1 axial plane, suggesting that the minerals are of F_1 age. Some mineral formation seems to have taken place later than the F_1 period. The garnet crystals have often an idiomorfic form suggesting a post-tectonic age.

The original L_1 orientation seems to have been about E-W in the whole area. L_1 is refolded by F_2 and has now a varying orientation. In the northern part of the area the F_2 axes are nearly parallel to the original L_1 orientation and L_1 is therefore only slightly rotated. In the Tinnfjellet area the angle between the F_2 axes and the original L_1 orientation changes, and the L_1

lineation has therefore been rotated in different ways in various parts of the area. The orientation of the F_2 axes tangential to the dome may be explained by local stresses set up during the dome formation. The highest compressive stress axis seems everywhere to have been radiating from the centre of the dome and outwards. The dome formation is therefore probably simultaneous with the folding of the smaller F_2 folds, and this may explain the rather variable orientation of the F_2 axial planes.

The F_3 folding deformed the F_2 folds. This is directly observed in small F_2 folds on the eastern side of the dome structure where the F_3 axes strike nearly perpendicular to the F_2 axes. The F_3 axes always seem to strike E-W and the axial planes are steep. In the northern part of the area the F_3 axes are parallel to the F_2 axes, and the only deformation of the F_2 folds is a rotation of the F_2 axial planes.

Acknowledgements. – This paper is a part of a thesis submitted for the author's cand. real. examination in 1969 at the University of Oslo. The field work was carried out 1966–1968 with a grant from Norges Almenvitenskapelige Forskningsråd. The author would like to express his thanks to førstekonservator Inge Bryhni for help and criticism in preparing this paper. He is indebted to the late Professor Trygve Strand for supervising the work.
November 1975

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