Deformation in the Gangåsvann Area.

By

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Abstract.

The effect of multiple deformation on a series of banded metasedimentary rocks is described. Disharmonic folding has occurred and a slide formed during the first phase of movement separates highly folded rocks from those above which are less deformed. The isoclinal recumbent folds of the first phase have been re-folded across steeply-dipping axial planes to give a characteristic pattern of acurate outcrops. Later movements have produced open folds and rejuvenation of the slide. The development of faults and a fracture system is the final phase of deformation.

Introduction.

The broad outlines of the geology on the eastern flank of the Caledonian fold belt can be seen from the 1:1,000,000 map of the Norwegian Geological Survey — and in Fig. 1 *(N.G.U. 208, 1960)*. These show a belt of granitic gneisses, extending inland from the coast, overlain by a strip of Eocambrian and finally by the Lower Palaeozoic rocks of the Trondheim synclinorium. The upper parts of the Cambro-Silurian sequence are fossiliferous and hence a stratigraphy may be established, but towards the west these rocks are too strongly metamorphosed for such evidence to be preserved and the recognition of stratigraphical units is based on the differing lithologies; thus massive greenstones and pillow lavas are generally taken to be equivalent to the Støren Group (lowest Ordovician-Upper Cambrian), mica schists with amphibolites as the Røros Group (Upper Cambrian-uppermost Eocambrian), and felspathic quartz schists or flagstones as the Eocambrian. The "basement", which conformably underlies these units, is a complex of granitic gneisses, and the remnants of Eocambrian and Palaeozoic metasediments which have been identified in it suggest that the original rocks ranged in age from Archaen to Palaeozoic. However, the widespread metamorphism and migmatization, which took place during the Caledonian orogeny, has so transformed them that it is generally very difficult to infer anything of their original age or disposition.

The Gangåsvann area, which lies west of Trondheim between Orkdal and the sea, spans the transition zone between the gneiss and the Palaeozoic schists, but although the stratigraphy and metamorphism will be briefly discussed, the principal aim of this paper is to describe the effect on the Eocambrian rocks of several phases of deformation, and to show how these phases are related in time.

Little previous work has been done in the area and the few observations are summarized by Holtedahl and by Strand in the Survey publications (N.G.U. 164, 208). However, it is possible to collect structural data from the literature of surrounding areas and from these to predict something of the tectonic patterns which may be expected. Amongst the most obvious structures along the border of the gneiss region are the elongate folds whose axial planes follow the north-east grain of the country (Fig. 1). They are seen both in the Palaeozoic rocks and in the granite-gneiss; the axial planes are generally steeply dipping, but in Surnadal (Hernes 1956 b) a large syncline whose axial plane is sharply bent into an almost horizontal position suggests that locally later deformation has taken place.

In the Trollheim region, where large, recumbent folds overturned north-west, are bent across east-west axial planes (Holtedahl 1938, H. Holtedahl 1950), it is even more obvious that several phases of deformation have occurred; these structures are bounded to the east by the thrust-plane delimiting the Trondheim schists, which can be traced for more than 100 km northwards towards Surnadal. Thus, in the Gangåsvann area, it would be reasonable to expect evidence of several periods of deformation and thrusting.

Lithological succession.

The three major units of the succession, the Våvann Group, the Sognsjø Group and the Gangåsvann Group, strike north-eastwards forming the elongate outcrops shown in Fig. 1. The rocks dip south-eastwards to varying extents and hence the Gangåsvann Group lies uppermost, but since deformation and metamorphism have destroyed any direct evidence of their age or original relationships, the succession is a purely structural

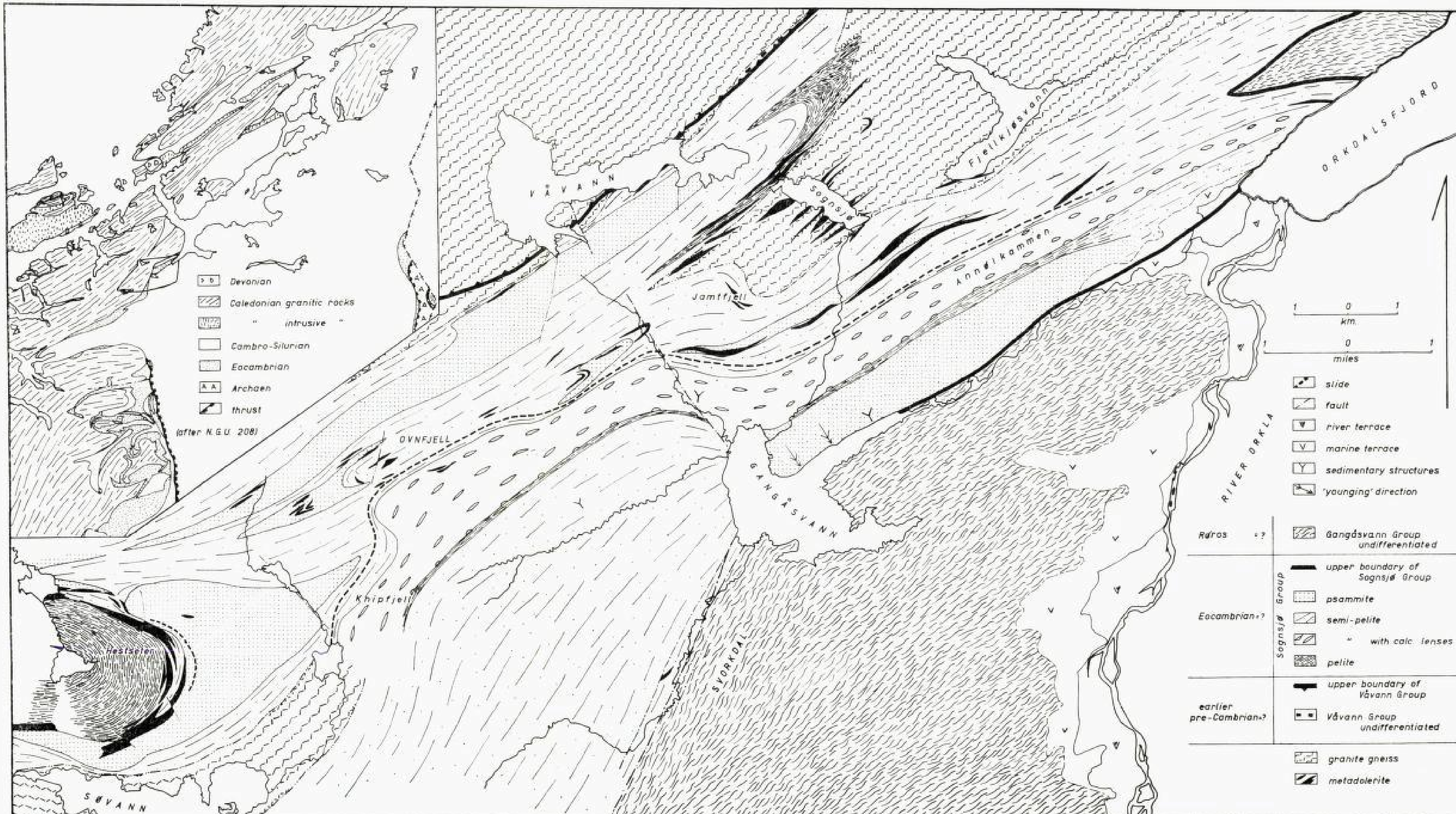

Fig. 1. Simplified geological map of the Gangåsvann area with inset to show its regional setting.

one and the tentative stratigraphical correlation is based on evidence from other areas.

The three groups, all of which have been metamorphosed in the "garnet grade", can generally be distinguished on lithology but in the north-east where the two lower units grade into microcline-bearing gneisses the differences are no longer so apparent. The Gangåsvann Group consists of garnet-hornblende-mica schists and amphibolites, with sheets or lenses of trondhjemite; the amphibolites are perfectly concordant, showing very little felspar and no evidence of relict igneous texture. The Sognsjø Group, which lies below it with apparent conformity, is a series of quartzites and banded semi-pelites with small amounts of pelite. It can be divided into two units separated by a slide, which dies away north-eastwards; the upper unit consists of a quartzite in which graded bedding and poorly-preserved false bedding (exposed along the north shore of Gangåsvann) young eastwards i.e. up the structural succession, and this is followed by a horizon of dark semi-pelite containing small calcareous lenses. The rocks of the unit below, which comprise alternating quartzites and semi-pelites, are much more deformed and no sedimentary structures have been seen in them. Both units contain bands and lenses of amphibolite which occasionally show the remains of igneous texture; locally they cut across the primary banding of the metasediments or push it aside (Fig. 2) and hence they are interpreted as a swarm of dolerite sheets. Similar dolerites are seen in the group beneath but they have not been found in the Gangåsvann Group.

The Våvann Group is a variable complex of grey, plagioclase-rich gneisses in which are found thin bands of quartzite, mica schist and amphibolite. These rocks are cut both by metadolerites, which show remnants of ophitic texture, and by basic sheets in which metamorphic differentiation has induced the formation of zoned garnet-plagioclase segregations. There are several generations of pegmatites and locally the mica schists grade into coarse augen-gneiss with rapakivi texture. In some of the thicker horizons of banded hornblende gneiss there are patches of metastable pyroxene which suggest that these may once have been higher grade rocks.

These criteria, which distinguish the rocks of the Våvann Group from the quartzites and semi-pelites of the group above, make it evident that the two have had differing histories: the former group shows traces of a period of magmatic segregation and high-grade metamorphism which has not affected the Sognsjø rocks and this probably indicates that the Våvann

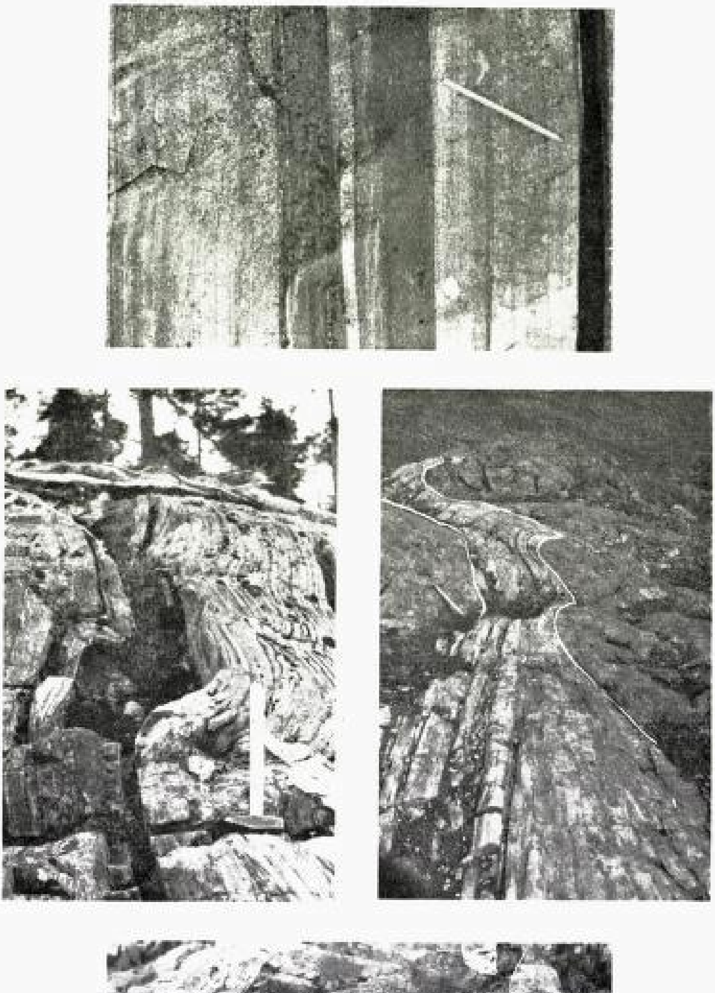

Fig. 2. Dolerite sheets in rocks of the Sognsjø Group.

group represents the earlier pre-Cambrian "basement". As the rocks of the Gangåsvann Group can be traced laterally beneath the pillow lavas which are typical of the Støren Group, it is presumed that they can be correlated with the Røros Group; hence the Sognsjø Group, lying below this, would be equivalent to the Eocambrian.

Structural History.

Although rocks of all three groups have been affected by the several episodes of folding, in those of the Sognsjø Group the evidence of repeated deformation is particularly well-preserved and hence they will provide the principal illustrations. This group forms the high ground immediately west of Orkdal and glaciation, which has removed most of the soil cover, has provided good exposures of bare rock. Aerial photographs with a scale of 1:40–50,000 were used as a basis for geological mapping and, from these and trigonometric data from the Norges Geografiske Oppmåling "rectangle" maps, a topographic map at a scale 1:40–000 was made using a Zeiss Stereotope.

The structural history can be divided into four phases:

(a) Early folding
(b) Main folding
(c) Late folding
(d) fracturing

and the data have been plotted on the map, which is shown in Fig. 9 (p. 293).

Early Structures: the Knipfjell slide.

The map shows that the slide running from Knipfjell north-east towards Annølkammen, which separates the two units of the Sognsjø Group, (see p. 277), also represents a discontinuity in the tectonic pattern; the rocks lying west of it are much more deformed and show major structures of the two earlier fold periods, whose combined effect has produced a complex pattern of outcrops. The slide is also shown in the diagrammatic sections across the area illustrated in Fig. 8 (p. 291), and it can be seen that whereas on Knipfjell the rocks of Unit 1 lie with strong unconformity upon the unit below, as the slide is traced north-eastwards the angle between the two becomes smaller and smaller until on Annølkammen the banding in the two units dips conformably south-east. This discontinuity might represent a plane of original discontinuity separating relatively undisturbed rocks from a series of already-folded metasediments, but as the rocks of the upper unit show minor structures similar in style and orientation to the Early and Main folds seen elsewhere, and since the mineral growth parallel to the axial planes and lineations of Early age in the lower unit is abundantly seen in the rocks above, it is considered that the two units have had a common history. This implies that disharmonic folding has occurred and that the Knipfjell slide is a décollement, which has protected the rocks above from more intense deformation.

The Early folds.

Structures of this age are shown in Fig. 9 and it is obvious that the present attitude of both the major and minor structures has been strongly influenced by refolding. Ramsay (1958) and others, dealing with areas of multiple deformation, have applied techniques of statistical analysis to the structural data but in this area co-axial folding (e.g. near Hestseter) and the small amount of data available make such techniques unsuitable. The following hypotheses are based on the evidence of major and minor folds and on comparison of the outcrop patterns with those produced in models of superimposed folding (Reynolds and Holmes, 1954; Ramsay, 1962).

Typical minor folds of Early age are shown in Figs. 3b, 4; they are isoclinal with sharp crests and often show great thinning of the limbs: the linear structures comprise minor fold axes, the outcrop of cleavage on bedding and shape-oriented mineral grains. These structures affect both the Sognsjø metasediments and the enclosed dolerites (Fig. 3b, 4b;) hence the dolerite intrusion must have preceeded the Early folding. There has been mineral growth associated with the folding, which is recorded both macroscopically and in thin section: micas or shape-oriented quartz and hornblende mark out the axial plane in the pelites, the quartzites and the amphibolites respectively, whilst hornblende, quartz and acicular kyanite follow the linear structures; in the calcareous lenses of Unit 1 (Fig. 4 g) hornblende crystals flattened parallel to the biotite cleavage are elongated in the direction of the fold plunge. The age of these structures relative to the Main deformation is shown by examples such as Figs. 4a, c, d, f, and by Fig. 3a, b, where the Early folds are bent across axial planes of Main age.

In general the major Early folds beneath the Knipfjell slide have been too severely deformed by the later movements for any estimate of their

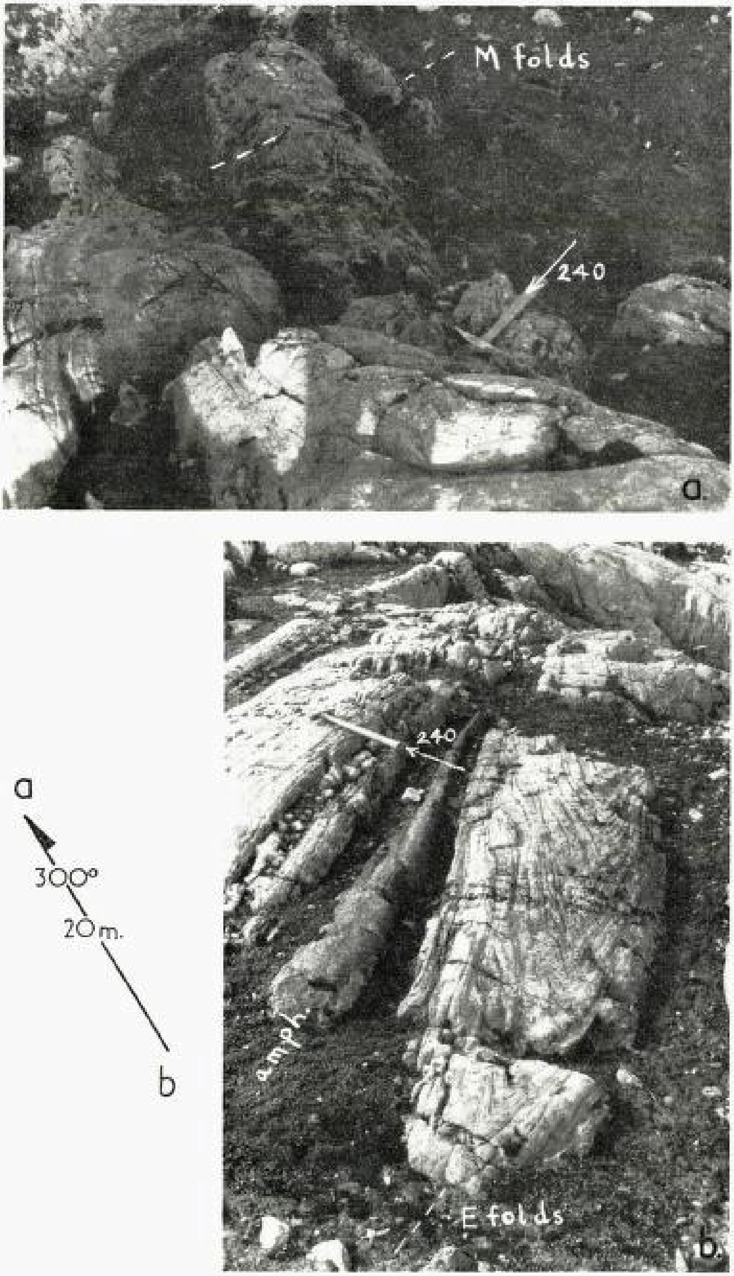

Fig. 3. Minor fold structures on Ovnfjell. (a) Main fold in the core of the synform M2 (see trend map in Fig. 9). (b) Early folds on south limb of M2.

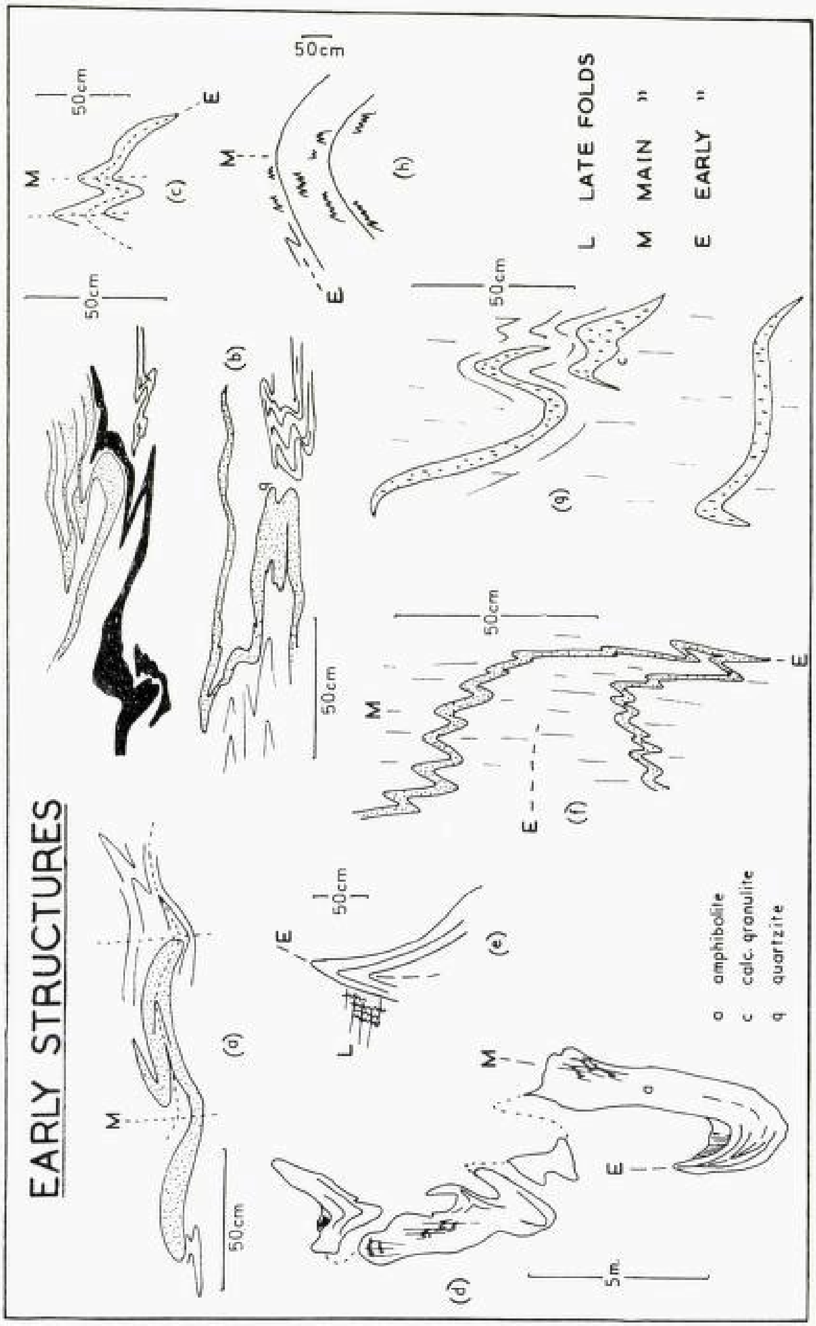
EARLY STRUCTURES
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
50cm
5m.
L LATE FOLDS
M MAIN "
E EARLY "
a amphibolite
c calc. granulite
q quartzite

Fig. 4.

original position to be made, but above the slide two structures have been preserved. These are seen along Orkdalsfjord (Fig. 9) where rocks of the Gangåsvann Group occupy the core of a narrow syncline plunging gently east-north-east and overturned northwards. The axial plane of this structure dies out south-west along Annølkammen but that of the complementary antiform can be followed for a greater distance until it eventually becomes almost coincident with the Knipfjell dislocation. The minor fold relationships are diagrammatically shown in Fig. 8 and from this it appears that the rocks above the slide are the crest and the southern limb of an Early antiform, whose axial plane has acted as a plane of discontinuity (cross sections 8b, c, d, from Knipfjell to Jamtfjell); the upper limb has slid northwards and comes to rest with increasing unconformity on the underlying rocks as the plane is traced south-west.

These folds, overturned northwards, are the only Early structures whose orientation may be original; however, in the rocks beneath, the presence of recumbent structures may be inferred from the attitude of minor folds and from the lunate outcrop patterns which Reynolds and Holmes (1954) and Ramsay (1962) have shown to be characteristic of certain types of multiple deformation. Ramsay, whose fine block diagrams illustrate the effects of superposed folding, has divided the patterns obtained from the interference of two fold systems into three types; the outcrop shapes seen in this area approximate most closely to the type in which the 'a' direction of the second folds makes a high angle with the axial plane of the first fold, and the axis of first folding a high or moderate angle with the second axial plane; arcuate patterns are produced when recumbent structures, folded across the new axial planes, intersect the topography; hence both extremities of the arc are closures and the plunge of the new folds will be dependent upon the attitude of the limbs of the earlier structures (Ramsay, 1960).

Whereas the structures shown by Ramsay are symmetrical, those exposed beneath the Knipfjell slide are strongly assymmetrical (Fig. 9) and show one long and one short limb. This is due to the small angle between the two axes of folding and whilst on the short limb the Early fold hinges can be traced, on the long one the folds are too attenuated to be visible and the position of the Early axial plane can only be inferred. Along the axial planes of the Main folds, (numbered for reference), the plunge of the second structures gives an indication of the original orientation of the Early fold limbs: thus along M1 the second-fold minor structures plunge consistently north-east on both limbs of the Early fold, suggesting that the fold was recumbent north-westwards. Thinning of the limbs of the Main folds and distortion of the Early minor structures has made the minor folds of the two generations almost coincident along M1 and it is only possible to differentiate the minor structures where they are re-folded (Fig. 4h) or are accompanied by mineral growth, but on the axial planes M2 and M3 Early folds, plunging steeply north-west, are preserved in the Main fold hinges. The north-east plunge of the Main folds on all the Early fold limbs again indicates that the first structures were probably recumbent north-west.

In the best documented of these composite folds, which is exposed near Hestseter, the Early structures are well-preserved and can be traced in their varying orientations across the Main axial plane (M4). From Fig. 9 it can be seen that this structure is unusual firstly, in that it is a more open shape – this may indicate less intense Main deformation or that the massive quartzites, that form the core, have resisted folding – and secondly, in that most of the minor structures plunge south-west. The data seen in Fig. 9 show that the Early axial plane can be traced across M4 and that the minor-fold axial planes change gradually from dipping steeply south, to dipping west and finally to dipping gently north-west. The attitude of the lineations is more variable and it is difficult to estimate how much their orientation has been affected by shearing during the later movements; at the Early fold closure north of M4 minor fold-axes plunge steeply south or south-west but as they are traced southwards on the western Early limb the plunge becomes less and the folds of the two phases are virtually co-axial. South of M4 on this same limb the lineations plunge more gently south-west and finally turn north-east. On the eastern limb of the Early fold the pattern is similar except that as the lineations are traced east-wards along the Main axial plane they change from plunging south-west to plunging north-east. The Early minor structures are better preserved on the western limb than east of the Early axial plane and it appears that this thickened part of the fold has resisted the penetrative shearing of Main age, which has partly destroyed the structures elsewhere. This hypothesis is perhaps supported by the presence of a local slide which follows the inner curvature of the west limb (Fig. 9); it is suggested that dislocation along this plane occurred when the Early fold closure could no longer be further tightened.

Form and attitude of the Early structures.

Although a more detailed study than this would be necessary to discover the exact initial shape and orientation of the Early folds some deductions may be made from the present data: Ramsay (1958, 1960) has shown that when re-folding occurs two sets of linear structures, one on each limb, may develop if the limbs of the first fold diverged, and it is thus perhaps valid to suggest that in the Gangåsvann area, where the Main folds plunge with constant orientation on the limbs of the Early folds, the Early folds were isoclinal, recumbent structures, overturned to the north-west; on this hypothesis it would be necessary to assume that the Early Hestseter fold was overturned eastwards, perhaps forming the nose of a recumbent structure.

A method for finding the trend of the earlier axes in "double" folds was suggested by Reynolds and Holmes (1954) and modified by Ramsay (1960) for more accurate determination; in this the apices of the lunate outcrops are joined by a line, which gives the approximate direction of the earlier fold axis, and for the Early folds this direction is about N 50 E. The shape of the outcrops is then consistent with the hypothesis that these structures represent two antiforms and a synform, overturned north-west and a synform closing westwards, and this is diagrammatically shown in Fig. 8.

The Main folds.

Major folds of this phase do not occur above the Knipfjell dislocation although minor structures are present. The folds are much simpler than the structures previously discussed and their axial planes, trending north-east and dipping at a high angle north or south, are very constant in attitude; it is only near Hestseter that M4, the most southerly axial plane, begins to swing east-west; M1 and M3 are axial planes of antiformal folds whilst the structures shown by M2 and M4 are synformal. The orientation of the axial planes of major and minor folds is shown in Fig. 9 and the style of these folds in Figs. 3a, 5; they are open structures with angles of 60° to 120° between the limbs and, although there may locally be an orientation of quartz grains parallel to the fold axis or of mica along the axial plane, they do not normally show an axial plane cleavage or linear arrangement of minerals. There has, however, been subsequent recrystallization so that in thin section, the fabrics related to the Main folds are unstrained.

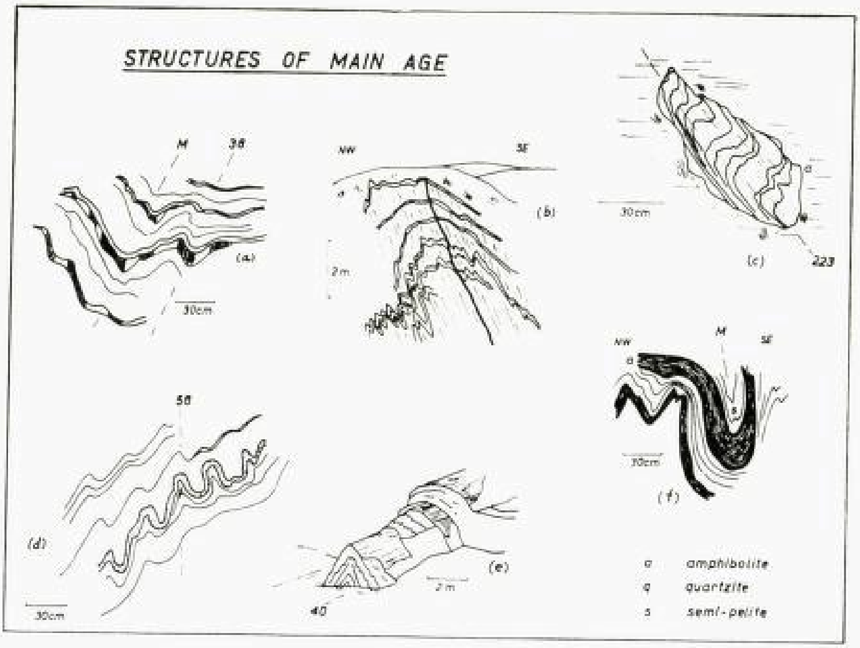

Fig. 5.

The deformation during this phase has apparently destroyed some of the minor structures of the Early period; an example of this is the difference seen on the two Early limbs of the Hestseter fold (see p. 284), and it is further illustrated by the destruction of kyanite in the pelitic schists lying west of this fold: here the acicular crystals oriented parallel to the Early fold axes are progressively destroyed by shearing as one goes south from M4 towards the thin limb of the Early fold. This is interpreted as an indication of the differential movement which has taken place on the limbs in this Main fold, whereby one limb, comprising a massive Early fold hinge has deformed by tightening of the fold and eventual dislocation and the other, thinner limb has deformed by rotation and shear.

The linear structures of Main age are also rather constant in attitude; the north-east plunge along M1 varies between 20° and 35° but turns south-west on Ovnfjell; along M2 the plunge, which is again to the north-east, varies from 20° on one limb to 40° on the other; structures on M3 plunge between 30° and 40° north-east and more steeply – up to 55° – on Jamtfjell. In the Hestseter fold the most easterly lineations plunge north-east, presumably reflecting the position of the Early limb, but westwards they begin to plunge west and finally to show a consistent south-west plunge between 20° and 40°.

Late structures.

These are of many kinds and include small rucks, fractures, broad, open folds, monoclinal folds associated with fracturing, quartz-filled gashes and slickensides. Their common feature is that they occurred after the widespread mimetic recrystallization, which took place subsequent to the Main deformation.

They are shown in Fig. 9 and their style in Fig. 6; they can conveniently

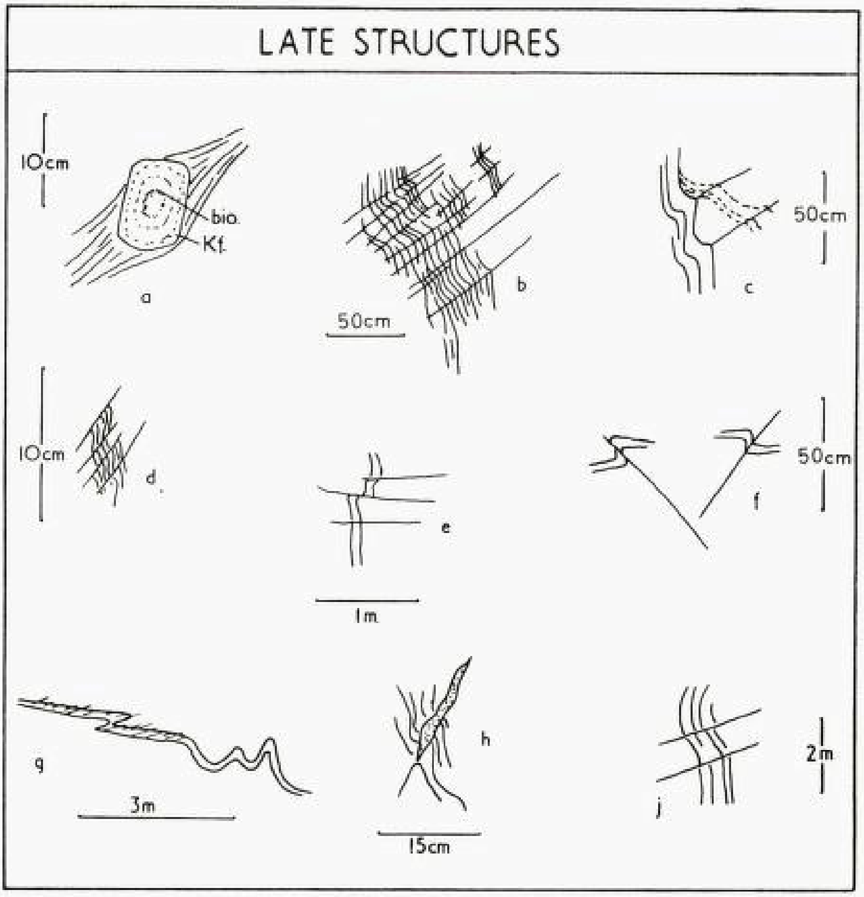

Fig. 6.

be divided into those associated with folding and those related to the fracture pattern:

(a) fold structures.

In the rocks of Unit 1, especially along the south-east border, broad folds, which distort both Early and Main strucures, are seen. The largest of these which has an amplitude of nearly 1 km, deflects the banding north of Gangåsvann and contributes to the gentle dip west of it; other examples, varying in size from a few metres down to 10 cm., can be seen along the north shore of the same lake (Fig. 6b, c). These folds are open structures, cylindroidal in type and they show only dextral movement; their axial planes are steeply inclined north-west and may be marked by thin stringers of quartz or quartz and felspar; locally, on Jamtfjell and Ovnfjell, prismatic crystals of potash felspar are oriented parallel to the axial planes of brittle kinks of this age (Fig. 6a). In general these structures show a very gentle plunge but on Knipfjell, where the rocks of Unit 1 are strongly affected by Late folding, the plunges may reach 30° NE; it seems probable that the décollement here has been rejuvenated and that Unit 1 has again moved north-westwards over the rocks below.

(b) Structures related to the fracture pattern; the fracture pattern itself.

The other structures in this group are mostly associated with joints or fractures. Fig. 7, which is compiled from aerial photographs and from field data, shows the dominant joint pattern, and in Fig. 6f the relationship between monoclinal folds and jointing will be seen; often the movements which culminate in a fracture deflect the bedding first so that kinks and stepped folds are formed. Sometimes a closely-spaced set of small fracture planes produce a strain-slip cleavage (Fig. 6d) but although the minerals may be dragged into the shear planes there is no true cleavage formed.

Other types of Late structure are small gashes in the schists which may be filled with quartz or quartz-felspar pods (Fig. 6h), similar to the structures described by Ramberg (1961), or the brittle zig-zag crenulations seen in Fig. 4c. The latter are formed on very gently dipping axial planes and may often be accompanied by displacements on low-angle faults so that the rocks seem to be divided into horizontal slices which have moved relative to one another (Fig. 6e). They are obviously associated with the

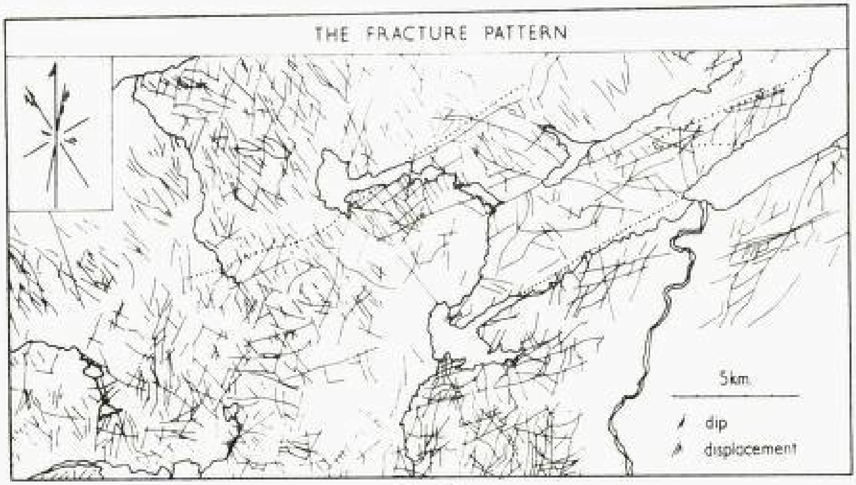

Fig. 7.

fracture pattern but, because of their orientation, do not appear as a regular set on Fig. 7.

The fracture pattern shown in Fig. 7 can be resolved into four sets of planes along which movement has taken place, one of which is the bedding or the Early cleavage. The most frequently developed joints strike approximately 330° and they dip at high angles variably north-east or south-west; very often they show small dextral displacements. They bear a "cross-joint" relationship to the Main folds. A complementary set parallel to the regional schistosity is particularly well-developed in the Gangåsvann Group and this is perhaps because of the well foliated nature of the rocks; there is not a preferred direction of displacement on these planes and the amount of movement is difficult to assess. In the Sognsjø and Våvann Groups fractures with this orientation (60°) tend to control the location of the larger river valleys. The set of fractures which shows the greatest displacement strikes 10° and generally dips steeply east; it is complementary to the "cross-joint" set and one of its members forms the main boundary between the Sognsjø and Gangåsvann Groups, south of Gangåsvann. These joints are few in number but the horizontal displacement may be up to several kilometres; on the fracture, which runs south from Gangåsvann along the Svorka, the apparent movement has been as least 6 km. and the zone of crushing is 1 kilometre wide; crush breccias have been formed along this zone and in similar zones on Ovnfjell. At the north end of this fracture the movement has partly been dissipated along the boundary of the Sognsjø Group and the overlying greenschists have been slightly rotated so that they are not always perfectly conformable with the psammites below. There is no constantly preferred horizontal displacement on these fractures.

The fourth component in the joint pattern is a set of fractures which strikes 110°; they are not common but where they occur seem to form extensive zones of weakness. Some of the larger valleys, e.g. Sognsjø, seem to have been controlled by them. These fractures dip rather variably but most frequently to the south-west, and they show a dextral displacement of differing amounts.

Many of the fracture planes are partly mineralized, and along some of them mylonite is developed; the commonest gangue minerals are quartz, epidote, calcite, pink felspar and chlorite. Locally veins of white potash felspar with chlorite or quartz-chlorite seams are found, and an unusual assemblage found along the north shore of Orkdalsfjord consists of epidote calcite and cubes of purple fluorite.

Conclusions.

The metamorphic rocks of the Gangåsvann area can be separated on lithology into three groups: the Gangåsvann Group consists of hornblende-mica schists and amphibolites; the Sognsjø Group is a series of banded semipelites and quartzites, cut by meta-dolerites, and the Våvann Group consists of mica schists, amphibolites and plagioclase gneisses, which are cut by several generations of basic sheets and pegmatites. A tentative correlation is made thus:

Gangåsvann Group = Røros Group = U. Cambrian-U. Eocambrian.
Sognsjø Group = Eocambrian.
Våvann Group = earlier pre-Cambrian "basement".

The effects of several periods of deformation are seen in the area and examples are taken from the Sognsjø Group. The first phase, the Early phase, gave rise to isoclinal structures overturned north-westwards. A plane of discontinuity, the Knipfjell slide, which separates highly folded rocks beneath, from those above containing sedimentary structures, can be traced until it becomes the axial plane of one of these Early folds, and there has been a relative displacement of the upper unit north-westwards.

Re-folding of the Early structures about steeply dipping Main axial

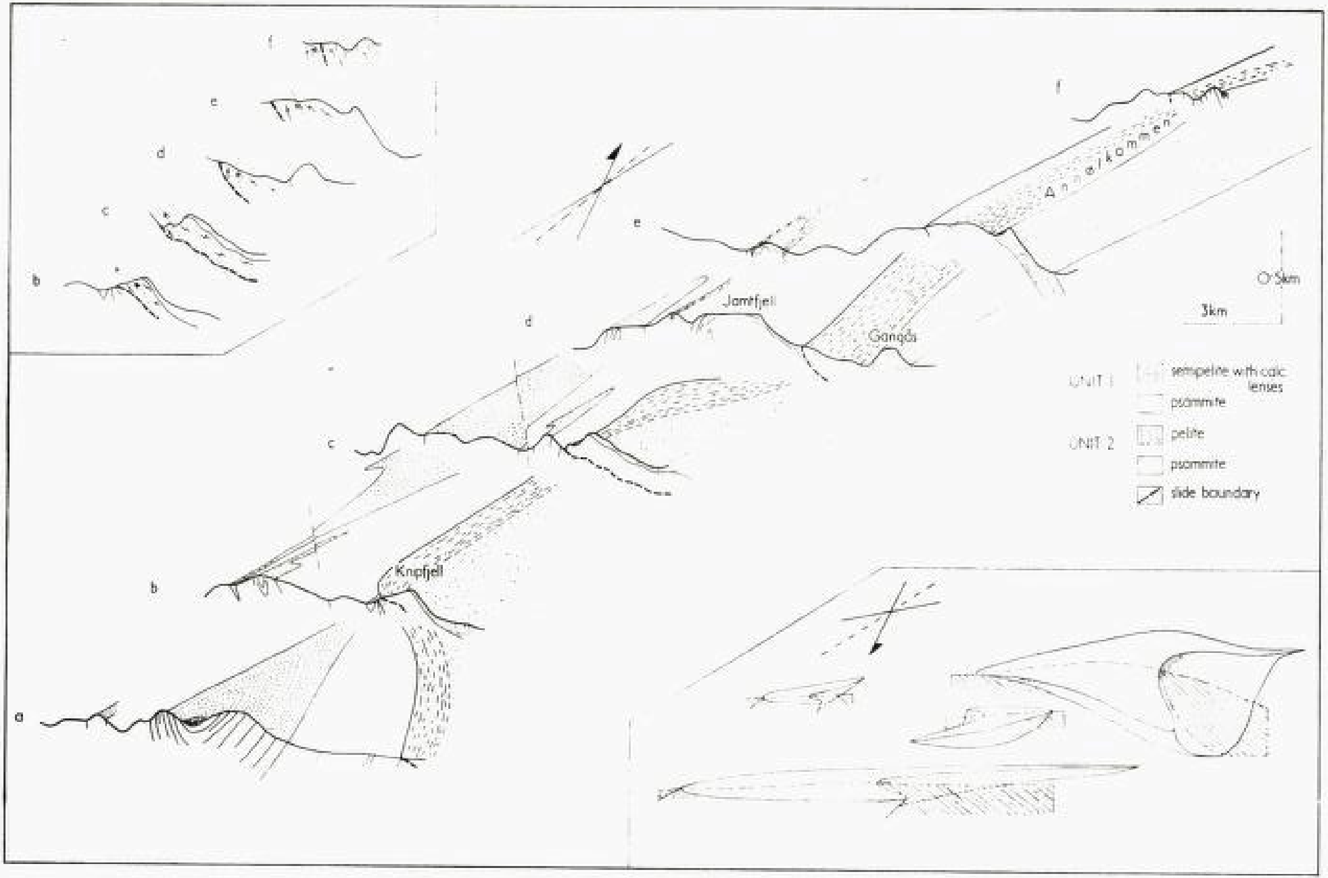

Fig. 8. Block diagram of the Gangåsvann area.
Upper inset: Serial sections to show Early minor folds in relation to the Knipfjell slide.
Lower inset: Simplified drawing of the hypothetical structure.

planes, which trend north-east, has produced a complex pattern of outcrops; the north-easterly trend of the Early fold axes can be reconstructed from these outcrops, and it can be shown how the first structures are deformed by the second folds. The first folds were accompanied by mineral growth at sufficient grade to form kyanite in the pelitic schists, but in the second phase many of the first structures and their lineations were destroyed by shearing.

The third phase of deformation, which took place after recrystallisation had stopped, produced open folds and there was renewed movement on the Knipfjell slide. This phase is closely associated with the fracture pattern, whose most important component, fractures striking N 10° E, have apparently displaced the southern boundary of the Sognsjø Group for at least 6 km. near Gangåsvann.

Acknowledgements.

This work was carried out during the tenure of a D.S.I.R. Research Studentship at Imperial College, London, and I am most grateful for the help of the staff and students both there and at the University in Oslo.

The field mapping would have been impossible without the kindness of the people in Trøndelag, particularly Bergingeniør Per Sandvik at Løkken Mine and Malernes Foreningen in Trondheim, who arranged accommodation for me. I am greatly indebted also to Prof. J. Sutton, Dr. M. Wells and Prof. T. Strand for reading and critical discussion of the manuscript.

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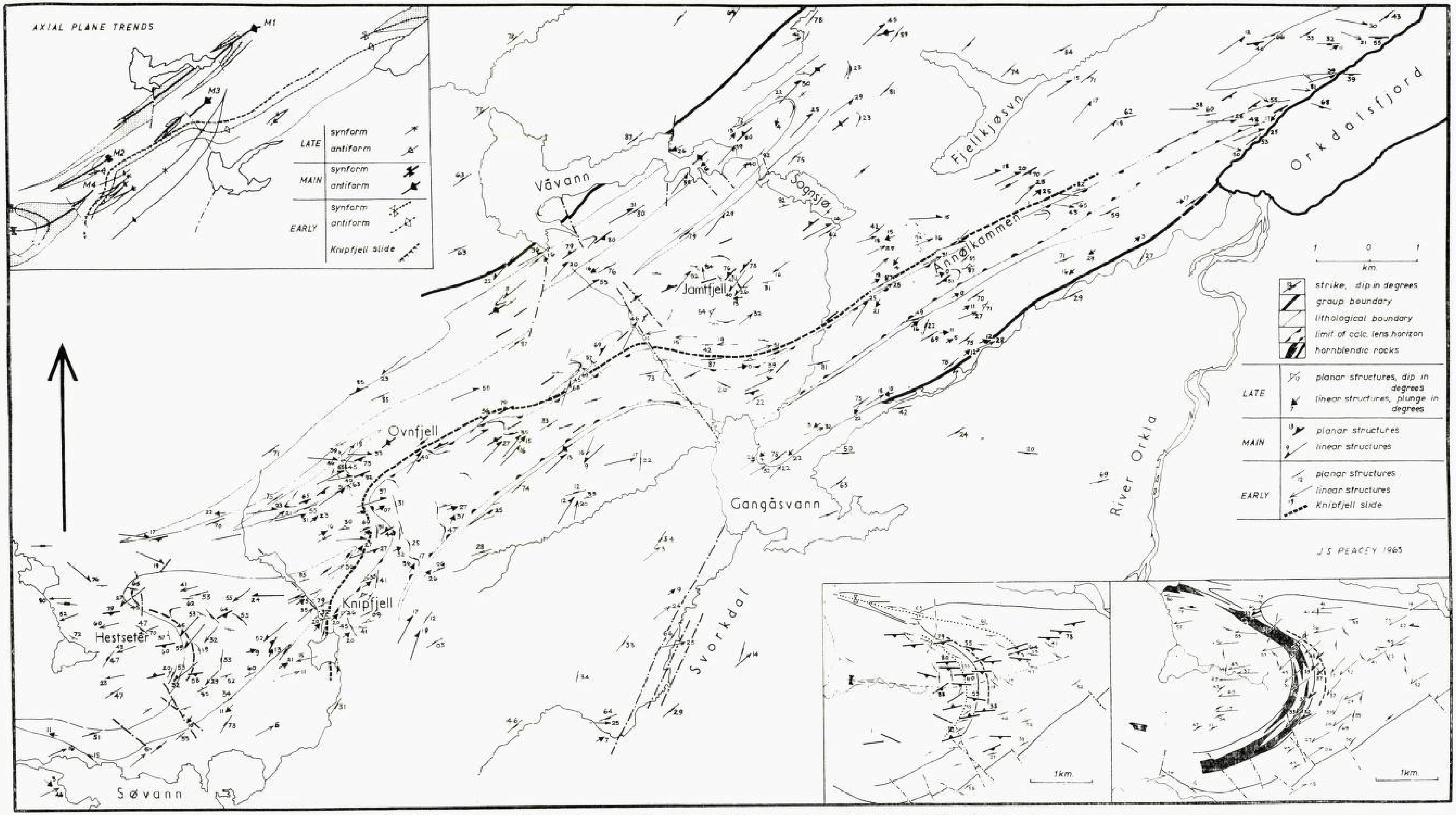

Fig. 9. Structural map of the Gangåsvann area. Upper inset: Axial plane trend map. Lower inset: Details of the Hestseter area.

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