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A Section across the Norwegian Caledonides; Bodø to Sulitjelma

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ABSTRACT

Between coastal regions near Bodø and the relatively well-known Sulitjelma area on the Norwegian-Swedish border a number of metasedimentary structural units have been distinguished lying above an apparently region-wide granite gneiss basement. Basement is revealed in two sets of culminations along the fold belt and at least in this traverse basement domes are present only as far east as the whole cover is high grade. Western basement culminations have an entirely Caledonian structure but eastern ones sometimes contain structures older than those in the cover.

In the west the lowest rocks of the cover generally are concordant on the basement and at least pseudo-autochthonous (described then as conjunctive). They are overlain by the disjunctive Beiarn nappe. To the east of this nappe there are several structural-lithological sub-units which thin to nothing to the west replacing one another as elements of local structural sequences. (In the Fauske region such sub-units are conjunctive.) The upper part forms our version of the Gasak (Rødingsfjell) nappe (disjunctive to the east). The lower part belongs almost entirely to the Køli division of Swedish geologists and is conjunctive on the basement of the western side of the eastern culminations but to the east is separated from basement not only by a thin and probably autochthonous sequence but also by rocks of the widely developed but little known and varied Seve which also thins westwards. It is fairly clear that the major structural units persist at least as far north as the Narvik region. Correlation to the south is less clear.

Linear fabrics are widespread in the Køli and Gasak units but not in the western conjunctive unit. Pebble elongation is east-west at Sulitjelma. In the west there are prominent isoclinal folds later than schistosity as well as less common isoclinal folds coeval with it. Most porphyroblasts seem to be non-kinematic (between F_1 and F_2). In the Sulitjelma region major tight folds later or coeval with schistosity are rare (minor folds are abundant). Many porphyroblasts are synkinematic (F_2). In eastern Sulitjelma the high-grade Gasak nappe overlies low-grade Furulund (Køli) within which in the east, however, higher grade developments also overlie lower grade ones (to the west all is higher grade). This relation can be explained only in part by the thrusting of Gasak over Køli; it is suggested that heat from the transported upper unit may have contributed to the metamorphism of the lower.

There are no major granitic intrusions in the region although granitic vein complexes are well-developed in the Beiarn nappe. There is one large and broadly synkinematic

gabbro (the Sulitjelma gabbro) but otherwise major basic intrusives are few. Serpentinized peridotites occur as small bodies strung out at various structural levels.

There are some well-known fossil occurrences at Sulitjelma from which it is possible to say that the main metamorphism, deformation and translation there are later than mid-Ordovician. An early Ordovician phase like that recognized in the British Isles cannot be distinguished in the Bodø-Sulitjelma tract.

INTRODUCTION

In a previous paper the present authors (Rutland & Nicholson 1965) attempted to outline the main features of the structural geometry and tectonic history of an area several thousand square kilometres in extent north and south of Bodø. Earlier studies of the region (e.g. Holmsen 1932, Vogt 1927) had greatly underestimated the degree of tectonism while extrapolations based on the tectonic style encountered to the east in Sweden were found to be invalid. It was shown in the earlier paper that the main granitic gneiss massifs near the Norwegian coast represent basement culminations. These are overlain by rock groups which although highly deformed, retain what appear to be original stratigraphic relationships and which have therefore been described as conjunctive nappes. Above these again a disjunctive nappe complex has been recognized, the Beiarn Nappe Complex, which was emplaced early in the deformation history (F_1) and before the main metamorphism (overlapping F_2). The Beiarn Nappe Complex was correlated structurally with the Rödingsfjäll Nappe Complex in Sweden (Kulling 1955) and with the Gasak nappe of Sulitjelma (Kautsky 1953) (Fig. 1). The published interpretations of the structural histories of these nappe complexes are not easily related to that of the Beiarn Complex however. Moreover the Gasak and Rödingsfjäll complexes are underlain by the Seve-Køli nappe complex of Swedish geologists. On its eastern margins this latter metamorphic complex is clearly disjunctive and overlies younger unmetamorphosed rocks of the para-autochthonous and autochthonous Cambro-Silurian succession (Fig. 1); Swedish geologists generally regard it as far travelled, and derived from the west. As indicated above no such exotic complex has been recognized in the Norwegian coastal regions below the Beiarn Nappe Complex. Moreover some published sections (e.g. Kulling 1955, 1960) suggest that the nappes in Sweden (by extrapolation extended into Norway) are relatively thin sheets of fairly constant thickness and great areal extent. The mechanics of formation of such nappes is better understood if they are regarded as essentially conjunctive as suggested by Rutland & Nicholson (1965). However the presence of slices of Archaean

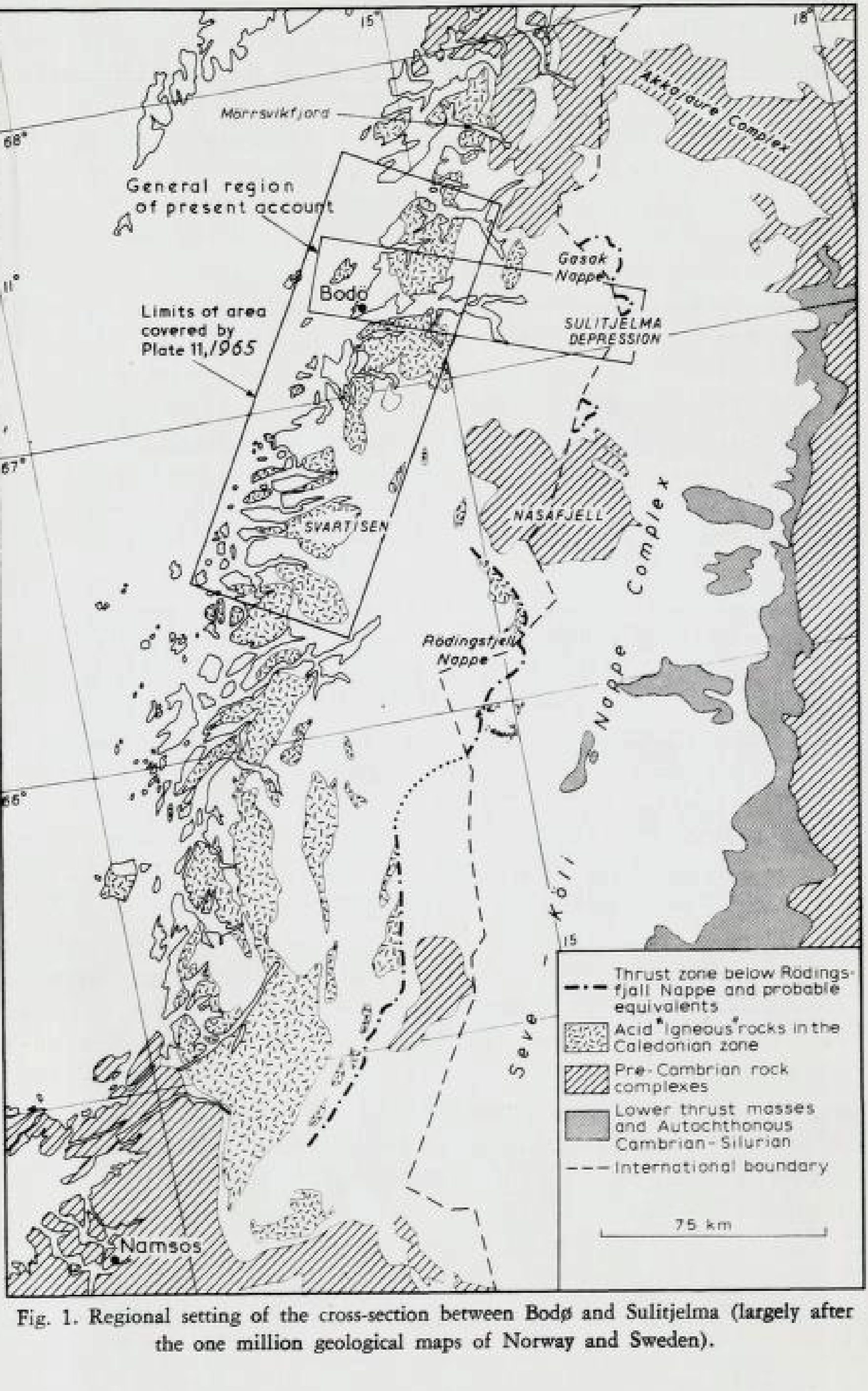

Fig. 1. Regional setting of the cross-section between Bodø and Sulitjelma (largely after the one million geological maps of Norway and Sweden).

Basement at the base of some nappes and the postulated postmetamorphic thrusting make current theories of mechanics of thrusting (Hubbert & Rubey 1959, 1961) difficult to apply. In any case the Swedish model is not applicable in Norway where the nappe structures show enormous tectonic thickness variations and where the main translations of the nappes have occurred early in the metamorphic history. The present writers' previous work thus emphasised the inadequacy of earlier interpretations based on the Swedish studies but it gave little clue to the true relationships between the coastal (western) and Swedish (eastern) nappe complexes.

The present study was made therefore in an attempt to resolve these problems. It was decided to map a section across the Caledonides in order to make a comparison of the rock units, structures and structural histories of the eastern and western nappe complexes, and if possible to establish directly the relationship between them. The cross-section between Bodø and Sulitjelma was the obvious choice because it links directly the coastal succession previously studied by the authors with the Sulitjelma succession of the Seve-Køli Complex described by Kautsky (1953). It is also relatively accessible along the whole of its 100 km length. It was studied earlier, under much less favourable circumstances, by Holmqvist (1900).

The complexity of the deformation in this general region has been demonstrated in earlier publications (Rutland 1959, Nicholson & Walton 1963, Holmes 1966). In particular it has been established that the earliest recognizable major folds have axial trends near east-west. Only the late folds have axial trends parallel or nearly parallel to the trend of the orogenic belt as a whole (here NNE-SSW). Consequently sections drawn across the orogenic belt tend not to reveal the earlier structures and it has been necessary to map a wide sections, averaging 50 km, in order to establish the relations between rock groups. In dealing with such a large area (approx. 5,000 sq.km.) the writers have not been able to carry out complete structural analysis. Relations between phases of minor structures have been observed and recorded but greatest attention has been given to mapping the major rock groups and thus to the direct determination of major structures. This approach has been aided by the presence of a wide variety of lithological types. It will be obvious however that much detailed work remains to be done to test and, if necessary, to revise the interpretations presented here.

The field work has been carried out over a number of years since 1959, at first by both, and latterly by one of us (R.N.). In addition detailed studies have been made on parts of the section by Mr. R. Bradshaw of the University of Bristol and by several of our post-graduate students. The authors are grateful for their contributions to the present paper, detailed acknowledgement of which is made in the text.

For ease of publication the cross-section has been divided into three parts (Fig. 1) viz.

(1) Bodø to Fauske - the coastal region (cf. Rutland & Nicholson 1965).

(2) Fauske to Hellarmo - the critical intermediate region.

(3) Hellarmo to Swedish Frontier - the Sulitjelma region (cf. Kautsky 1953).

A fourth chapter will present a discussion of the cross-section as a whole.

PART I:
Bodø to Fauske

Introduction

This first part contains the description of the region between Bodø and Fauske, in elaboration of the brief outline already published (Rutland & Nicholson, 1965). This part of the section itself divides naturally into three units corresponding to two major synformal structures flanking a major basement antiform. The rock groups of the two synforms are not identical and the three units are described separately in the following account. Brief lithological descriptions are given with a view to subsequent comparison with major rock groups further east in the section.

The Steigtind Synform

The Bodø Schist Group occupies the Steigtind synform between Bodø and Hopen. It consists dominantly of quartzo-feldspathic schists grading with increase of calcite into impure marbles. The dominant mafic mineral is a bronzy biotite which is always sufficient to give a schistose appearance, but is never abundant. The calcareous element together with the more evenly distributed biotite distinguishes the group from the sparagmitic rocks of the Vågan Group, to be described later. The schists at Bodø itself are relatively poor in calcite but types rich in calcite are dominant, for example, in the ridge through Svendalsfjell (Fig. 2).

The fresh schist has a distinctive pale bluish-grey colour. Bedding is usually indistinct, especially since prominent secondary schistosities are developed. Garnet is rare but sometimes emphasises the faint bedding, and individual garnets can then reach 5 mms. in diameter. In the highly tectonized zone beneath the gneisses of Hjartøy, staurolite is present in an oligoclase-quartz schist with sparse but well orientated hornblende and biotite. The bedding is also emphasised by thin pale-green calc-silicate bands and occasionally by quartzo-feldspathic bands. Both these types are more competent than the micaceous schists and have been folded and sometimes disrupted during the deformation.

The schist is commonly characterized by irregular quartzo-feldspathic rods and stringers which usually contain some calcite. The largest pods exceed a metre in length and ½ metre in diameter. The direction of elongation is roughly parallel to the mineral lineation and fold axes in the schist.

The schists are cut by late quartz and pegmatite veins. The pegmatites are most common close to granitic gneisses of Hjartøy, and the basement gneisses of Valvik. They are clearly discordant to and later than the fold structures. Along the ridge from Steigtind through Svendalsfjell they strike along the ridge with the general strike of bedding and schistosity but dip at about 30° to the south-east against the sheet dip. Elsewhere, on the shore of Saltfjord, the pegmatites are nearly vertical and strike NNW.

East of Vikan and extending to the Hopen Slide a different lithology is present. This is a unit of green schist rich in mica, amphibole and chlorite, and relatively poor in quartz, feldspar and calcite. The boundary of these schists has been mapped in the wooded area immediately north of Vikan by Mr A. C. Hills but the unit has not been recognized in the appropriate position in the structural succession south of Valvik. Thin marble bands in more normal Bodø schists characterize the latter locality.

Primary sedimentary structures are rare. Southward younging graded bedding has been observed near Støver, however, and shows that the local folds face upwards and that the succession is normal.

The Bodø schists extend northwards towards Mistfjord and they reappear further north along the same synformal axis around Kjerringøy. Similar rocks are also found about 20 kms. south-west on S. Arnøy and about 20 kms. north-west on Sørvær. Structural considerations suggest that both these occurrences may be direct continuations of the Bodø Schist Group beneath the sea. Towards the east and south-east no rock groups can be correlated precisely with the Bodø schists on lithological grounds, and the structural relations are complex (Rutland and Nicholson, 1965, Pl. 12).

Major Structure[1])

The major structure of the Bodø Schist Group is not immediately evident from examination of the complex minor structures; and marker beds which would reveal the larger structures are absent. The broad structure of the

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1) The terms 'major structures' and 'minor structures' which are old established, clear and well understood are here preferred to the recently introduced macroscopic and mesoscopic (e.g. Weiss and Turner 1963, pp. 15-16).

Group is therefore best seen from the relations to adjacent rock groups. On the east the group is separated from the Saura Marble Group by the Hopen Slide. The slide dips steeply west like the rocks on both sides. It is discordant in detail and cuts obliquely across the strike of the marbles so that they are progressively elimated northwards, and only a thin marble then separates the Bodø schists from the Vågen group and the underlying gneisses. A broad shallow synform in these gneisses is clearly seen on the north shore of Mistfjord, and it is evident that the south-easterly dipping gneisses north of Valvik correspond with the westward dipping gneisses of the Heggmovatn massif. The sparagmitic rocks of the Vågen Group are absent near Valvik, though a thin development is present in the west limb of the synform north of Mistfjord. In the Bodø schists themselves this broad synform is well seen in the north face of Steigtind and it is therefore called the Steigtind synform. The axial trace of the synform runs south-westerly from Steigtind through Svendalsfjell towards Bodø.

The basement gneisses at Valvik have a strike only slightly south of west. The granitic gneisses of Landegode lie along this strike and probably represent another major anticline of the basement, similar to the Heggmovatn massif.

Granitic gneisses also occur on Hjartøy north-west of Bodø, where they overlie the Bodø schists on a north-westerly dip. These might also be regarded as basement gneisses, but if so it would be necessary for the schists to become overturned between Valvik and Bodø. A small antiformal fold fold with south easterly vergence has an overturned south-east limb near Gjeitvåg, but in general the dip of both schistosity and bedding is gentle throughout this tract. Thus it is evident that the Hjartøy gneisses lie on top of the Bodø schists in the core of the Steigtind synform. The gneisses must therefore have been emplaced during or before the formation of the principal schistosity and they are therefore regarded as a small klippen of the Beiarn nappe which has its main extension south of Saltfjord (Rutland & Nicholson 1965, p. 99).

The Hopen Slide strikes nearly north-south where it runs into Saltfjord, but it does not cross the fjord and the Bodø schists do not appear on the south side. The strike of the Saura marbles turns W.S.W. through Straumøy along an anticlinal structure extending from the Heggmovatn massif (Rutland & Nicholson 1965, p. 93), and the Hopen Slide must therefore also run W.S.W. along Saltfjord. The structure shows analogies with that at the southern end of the Sokumvatn Synform further south (Rutland 1959).

Thus the Bodø Schists lie in a broad synformal depression. Both the northern and southern limits are largely beneath the sea, but both must trend only slightly south of west. The western limit of the Group is unknown, though similar schists definitely occur on S. Arnøy and on Sørvær. The eastern limit of the Group has a north-south trend marked by the Hopen Slide. The sheet dip[1]) within the Bodø Schist group conforms with this broad structure when it can be determined and the minor structures provide evidence of the deformation history.

Minor Structures

The Bodø Schist Group has suffered small-scale folding during several periods of deformation. Secondary structures of the later deformation episodes are often the most prominent planar structures. Most of the ground is heavily wooded, so that good natural exposures of these structures are found only round the coast and on the higher hills. These are supplemented by excellent exposures in cuttings along the main coastal road and railway which run east from Bodø to Fauske. Unfortunately, these routes run nearly parallel to the general strike and to the trend of the linear structures so that extensive profiles of the structures are rare.

In the extreme east against the Hopen Slide the sheet dip is fairly steep to the west but elsewhere it is gentle. In the road section north of Bodøgård, for example, the bedding shows open folding of a few metres' amplitude on very gently plunging E.N.E. axes. The folds have a southerly vergence. They are accompanied by a schistosity which dips very steeply northwards and the southern limbs of the anticlines have dips of about 60°. But these limbs are short compared with the gently dipping northern limbs, so that the enveloping surface of the folds dips only gently southwards.

The folding on the peninsulas south-west of Bodø is much more complex and the folds are tightly appressed, with an axial plane schistosity which dips very steeply to the south. The enveloping surfaces again have very gentle dips however. The intense plication may be partly due to the more pronounced lithological banding in the locality, but also suggests that this locality is in the axial zone of a major structure.

A flat sheet dip is also apparent in the high ground running south-westwards from Steigtind towards Bodø, but on Svendalsfjell, for example, minor folds with a south-easterly vergence are accompanied by a flat

1) The term 'sheet dip' refers to the dip of the enveloping surface of a folded layer.

schistosity, nearly parallel to the flat long limbs and cutting across the steep short limbs.

In other localities, as at Støver and near Jensvold, the bedding dips steeply either north or south and minor folds viewed down the W.S.W. plunge have a dextral sense of rotation. Two secondary schistosities are commonly present, and both are normally lamination schistosities[1]), oblique to the bedding. Neither schistosity, however, seems to be strictly an axial plane schistosity to the minor folds, though one usually approximates to this, and the intersection of the two schistosities is only roughly parallel to the minor fold axes. The intersections of the two schistosities on the bedding may have widely differing pitch. The attitude of the two schistosities is not constant, neither is the angle between them, but the bedding attitude does appear to exercise some control since the bedding is close to the bisectrix of the obtuse angle between the schistosities. Thus when the beds dips steeply south, one schistosity is about horizontal while one dips about 45° to the north: when the beds dip steeply north one schistosity dips gently north while one dips steeply south.

Elsewhere, as in the railway cutting west of Vikan, two strain slip cleavages are present and it is inferred that the lamination schistosities are closely related to strain slip cleavage. The two sets, both of lamination schistosity and strain slip cleavage, are probably conjugate shear directions which have developed at a late stage in the deformation history.

In any event, the paired schistosities seem to occur in association with steep bedding, which is interpreted as the steep limb of overturned folds of southerly vergence of the same style as the smaller folds, described for example from near Bodøgård. Where the sheet dip is gentle only one schistosity and that nearly vertical is commonly developed. Presumably the bedding has acted as the conjugate shear plane in this case but could not do so where it had a generally steep attitude. This interpretation implies that the general form of the folds was already established before the secondary schistosities developed but suggests that some bedding plane slip was still possible in the gentle limbs. It seems unlikely, however, that the formation of the secondary schistosities was accompanied by large strains or that the planes have suffered large bodily rotations since

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[1]) A lamination schistosity is here defined as one which shows a segregation of the micaceous minerals into laminae parallel to the schistosity (the plane of preferred orientation). The laminae are normally a few millimetres apart and less than a millimetre thick, but larger scale examples have also been observed.

their formation. More detailed work is undoubtedly required to test the validity of this analysis.

The area of Bodø schists is one of fairly uniform south-westerly plunge. However, on the peninsulas south-west of Bodø the plunge is reversed and steep plunges to the north-east occur. Extrapolation of the structure towards the off-shore islands is therefore difficult. On the island of S. Arnøy, folds of rather similar style occur but they plunge south-east and have a north-easterly vergence. The upward (presumably inverted) succession from the schists there into the granitic gneisses of Fugløy is similar to the downward (presumably normal) succession from the Bodø schists into the granitic gneisses of the Heggmovatn massif (Rutland and Nicholson, 1965, Pl. 12).

The dominant fold structures so far described belong to the second of three episodes of minor folding. In several localities they are superposed on nearly isoclinal folds of an earlier generation. Examples are well displayed in the railway cuttings near Jensvold and on the peninsulas south-west of Bodø. In the latter locality the later folds have appreciable plunge to the north-east or east-north-east so that the early isoclines are displayed on nearly horizontal surfaces. They have axial traces trending nearly north-south, and plunge more nearly easterly than the later folds. No large folds of this age have been recognised in the Bodø schists.

Later structures are most notable in a zone of great structural complication west of the Hopen Slide. Here the bedding and main penetrative schistosity are roughly parallel and dip west-north-west. Tight isoclinal folds plunge down the dip and show a lamination schistosity along their axial planes. Later folds are related to two sets of strain slip cleavage with cleavage planes 0.5 cm. or more apart. One set of folds has moderate westerly plunges. Near to the Hopen Slide, strain slip cleavage with east-west strike and gentle southerly dip produces gentle southerly plunging intersections on the steep bedding related to open folding of the latter. Quite tight folds of the main schistosity also occur and small discordant thrusts add further complications.

It is evident that this zone has a long deformation history. The main sliding, however, probably occurred at an early stage in this history. The late strain slip cleavage was clearly imposed after the main sliding and after the zone had acquired its present northerly strike and relatively steep westerly dip. This latter feature is apparently due to a third deformation episode later than the main folding on E.N.E.-W.S.W. axes. The major Steigtind Synform is therefore composed of two elements: the dominant (F_2), E.N.E.-W.S.W. folding which is most evident in the gentle western limb, and the localised (F_3) north-south folding which controls the strike of the steep eastern limb. The structure as a whole, therefore, has much in common with the Sokumvatn synform (Rutland, 1959), some 40 kms. to S.S.W. The possible relations between these structures are discussed by Rutland & Nicholson (1965).

The Heggmovatn Antiform

Lithological units

The western limb of the Heggmovatn antiform (fig. 3) shows a broadly simple succession of four main rock groups (see also Rutland & Nicholson 1965), which probably represents the original stratigraphic succession.

4. Saura Marble Group
3. Upper Vågen Schist Group
2. Lower Vågen 'Sparagmite' Group
1. Heggmovatn Gneiss Group

1. *The Heggmovatn Gneisses.* Examination of the Heggmovatn gneisses has been limited to a number of peripheral localities. From these occurences the status of the gneisses as a separate unit underlying the sparagmitic meta-sediments of the Vågen Group is readily demonstrated. This structural relationship is especially well seen in the sections on the north shores of Sørfolda and of Mistfjord. It is therefore confidently inferred that the gneisses of this massif represent Caledonised basement gneisses like those of the Glomfjord area to the south (Rutland et al 1960, Rutland & Nicholson 1965). However, the gneisses are more variable in composition than to the south and structural relationships are locally obscured by Caledonian granitic veining. Such is the case in the area close to the contact with the Vågen Group southwest of Heggmovatn. The gneisses there are generally coarse grained garnetiferous quartzofeldspathic rocks with a prominent schistosity. The mica is often segregated into discrete laminae, and the rocks generally appear to be the product of granitisation of pelitic or semi-pelitic sediments. These more pelitic rocks are interlayered with sparagmitic rocks which have retained a similar character to those of the overlying Vågen Group. Irregular, discrete and diffuse granitic veins are numerous.

Some of these marginal gneisses may well not belong to the Precambrian basement therefore, but represent younger meta-sediments of the Vågen Group granitised during the Caledonian[1]) orogeny (cf. Barth 1938).

2. *Lower Vågen Group.* This group consists of typical sparagmitic meta-sediments like those found elsewhere in this part of Nordland, and better known from numerous studies in the Oppdal region. The more massive quartzofeldspathic layers are fairly free of biotite which occurs principally in thin laminae. The schistosity is sensibly parallel to the bedding, but locally it can be seen to be axial planar to isoclinal folds.

3. *Upper Vågen Group.* This group displays rapid alternations of a wide variety of lithologies corresponding to original sediments of shelf-facies. They form a natural transition to the overlying Saura marbles and some marble bands are already present. The more calcareous schists have a greenish tinge imparted by epidote and diopside, and these alternate with more pelitic schists of slightly purplish colouration. Some types are closely similar to typical lithologies of the Bodø schists which, however, are more uniform in general.

4. *Saura Marbles.* The Saura marbles consist of calcite marbles, often coarse-grained and saccharoidal, characterized by numerous thin laminae of micaceous and quartzofeldspathic minerals. A few thicker bands of schist occur and there bands of pure quartzite several metres thick close to the base.

The four groups show broad conformity of sheet dip and there is no evidence of discordant slides between them. There is intense folding within each group which does not in general affect the boundaries between them. The boundaries must, therefore, have functioned as slides. There is no reason to believe, however, that the slides are disjunctive and it therefore appears that the structural succession corresponds to the original stratigraphic succession.

Structure

The Lower Vågen Group is the only group which has been mapped continuously round the Heggmovatn antiform. The outer limit of the group is clearly døfined in both limbs, and even where it passes under the fjord around the closure of the structure its position is quite closely controlled. The inner boundary of the group has been mapped only locally. How-

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[1]) This term is here used in the broadest sense to cover all deformation, from Eo-Cambrian to Devonian, of the rocks of the Caledonian geosyncline.

ever, its position is known in the western limb of the structure across Vatnevatn and in the eastern limb of the structure across Sørskarvatn (some kilometres north of the area shown on the map, fig. 3). In the western limb, the strike is about N-S and in the eastern limb about N.N.W.-S.S.E. The dip in both limbs is moderate to steep westerly, and the outcrop width of the Lower Vågen Group is about 2½ kms in the east limb and 1½ kms in the west. This difference may be a consequence of deformation or it may reflect an original difference in thickness.

The maximum outcrop width around the fold closure S.S.E. of Kistrandfjellet is some 6 or 7 km., but this is not essentially due to thickening of the group. The sheet dip is also S.S.E. in the same general direction as the slope. This sheet dip corresponds to the enveloping sufaces of numerous asymmetric minor folds on axial planes which dip N.W. Both limbs of these folds also commonly dip into the N.W. quadrant. The folds plunge west-south-westerly and similar folds in the western limb of the structure plunge down the sheet dip.

The numerous minor folds seen in the section from Vågen to Storøy are therefore believed to lie in the hinge zone of a major reclined fold plunging to W.S.W. The approximate limits of the strong minor folding are marked on the map and may be taken to separate the hinge zone of the major structure from the limbs. The axial trace of a major structure can be recognized on the col between Sagelven and Heggmovatn. Southwest of the col, the sheet dip is to the south, while to the north-west of the col it is north-westerly. On the col itself granitized gneisses appear beneath the schist.

Only a limited amount of structural data has been collected in the Heggmovatn antiform, but it provides fairly consistent and useful information. Measurements of linear structures (fold axes, lineation and bedding schistosity intersections) show a considerable scatter from W.N.W. to S.W. Bedding poles combine to produce a rough girdle about a W.S.W. axis with moderate plunge, agreeing with the interpretation of the major structure given above. The bedding observations have also been used to obtain approximate maxima in several sub-areas and give the following results:

Sub-area	Plunge	Tlend
Vågen to Storøy (hinge area)	40°	255°
Kistrand section (E. limb)	25°	225°
Alvnes to Venset (E. limb)	50°	285°

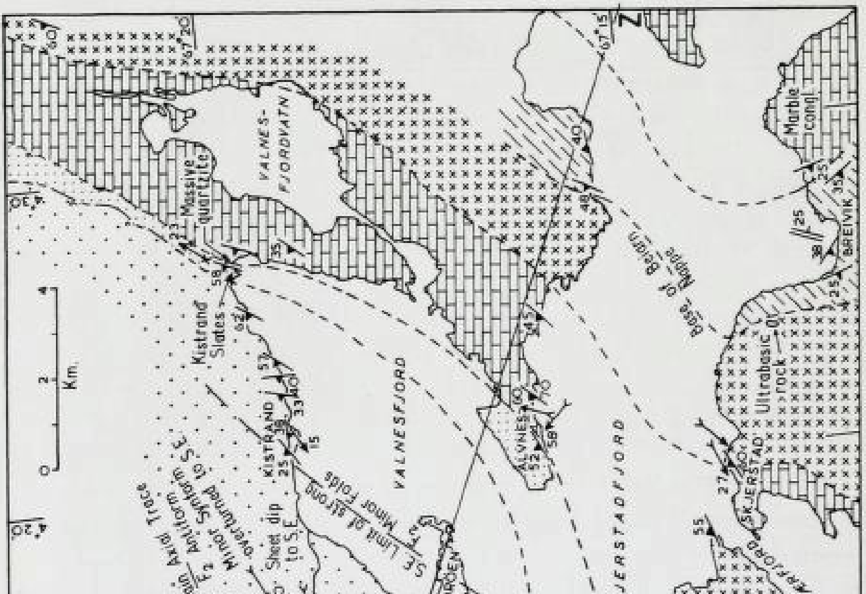

Fig. 3. Structural sketch-map of the Heggmovatn Antiform.

These three maxima fall very close to a single plane, striking 20°E. of N. and dipping about 50° towards W.N.W. This might represent the attitude of the axial plane of the major structure, since variable plunges in a single axial plane are known elsewhere in this part of Nordland. In any case, minor folds with axial planes of about this attitude are common. The

Bordstolfjell area which lies to the N.N.W. of the Kistrand section along the strike has dominant minor folds plunging about 50° at 215° which is also close to this plane.

When the complete section from Bodø to Venset is considered, however, another type of variation is evident. The early F_1 and F_2 folds maintain a generally W.-W.S.W. plunge right across the region, but the plunge varies from 0° to about 60°. This variation is supposed to be due to the latest phase of deformation on N-S axes. Late strain slip cleavage commonly produces roughly N-S intersection on bedding and schistosity especially in the zone of steeper sheet dip and N-S strike between Hopen and Vågen[1]). It appears, therefore, that an open N-S folding has been superimposed on the earlier W.S.W.-E.N.E. folding, and is responsible for their reclined nature of the Heggmovatn antiform.

The Valnesfjord Synform in the Beiarn Nappe

The structural succession east of the Lower Vågen Group at Kistrand appears quite simple and the dip is generally westerly. Thus a repetition of the rock units mapped on the west side of the Heggmovatn antiform above the Lower Vågen Group may be anticipated. This expectation is realized on Alvnes (fig. 3) where a group of schists (fine bluish schists and impure marbles) and the adjacent marble group can readily be correlated with the Upper Vågen Group and Saura Marbles. Attempts to extend this correlation reveal complications however.

The schists on Alvnes are not found in the expected position east of the sparagmitic Lower Vågen Group near Kistrand. Instead there is a very thin succession of garnet mica schist in which there is a strong down dip lineation in a schistosity which post-dates garnet growth. This structure is attributed to intense F_2 deformation which has attenuated the schists in this zone. The schists in fact have lithological affinities with the sparagmitic rocks of the Lower Vågen Group although they are more micaceous and quarried as roofing slates. It appears therefore that the Upper Vågen Group has been virtually eliminated from this zone by sliding.

Both on Alvnes and at Kistrand a prominant band of pure quartzite occurs within the marbles adjacent or close to the schists and this supports the stratigraphic correlation with the Saura marbles since similar quartzites occur adjacent to the Upper Vågen Group on Tvertland (fig. 3). The

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[1]) A detailed study of the structures in this region has been made by Mr A. C. Hills.

rocks beyond the eastern margin of the Valnesfjord marbles are not, however, comparable to the Bodø Schist Group which lies west of the Saura marbles. Instead a group of biotite-microcline gneisses, the Venset Group, appears. The contact between the Valnesfjord marbles and the Venset Group can be recognized again south of Skjerstadfjord near Skjerstad, so that it is evident that the Valnesfjord marbles are continuous with the Sokumfjell Marble Group (fig. 3). South of Skjerstadfjord the Saura and Sokumfjell Marble Groups are separated by the Palbrakken Group of schists and gneisses, which was regarded by Rutland & Nicholson (1965) as structurally equivalent to the Venset Group. These schist and gneiss groups were shown to lie at the base of the F_1 Beiarn nappe which is now preserved in later synformal structures. Thus the Sokumfjell marbles south of Skjerstadfjord lie in a synformal structure which must also be present north of the fjord and which must contain the Valnesfjord marbles. The absence of the Palbrakken Group north of the fjord however locally removes the evidence of structural separation of the Valnesfjord marbles within the Beiarn nappe and the Saura marbles below the nappe. There is therefore a false appearance of structural and stratigraphic simplicity.

More direct evidence of the structural complexity in this zone is found when the rock units are followed northwards (fig. 4). Near Sørfjord the sparagmitic rocks are folded in the broad F_2 Korsviktind Synform and they are followed eastwards by a group of muscovite schists and then by a marble band marking the Korsvik Slide. Eastwards again a further schist group bearing lithological similarities to the Upper Vågen Group is folded in the major Bordstolfjell Synform. Thus two major F_2 synformal structures are separated by the Korsvik Slide in this region (cf. Rutland & Nicholson, 1965, p. 89) while further south the schists at Kistrand appear to lie in simple succession between the Lower Vågen sparagmites and the Valnesfjord marbles.

The Valnesfjord marbles on the other hand are attenuated rapidly north of Åsvikvatn. Exposure is poor and no direct evidence has been found of a fold closure in the marbles. In fact the Valnesfjord marbles appear to continue northwards towards the coast as a thin marble band along Røssvikelv. The structure shows a close analogy with the Navervatn Fold in the Glomfjord Region (Nicholson & Walton, 1963) and for this reason the present writers have inferred that the Valnesfjord marble outcrop does contain the axial trace of a major synformal fold (Rutland & Nicholson, 1965).

Schists immediately east of the Valnesfjord marbles near Åsvikvatn (fig. 4) bear some lithological similarity to those of the Bordstolfjell synform but they are followed eastwards by pelitic gneisses of the Venset Group.

The writers therefore conclude that the Valnesfjord marbles and Venset gneiss are part of the Beiarn nappe and lie in a synformal structure from which the Palbrakken Group has been eliminated in the western limb. This interpretation is heavily dependent on the work south of Skjerstadfjord (Rutland & Nicholson, 1965) and more detailed studies to test this interpretation are highly desirable. It should be mentioned however that attenuation of the western limbs of major late synforms has been found to be a characteristic feature in Nordland (Rutland & Nicholson, 1965, p. 97). It is of the greatest importance in the Tverstifjell synform, to be described in Part II of this account.

The succession and structure east of the Venset Gneiss (below the Beiarn Nappe) is examined in Part II of this paper in relation to the Fauske Marble. Here it need only be pointed out that the westerly dip is maintained so that the Holstad schists and Fauske marbles successively underlie the Venset Gneisses. The Fauske marbles are therefore clearly at a lower structural level than the Valnesfjord marbles and may correspond with the Saura Marbles (Rutland & Nicholson, 1965, p. 94). The Holstad schists bear some lithological resemblance to rocks of the Vågen Group and, if the correlation were made, it would suggest that the succession is inverted. In any case there is no equivalent of the Bodø schists above the Fauske marbles.

Conclusions

The present paper provides a more comprehensive discussion of the area between Bodø and Fauske than previously presented (Rutland & Nicholson, 1965).

The intimate structural relation between the basement gneisses and sparagmitic rocks of the Lower Vågen Group is similar to that in the Glomfjord region and it can be inferred that the sparagmitic rocks are autochthonous, although the basement and the original unconformity above it have been highly deformed. The succeeding rock units on the west of the Heggmovatn Antiform, in the Steigtind Synform, are also highly deformed but in the absence of evidence to the contrary may be taken to represent the original stratigraphic succession. The succession in the Valnesfjord Synform east of the Heggmovatn Antiform is different however, and is

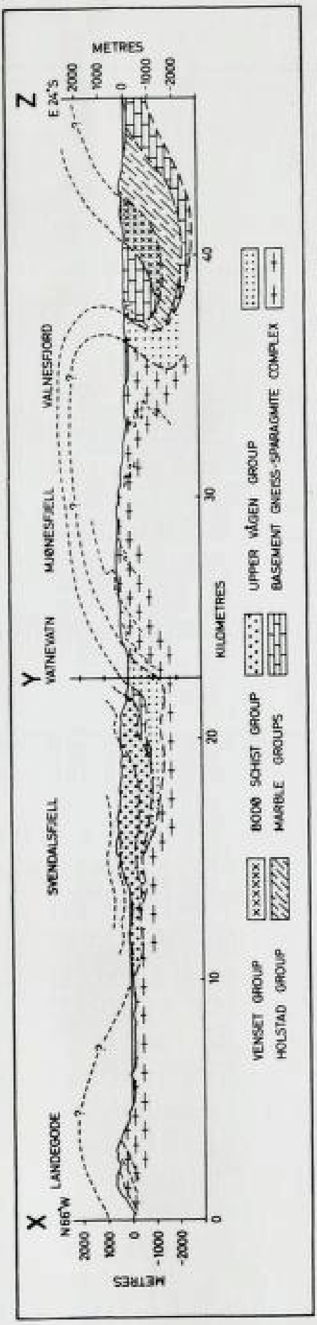

Fig. 5. Sketch section along the line shown on figs. 2 and 3. Note that on Mjønesfjell the antiformal basement core is not distinguished from its immediate cover of sparagmitic metasediments.

attributed to the F_1 Beiarn nappe. The Fauske marbles beneath this nappe to the east are probably equivalent to the Saura marbles but they may be inverted, and the Bodø Schist Group is not found there.

F_1 minor structures have been recognized locally but purely structural evidence of major F_1 structures or inversions has not been found. The three major structures described are essentially F_2 with some F_3 modification. Penetrative post-metamorphic deformation (late F_2 or F_3) appears to be localized in the Hopen and Kistrand slide zones, both east and west of the Heggmovatn massif. A generalized section across the area is given in fig. 5.

PART II:

Fauske to Hellarmo

Introduction

In Part I of this account we described the geology of that part of our section which lies between Fauske and the western coast in amplification of the general account of the tectonics of the coastal regions given by Ruland and Nicholson (1965). It was shown there that the coastal regions display complex culminations of basement and conjunctive nappes of enveloping metasediments separated by depressions containing outliers of a disjunctive exotic nappe complex (the Beiarn Nappe Complex).

Here we describe a region generally east of Fauske which is of critical importance in that it offers evidence of the tectonic relationship between the coastal regions and the Norwegian-Swedish frontier area which has many very different features of lithology and structure from more western ones (principal descriptions by Sjögren, 1896; Holmsen, 1917; 1918; T. Vogt, 1927; Kautsky, 1953). The Sulitjelma region has been most recently interpreted as a pile of exotic thrust sheets (Kautsky, 1953) derived from far to the west and the uppermost nappe has been correlated with the Rödingsfjäll Nappe south of Nasafjell (Kulling, 1955) and this in turn has been correlated with the Beiarn Nappe (Rutland & Nicholson, 1965). In the coastal regions the main part of the Seve-Køli nappe complex of the eastern Caledonides was not identified between the Beiarn Nappe and the meta-sedimentary cover of the basement (Rutland and Nicholson, 1965, p. 102 and p. 107) but the present area allows the western extension of the Seve-Køli rocks towards to coastal region to be examined.

The first account of this relationship was made by J. H. L. Vogt, who proposed that the generally gently dipping rocks of Sulitjelma were structurally a b o v e the more steeply dipping western ones of the tract east of Fauske (J. H. L. Vogt, 1890, plate II) and this explanation seems to have been accepted by all succeeding workers in the region (Holmqvist, 1900; Holmsen, 1918; T. Vogt, 1927; Kautsky, 1947 and 1953) as well as in the tectonic synthesis of Nordland by Strand (1960). This is easily understood if one makes a traverse along Sjønstådalen where a critical major antiformal hinge, mentioned below, is not readily detected.

During field work early in 1965 it became clear from napping around Skoffedalstind (fig. 9) that the Sulitjelma rocks underlie the Fauske Marble Group (which itself underlies the Beiarn Nappe of the coastal regions) and the following account is largely devoted to a description of this relationship in terms of the principal deformation episodes which have been recognized. Dybdal (unpublished thesis, N.T.H., 1951) had earlier described part of this antiform in a region on the south edge of fig. 6. However, he does not appear to have realized either its regional extent or its structural significance. He named the fold the Vatnfjell anticline (here it is known as the Vatnfjell antiform).

Since it is not possible to discuss the regional tectonic implications until the description of the whole section between Bodø and Sulitjelma has been completed such discussion is reserved for part IV of this account.

Lithological units

In a region of complex structure the analysis of the stratigraphy and of structure itself depend heavily upon one another. Therefore the detailed structural description is preceeded by an examination of the major lithological units and some of the major structures controlling their distribution.

As in the coastal regions the major structures controlling the general outcrop pattern were produced in the later deformation episodes. In the present areas, however, the major structures are more open and upright than in the coastal regions, giving a deceptively simple appearance to the general structure. The earliest deformation produced the major deformation fabric of the rocks but its effect on general tectonic relationships is at present largely conjectural.

Figs. 6 and 7 show the obvious large structures in the tract between Fauske and Hellarmo. These are the two antiforms of Rishaugfjell and Vatnfjell (the northern extension of Dybdal's structure) and the Tverstifjell synform which lies between them. The Rishaugfjell antiform exposes the structurally lowest lithological unit of the region formed of the granite gneisses which occur so extensively in the Tysfjord culmination to the north and in the western coastal massifs, while the Tverstifjell synform carries the Fauske Marble Group in its core above the Sulitjelma structural succession or its very reduced western equivalents. This position above the Sulitjelma rocks can be mapped directly in areas shown in the north-east corner (up-plunge) of fig 6. The same upper position for the Fauske Marble Group can be inferred from Steenken's map of upper Saltdal (Steenken, 1957) and work by the writers' has confirmed this inference. Thus there is no doubt of the broad regional relation.

Structural successions above the granite gneisses of the Rishaugfjell antiform and the supposed concealed granite of the core of the Vatnfjell antiform and into the Tverstifjell synform are listed below.

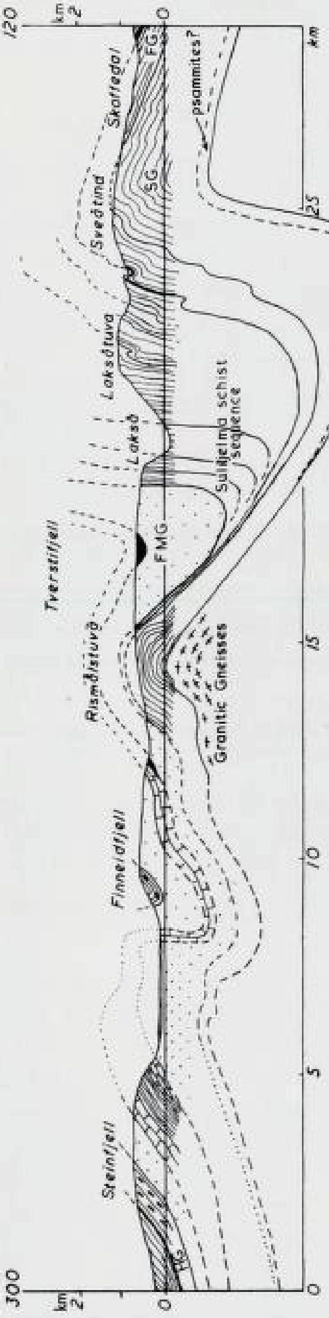

Fig. 7. Cross-section along line shown on fig. 6.
F.M.G. — Fauske Marble Group
F.G. — Furulund Group
S.G. — Sjønstå Group.

(i) Southern end of the Rishaugfjell antiform.

4. Fauske Marble Group.
3. Very thin succession of schists; at south end of antiform almost completely absent
   b) Hornblende pelite and marble-very thin to south of end of antiform.
   a) Semi-pelitic schists; very characteristic of the Sjønstå Group; generally directly next to granite gneisses.
2. Some few psammites.
1. Granite gneiss.

(ii) Core of the Vatnfjell antiform.

4. Fauske Marble Group.
3. f) Mica schists with marble and amphibolites.
   e) Thick muscovite schist group.
   d) Mixed group including marbles.
   c) Mixed group including well-bedded calc-psammite.
   b) Furulund Group.
   a) Sjønstå Group.
2. (possible psammites).
1. (probably granite gneiss).

Lithological units 1 and 2

a) Introduction.

Granite gneisses form the basal unit of the region appearing wherever erosion has cut deeply enough through the overlying meta-sediments whether they are of the Rishaugfjell or the Sulitjelma successions (of which unit 3 of the Vatnfjell antiform succession is an example). As noted above (p. 25) they are widespread in the Tysfjord culmination and also widely developed in the culmination of Nasafjell. In addition we have discovered a small inlier of the basal granite gneiss in Krågdal (fig. 13) more or less one third of the way from the gneiss of the Nasafjell massif in upper Saltdal and the line of section of fig. 6. As shown by fig. 13 this granite gneiss inlier occurs in the southern prolongation of the Vatnfjell antiform which runs between the Tysfjord and Nasafjell culminations and which reveals a marginal succession to the granite gneiss in Krågdal identical with that next to the granite gneisses of Nasafjell in Junkerdal. There seems very little doubt, therefore, that granite gneisses also occur in the concealed core of the Vatnfjell antiform in Sjønstådal on the line of our section although it seems unlikely that they are overlain by an immediate succession including marble as they are in Junkerdal or Krågdal as no marble is known in the marginal succession of the southern end of the Tysfjord culmination not far to the north nor in the nearby Rishaugfjell antiform although psammitic rocks of sparagmitian type are known at both places. [1 and 2])

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1) The sparagmitian character is regarded as an indication of stratigraphic level; such rocks were first discovered by us in marginal association with granite gneisses at Storglomvatn 100 km to the south-west, and are known to occur in the coastal granite gneiss massifs from Høgtuva to Heggmovatn (Rutland and Nicholson, 1965).

2) Work in 1967 by Mr. S. Knox of University College London has defined another occurrence of these basal rocks in the same inlier and Hr. N. Raith (Sulitjelma Gruber) has informed us that the marble is exposed north of Vatnfjell.

As fig. 6 indicates there is little psammite in the Rishaugfjell succession on the line of section although a smoothly continuous envelope of psammite is present at the north end of the antiform (fig. 10). The marble of the Krågdal inlier like that of Junkerdal is almost certainly to be correlated with the Pieske Marble of eastern Sulitjelma (Rekstad, 1913; F. Kautsky, 1949; G. Kautsky, 1953) but as demonstrated clearly by Steenken's map (1957) of upper Saltdal is not continuous with the Fauske Marble Group (Rekstad claimed (1930) that they were so continuous).

b) Rishaugfjell.

The granite gneisses at the southern end of the Rishaugfjell antiform for the most part lie directly against semi-pelitic schists without the intervention of any of the well-layered and distinctive psammites so characteristic of granite gneiss complexes to the west and south. The marginal series from the gneisses to the west on Rishaugfjell itself (and in the west limb of the antiform) is as follows;

5. Pale weathering coarsely muscovitic calcareous schist, well layered and pebbly, the base of the Fauske Marble Group.
4. Hornblendic schists well-banded (with an upper level of good white-weathering psammites); the Furulund Group. To the north towards and beyond Andkilvann there is an easily followed level of these hornblendic schists which joins to those of Lappfjell (see p. 43 and fig. 10).
3. Grey-weathering, massive, and rather gneissose schists with a characteristic black and white mottled appearance made up of quartz-rich and biotite-rich units (one-time fragmental material?). This lithology is very well developed at the same structural level to the north on the southern margin of the Tysfjord culmination and in the Krågdal inlier where it is developed in the lower levels of the Sjønstå Group. These rocks, therefore, can be correlated with the Sjønstå Group.
2. Thin series of micaceous schist with some quartzites.
1. Granite gneiss.

There may be some tectonic analogy between the Rishaugfjell granite-gneiss and those of Storglomvatn and Bjellåtind to the south-west for both the latter domes also have a metasedimentary cover much thinner than the regional development, and generally without sparagmite-like rocks (Rutland and Nicholson, 1965).

To the east of Rishaugfjell summit, over a small area, good layered sparagmitic psammites are found complexely interfolded with the granite gneisses below and the pelitic meta-sediments above. Here there are good examples of folded early folds otherwise rare in the region. This is the only place in which the meta-sediments and granite gneisses are folded together on a small scale. The presumed Sjønstå Group rocks on the Rishaugfjell antiform do not join with their supposed equivalents to the east but merely form a rim to the antiformal core of granite gneisses.

In upper Saltdal it is clear from Steenken's map (1957) and confirmed by the writer's work that several of the major rocks units of the east side of the valley continue as much reduced members of the meta-sedimentary envelope of the Nasafjell massif (fig. 13). Thus the dramatic attenuation of the Sulitjelma succession when traced westwards is a phenomenon of regional extent. Its structural significance is discussed below and in part IV of this account.

Lithological unit 3

In the Sjønstådal inlier (fig. 6 and 9) our Sjønstådal Group is well exposed although not to its structural base as in Krågdal. While the eastern part of this series of rocks corresponds to some of the Sjønstå Gneisses of T. Vogt (1927, 115) the western rocks of Vogt's group which contiuned west to Øvrevatn beyond our limits are now known to belong to higher rock units for Vogt did not recognize the repetition over the Vatnfjell antiform.

The commonest lithology in the Sjønstå Group of the Sjønstådal inlier is psammitic schist, rather massive and sometimes well-layered but too micaceous and too rich in epidote in general to resemble closely the sparagmitian psammites margining the granite gneisses. As exposed in the Ingeborgvann area (fig. 6) as the northern end om the Krågdal inlier the Sjønstå Group has an upper series of psammitic rocks against the Furulund Group and a more pelitic lower part which contains the distinctive black and white semi-pelite at its base (see p. 28). This pelitic core is not exposed in Sjønstådal. On the Tysfjord granite gneiss margin to the north, as described above, the distinctive black and white Sjønstå lithology is well developed and forms almost all of the sequence between the gneisses below and the Furulund Group above. There is no doubt, however, that like the Furulund the Sjønstå Group is much thinner there than in the Krågdal inlier.

Above and to the west of the Sjønstå Group in Sjønstådal lies our Furulund Group corresponding very closely with the Furulund schists as defined by Sjögren, (1895) but comprising only the lower part of the

Furulund unit of Vogt, 1927, Pl. XXXV. We (like Sjögren) use the name here for a very distinctive well-bedded rock which in the west and south is a garnetiferous and hornblendic calcareous semi-pelite with a thin but persistent amphibolite at its upper limit. As we note in pt. III finer subdivisions have been demonstrated by Sulitjelma Gruber but most of this work remains unpublished. The upper amphibolite is directly continuous to the east with the main Sulitjelma amphibolites.

The distinctive Furulund meta-sediments have been mapped well to the east where they contain mid-Ordovician fossils and the work of Sjögren (1896), T. Vogt (1927), and Kautsky (1953), has shown that they form a part of a development of similar schists at this same structural level which outcrops round the south and east sides of the Sulitjelma area from Norway to Sweden and back again to the Swedish-Norwegian border in the north-east of the region. From there they have been traced by one of the writers (RN) westwards back into Norway to where they join into the schist succession above the Rishaugfjell granite gneiss (fig. 10). This confirms the evidence of the Skoffedalsfjell region that the Furulund Group eventually underlies the more westerly Fauske Marble Group sequence.

Between the distinctive Furulund and Fauske Marble Groups on Skoffedalsfjell and Tverstifjell respectively (fig. 6) there is a 4½ km stretch of very steeply dipping schists marbles etc. which in this particular traverse are divisible into four distinct lithological groups. The structural succession above the Furulund Group differs from place to place over the Sulitjelma region and is varied in rock type and thickness and these variations make it unlikely that any one sequence will be an entirely satisfactory regional standard. In part this question concerns the problem of a regional structure explained by Kautsky (1953) as a pile of three nappes, the rocks described here belonging to this supposed nappe complex. These matters are discussed in parts III and IV. For this reason the four lithological groups noted above are not given names as such terminology would as yet have no general use.

With these reservations made we can proceed to describe the subdivisions of the rock between Skoffedalsfjell and Tverstifjell is being broadly that of a thick group of coarse semi-pelitic garnet mica schists on Laksåtuva, with immediately on either side more varied successions including marble and amphibolites, (this symmetry might be explained by a fold between the two but although the suggestion is tempting there is no direct evidence in its favour). A fourth unit, composed of rather gneissose and massive pelitic schists and well layered calc-semi-pelites lies directly above the Furulund amphibolites. Fig. 9 shows the relation between the marble bearing rocks between Skoffedalsfjell and Laksåtuva and shows the direct continuity between the rocks of the upper group and those above on the top of Skoffedalsfjell. Further forrelations eastward must await part III of this account.

Lithological unit 4

The Fauske Marble Group which lies at the top of the Rishaugfjell and Skoffedalsfjell structural successions is a very distinctive set of rocks and occupies a tract 15 km wide and 50 km to 60 km long stretching from north of Fauske itself to the north end of Nasafjell in upper Saltdal. The first comprehensive accounts of the group were by J. H. L. Vogt (1890 and 1897) from occurrences around Fauske; Mr. R. Bradshaw of the University of Bristol has almost completed a detailed study of the group near Fauske and we are indebted to him for some of the facts below and for all the information concerning the group in the north-west corner of the geological map, fig. 6.

Between Finneid and Laksâ (fig. 6) the Fauske marbles lie round the Rishaugfjell antiform and the Tverstifjell synform. To the south-west as revealed in exposures along the main road from Finneid (which runs on the east side of Skjerstadfjord) the overall structural arrangment is monoclinal (fig. 8). Not only do the major folds become less acute away from the granite gneiss core but the plunge lessens to become very gentle to the south west (see below p. 34). Very little conglomerate is present in the marbles south of Finneid while conglomerate is an extremely important com-

Fig. 8. Cross-section about along highway 6 south of Finneid.

ponent of the group west of Fauske and around the Rishaugfjell antiform and the Tvertifjell synform. A thin band of conglomerate does occur, however, at the western limit of the group near Tusviken on the road south of Finneid (figs. 6 and 8).

West of Fauske the conglomeratic marbles are overlain by conglomeratic calcareous semi-pelites included in our Holstad Group (pt. I, p. 19) and these rocks may be equivalent to the pelitic and sometimes conglomeratic rocks of the west side of Finneidfjell. As the section shows (fig. 7) these latter rocks are interpreted by us as they were by Rekstad (1917, fig. 5) as lying in a synform on top of the Marble Group.

On Tverstifjell the calcareous conglomeratic sequence consists of three major subdivisions suceeded by a fragmental hornblendic rock and then by a non-conglomeratic marble. (The fragmentary hornblendic rock is very like rocks well exposed by the new main road north of Fauske between Straumen and Helland west of and above the calcareous conglomerate). The upper and lower members of the Tverstifjell conglomerates have dominant marble fragments in a marble matrix while the middle member has dominant calc-psammite fragments in marble but all contain quartzite pebbles. The conglomeratic rocks are very well exposed on the shores of Øvrevatn.

On the west side of the Rishaugfjell antiform upper and lower quartzite and marble conglomeratic series are separated by a non-conglomeratic marble together with some amphibolites apparently continuous with those above the conglomeratic unit of Tverstifjell. The upper conglomerate as exposed on the long ridge of Finneidfjell east of Fauske is essentially a quartzite marble conglomerate. Thus there are major differences in pebble type and proportion but no suggestion that there is any major tectonic repetition of the succession in Finneidfjell and Tverstifjell. The variations may very well be local facies changes since the structurally equivalent succession south of Øvrevatn which runs through to the coast north and south of Setså on Saltdalsfjord is almost entirely devoid of conglomerate (see p. 34 below).

In the Fauske area, as described by J. H. L. Vogt (1897) (and as Mr. R. Bradshaw has mapped in much more detail) there are important conglomerates with very distinctive red or pink marble fragments and a thick dolomite not known to the east. Pink fragments do occur in some of the conglomerates of Tverstifjell as well as in rocks exposed on the road between Meby and Misvær in middle Saltdal and a dolomite is found, as Rekstad has described (1913, fig. 3), on Kvitberg, 8 km west of

Nordnes in upper Saltdal. Unfortunately none of the conglomerates, extremely deformed as they are, has provided any evidence of stratigraphic order.

Structural analysis

Introduction

There is some evidence in the Sulitjelma region to the east (pt. III; K. J. Henley, personal communication), that the penetrative rock fabric (schistosity and lineation) of the metasediments are structures developed during the two earliest deformation phases while later episodes for the most part merely produced reorientation of the old penetrative fabrics rather than the production of new ones. If this is so then is likely to be true also of the rocks with which we are concerned here. Thus, following Roberts and Treagus (1965, for Dalradian rocks) we may divide the rock structures into two types; primary when penetrative fabrics were developed, and secondary when the local reorientations took place. Of course, even the late episodes may locally produce new penetrative fabrics, as for example on Øines and in the Steinfjell region generally where folds bending elongated pebbles have a penetrative axial plane schistosity (personal communication, Mr. R. Bradshaw).

Late folds

The preceeding account of the major lithological groups and their distribution has included mention of the major structures controlling their outcrop. These major folds are secondary structures, as all Rishaugfjell antiform, Tverstifjell synform and Vatnfjell antiform, bend already schistose rocks whose earlier deformation is that which produced their penetrative fabric. Commonly only a little retrogressive metamorphism can be attributed to this late episode for both the schistose fabric and the porphyroblasts which frequently statically over-grow it are earlier than the folds. Occurrences of porphyroblasts with sigmoidal inclusion trails confluent with schistosity are known, however, from rocks to the south in Saltdal in the steep west limb of the Vatnfjell antiform. Thus the metamorphic history includes both static and synkinematic porphyroblast growth before the late folds formed as well as growth of the same age and retrogressive effects. The early synkinematic relation is well shown in the Furulund schists of Vogt (1927, pl. XXV). The discussion of whether there are significant differences of this type at different structural levels is left to part IV.

The small folds of schistosity which accompany the late major structures and which vary congruously in sense of overturn (vergence) over them (as is well shown in Sjønstådal as the axial trace of the Vatnfjell antiform is crossed) also bend the generally prolate ellipsoidal pebbles of the Fauske Marble Group conglomerates. The general trend of pebble elongation of the Fauske conglomerates in the Rishaugfjell antiform follows the trend of bedding round the fold; to the west on Finneidfjell and to the east on Tverstifjell elongate pebbles plunge moderately southwest while in the fold closure above Øvrevatn they lie with a more or less southeasterly plunge.

Bradshaw (personal communication) describes the general pebble elongation plunge in the conglomerates west of Fauske as gentle and either south-west or north-east and these rocks and their structures are very like those on Finneidfjell. At Klungset west of Fauske (fig. 6) bedding is clear in the quartzite marble conglomerates and its intersection with schistosity is parallel to the pebble elongation. Mr. R. Bradshaw has described this schistosity as developed in F_2 or later deformation. Generally, early-developed schistosity is parallel to bedding.

As noted above few examples of fold interference were found in the rocks of the region, essentially apparently because early minor scale folds are themselves rare. No sedimentary evidence of the order of any of the rock units is present.

The major structures and accompanying small folds, all bending schistosity, plunge either north-east or south-west (mostly the latter) with varying plunge. As a whole the plunge of these structures decreases from 35° to 40° south-west near the granite gneiss contact in the core of the Rishaugfjell antiform, to 10° or so where the Fauske Marble group is exposed on the main road south of Finneid. Occasionally the plunges are northerly, as for example in the layered and fragmental amphibolitic rocks at Sølvik (fig. 6).

Examination of the two primary surveys of this tract (Rekstad, 1917 fig. 5, and Holmsen, 1918 fig. 2) shows that Rekstad and Holmsen had to some degree recognized the late major structures although both believed that the Sulitjelma rocks overlay those to the west. However, Holmsen's accurate recording of fold style and sense of overturn (1918 fig. 2), allow the writers' interpretation to be placed on his results i.e. the Sulitjelma rocks underlie much of the western succession.

The style of the late folds is not uniform but varies from broad open structures like those of the Vatnfjell antiform region of fig 6 to strain-band or kink-zone types in the amphibolitic rocks on either side of Øvrevatn and near Sølvik and in the calcareous conglomerates of the core of the Tverstifjell synform. Sometimes in tightly crenulate pelites as on Finneidfjell metamorphic differentiation of quartz is developed along the late fold axial planes; generally no new axial plane structure is developed although there are exceptions as noted above.

Late fold axial planes in the Fauske Marble Group on the east side of the major Rishaugfjell closure and through the Tverstifjell synform dip steeply east, fitting the attitude of the major structures which have fairly steeply dipping axial planes defined by the alternate steep and gently dipping limbs. On the west side of the Rishaugfjell antiform, as may be well seen from the road east from Finneid along the north shore of Nedrevatn, axial planes still dip eastwards but rather more gently.

The late folds of the tract on either side of Fauske share the southwesterly plunge of those further east but have a general westerly axial plane dip. This difference from the rocks to the east is suggested by a diagram of Rekstad (1917, fig. 5).

The schist sequence between the Fauske Marble Group and the Furulund Group which is well exposed at the east end of Øvrevatn, is easily examined there from a boat. Rocks near the Fauske Marble on the northern shore and west of Laksâ have late minor folds whose style is very like folds of that group and in addition have the same attitude. To the east of Laksâ the strongly folded massive pelitic schists of the belt have folds of a less regular shape than those of the west but axial planes of late folds still dip steeply eastwards and have a vergence appropriate to their place on the west side of the Vatnfjell antiform. Here large folded granite sheets are quite common as they are at this level to the east on Skoffedalsfjell. They are rare to the west but found at this position in the steep limb of the Vatnfjell antiform from Øvrevatn to upper Saltdal.

Early deformation

The evidence of early deformation phase or phases lies in the small-scale fabric of the schists and in the elongate pebble fabric of the conglomerates. As described above (p. 34) conglomerates with elongate pebbles are bent on a broad scale around the major late folds and also by the minor folds accompanying them. On Finneidfjell a few minor folds were discovered which had the elongate pebbles parallel to their axes like

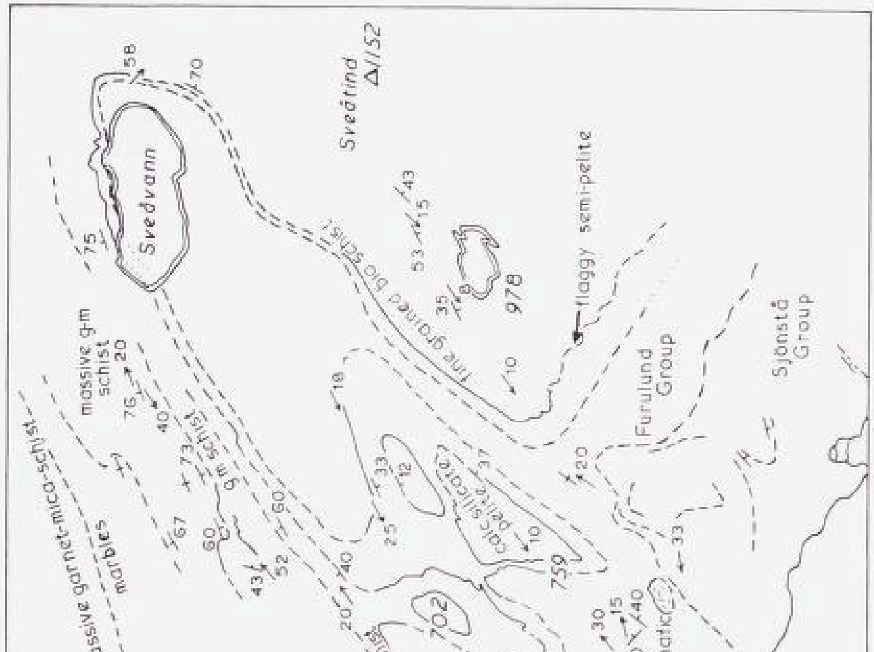

Fig. 9. Map of antiformal closure of the Furulund Group on west slopes of Skoffedalsfjell and Sveåtind (see fig. 6) north of Sjønstådal. Topographic data taken directly from aerial photograph overlay.

those in the bedded conglomerate at Klungset (p. ??). Mr. R. Bradshaw has reported that this is general west of Fauske (personal communication). Larger early folds are unknown in the thick schist succession east of Laksâ. However, even in the western coastal regions where folding is intense, early folds are not commonly seen except in the well-layered sparagmitic psammites (see for example Nicholson and Walton, 1963, plate I and p. 18). Thus there too the widespread evidence of early deformation is the small scale fabric detail of schistosity and lineation together with sctratigraphic notions essentially based upon the supposition that the psammites marginal to the granite gneisses are at the base of the gneiss-enveloping meta-sedimentary sequence. However, although there are such psammites in the Fauske-Hellarmo tract there is considerable doubt about the relation between the succession containing them and the Sulitjelma succession above, in which, even outside the area considered in detail here, there is very little evidence of stratigraphic order. The difficult matter of the nature of the early deformation will now be left until the description of the whole section has been completed. It should be mentioned however, that an important slide may occur above the Furulund Group (part III).

Thickness Changes

Even the most cursory examination of the section (fig. 7) makes it clear that the very great changes of thickness, between the granite gneisses at the bottom of the sequence and the Fauske Marbles at the top, take place round the Tverstifjell synform, that is round late fold structure. Our examination of the Sulitjelma rocks as they pass under the Tverstifjell synform is not yet complete but there seems to be some evidence that the Fauske marbles do not show such changes (certainly the group still is thick west of Fauske); equally their structures, early as well as late, do not seem to vary in type or relation from one limb of the Tverstifjell synform to the other. There is good evidence, however, that the Sulitjelma succession below them does vary and that lithologies which to the east form thick piles of rock are entirely missing when this junction region between Sulitjelma and western areas is reached (see pt. III and IV). Thus the thinning so obvious west of Laksâ is only part of a regional thinning which reaches a climax there. Since the late folds are especially situated on the thinning succession there may be a relation between the late folds and the regional thinning. Thus the late folding may be sited by the thinning which certainly is earlier than the late minor folds with steep axial planes. An analogous structure to the south west is the Sokumfjell synform (Rutland, 1959) while to the north the Håfjell synform of Foslie (1941) has a similar thickness difference between its limbs.

These spectacular thickness changes between Skoffedalsfjell and Tverstifjell seem to be closely analogous to those shown on Steenken's map of upper Saltdal (1957) where it is now clear to the writers (although not so described by Steenken) that the Sulitjelma sequence thins dramatically westwards to assume the appearance of a simple member of the structural succession of the meta-sedimentary cover of the Nasafjell massif. Parallel with the Sulitjelma strip there is a similar relatively narrow but laterally extensive strip (this time of calcareous schist with marble) which appears to represent the Fauske Marble Group for it as turns north into Saltdal it greatly widens in outcrop to become the main marble belt of Saltdal.

Mr. R. Bradshaw has suggested (personal communication) that some of the thickness changes in the Fauske Marble Group may be due to the presence of large-scale early and tight folds that are difficult to recognize. He has discovered such folds in the conglomerates of Steinfjell where they have axes about parallel to the common late ones (making distinction more difficult). We think this suggestion very reasonable although we do not have the evidence from other parts of the region to prove it correct there.

Clearly there is great westward thinning of major rock units so that a structural succession of steeply dipping rock sheets of extensive character in the west limb of the Vatnfjell antiform forms the 'root' of large and complicated eastern sequences. This character is an important element of the regional tectonic discussion of part IV of our description of the Bodø-Sulitjelma section and is closely connected with the problem of the stratigraphic relations between the Rishaugfjell succession described here and the Sulitjelma successions of pt III, and more broadly of the coastal rocks and those in the Norwegian-Swedish border region. It has an important bearing on the thrust nappe hypothesis for Sulitjelma proposed by Kautsky (1953).

PART III:

Hellarmo to the Swedish frontier

Introduction

The major structure of the eastern part of our Bodø-Sulitjelma section is the Sulitjelma tectonic depression formed of regionally gently dipping rocks in the east limb of the Vatnfjell Antiform (Dybdal, 1951, unpublished thesis N.T.H.). The depression lies between the culminations of the Tysfjord and Nasafjell basement granite-gneiss massifs (see part II, p. 27); further west the Beiarn nappe lies in a similar depression between the Heggmovatn and Glomfjord basement massifs (Rutland & Nicholson, 1965).

The Sulitjelma depression is subdivided by two east-west antiforms, (one along Langvann and the other through the southern end of Balvann) which are crossfolds with respect to the Vatnfjell antiform and which reflect the presence of two subsidiary culminations on the latter in Sjønstådal and Krågdal (fig. 14). These two antiforms isolate the synformal Baldoaivve outlier of the upper Sulitjelma succession from the two main lobes of that succession which lie next to the two granite-gneiss massifs to north and south. The southern or "Skaiti" lobe has been less studied than the northern Sulitjelma one which contains the well-known Sulitjelma gabbro (Vogt, 1927; Mason, 1967). In the following account we use the term Sulitjelma region to generally describe the ground north of Langvann and up to the latitude of Virijaure; Baldoiavve to describe the region south of Langvann and generally north of Balvann; and Skaiti to describe the southernmost development between Balvann and Junkerdal.

We have the advantage here of a considerable volume of earlier work on which to build. This work is broadly divisable into two sections: firstly that of Sjögren and his collaborators and Th. Vogt, on the Norwegian side of the frontier in the general area of the Sulitjelma copper mines; and of G. Kautsky and Kulling in Sweden. There are great differences in the structural interpretations of these two groups, differences which really amount to an almost complete absence of suggestions of thrusting in work developed in the earlier parts of this century and last decade of the nineteenth century on the Norwegian side, and the whole-hearted advocacy in Swedish work of the role of thrusting. Naturally this problems looms large in our enquiry but our results are described before it is discussed.

Our work in the Sulitjelma area was part of a combined project and we are grateful to Dr. K. J. Henley for information on the metamorphism and structure of the Furulund schists, to Dr. R. Mason for an account of the character of the Sulitjelma gabbro and its relation to the country rocks, to Mr. C. Halls for structural information on the Skoffedal area and to Dr. M. R. Wilson for information on the area of amphibolites and Furulund granite north of Sulitjelma town itself. Their work forms part of detailed studies some of which has already been published (Harte and Henley, 1966; Mason, 1967) but of which much is yet unpublished. Detailed acknowledgment is made when their work is quoted.

Rock units

The lower part of the Sulitjelma structural sequence

In this area (fig. 10), as in that described in part II of this account, the lower part of the Sulitjelma succession consists of rocks of the Furulund Group which can be followed across it from west to east together with the underlying Sjønstå Group, widely exposed in the east, but present in the west only in the two inliers of Sjønstådal and Krågdal. Above the ordinary metasediments of the Furulund there are amphibolites which Kautsky (1953) has suggested are separated from the Furulund schists by a major thrust (the base of his Vasten nappe). Mason (1967) has shown, however, from mapping along the north side of Lomivann, that the Furulund schists interdigitate with the bedded amphibolites above so that the two groups might be regarded as belonging together stratigraphically. However, for simplicity we keep a separate name for the amphibolite, the Sulitjelma amphibolites, rather than calling them the Furulund amphibolites and thus implying their stratigraphic union with the semi-pelitic sediments below.

In the east, as described by Kautsky, the Sulitjelma amphibolites are underlain by his thick Konglomerat-Sandstein Series which, including much of the Furulund level of Sjögren and Vogt, itself overlies the Pieske marble. To the west our Furulund Group has a clear boundary with the underlying Sjønstå Group in the Vatnfjell antiform while in the Krågdal inlier the Sjønstå Group is underlain by a marble which reappears in Junkerdal to the south. From Junkerdal this marble has been mapped more or less completely into the Pieske marble of the type area east of Sulitjelma and the general structural equivalence of the Sjønstå and Furulund groups with the Konglomerat-Sandstein series of Kautsky and the rocks which immediately overlie it is thus established although there are complications in detail.

As described in part II, the upper levels of the Sjønstå Group in the Krågdal inlier are psammitic like the mass of the less deeply cut Sjønstådal inlier but much of the lower levels are pelitic and, unlike the Furulund, generally non-calcareous. The metamorphic grade is uniform and high in the west but falls off eastwards as described by both Sjögren and Vogt and elaborated by Henley. This change of grade makes difficult the correlation of the rocks above the Pieske marble to east and west especially as this change has not been studied at low structural levels. The correlation is also complicated by probable sedimentary facies variation at the level at which Sjögren and Th. Vogt divided the sequence above the marble and below the Sulitjelma amphibolites. Such facies variation was first described from this level in Sweden by Kautsky (1953) and it been suggested that it occurs at the same level on the Norwegian side of the border (Nicholson, 1966).

Table I shows the ways in which the sequence below the Sulitjelma amphibolites has been divided by various investigators. It is clear that if east-west correlation at the Sjønstå Group level is accepted (as it seems it should) then there is a much less well developed psammtic border unit between it and the Furulund in the east than there is in the west and perhaps this is itself evidence of facies variation. Since it would seem better to have only one name for these rocks to be applied irrespective of metamorphic condition we propose here to call them the Sjønstå Group, qualifying the low grade development as the eastern Sjønstå Group. (The earliest term applied to much of these rocks was Sjønstå Gneiss (Vogt, 1927)). The results of detailed surveys near the copper horizon have provided Sulitjelma Gruber with evidence for much finer subdivisions than attempted here and in line with those of Sjögren (1900b); unfortunately much remains unpublished.

The Furulund can be followed eastwards into Sweden and northwards

Table 1. Structural sequences in the lower part of the rocks of the Sulitjelma region.

Krågdal inlier	*Sjønstådal inlier*	*Langvann*	*Lomivann — Pieskejaure*	*Our group divisions*	*Kautsky's divisions for Swedish developments*
(Nicholson)	(Nicholson)	(Sjögren, Vogt, Henley, Wilson)	(Mason, Nicholson)		
Schistose amphibolite thin and uniform	Schistose amphibolite, thin and uniform	Thick schistose amphibolite much secondary brecciation, whole unit thinning rapidly west	Thick amphibolite sequence interbedded calc-conglomerate; appears to interdigitate with Furulund below	Sulitjelma Amphibolites	Porphyritic amphibolite series
Well-bedded calcareous pelites, generally hornblendic and garnetiferous	Well-bedded calcareous pelites, generally hornblendic and garnetiferous	Well-bedded calcareous pelite, hornblendic and garnetiferous in west	Well-bedded calcareous pelite with garnet and biotite at upper levels but with well-bedded muscovite quartz schists below which include some crinoidal marble and conglomerate and volcanic rocks	Furulund Group	Schists above the Laotak Series Laotak Series
Well-bedded psammites, coarse-grained pelitic schist of high grade generally not calcareous			Quartz muscovite phyllites with some fine-grained quartzites Chlorite and muscovite phyllites - some marbles	Sjønstå Group	Stalo Series
Marble			Marble	Pieske Marble	Pieske Marble
Sparagmitian psammites				Sparagmite	Juron Quartzite (equivalents to west not clear)
Granitic gneisses				Pre-Cambrian basement	Pre-Cambrian basement

round the Sulitjelma area until it re-enters Norway and eventually takes its place in the structural sequence above the Rishaugfjell granite gneiss. Here it is very much thinned but still a distinctive hornblende semi-pelite and which overlies (see pt. II, p. 27) a distinctive member of the Sjønstå Group which itself lies directly on the granite gneisses. Thus the Furulund and Sjønstå Groups thin westwards like the groups above (see below) and at the south end of the Rishaugfjell antiform the Furulund lies almost directly in contact with the structurally higher Fauske Marble Group (see Table 2).

The upper part of the Sulitjelma structural sequence

The upper part of the Sulitjelma sequence, above the Furulund Group and its possible upper member the Sulitjelma amphibolites, seems more notable for variation of development than for consistency. Not only does the upper Sulitjelma sequence as developed in the Sulitjelma mountains contrast with the lower in the much greater variability of thickness of given lithologies from place to place but it also differs in two other characteristics. It contains a large gabbro (the Sulitjelma Gabbro complex of Mason, 1967) and large folds in the Duoaldagop area (fig. 10) of a scale unknown elsewhere in the region described here. Vogt (1927) attributed these folds to the activity of the intruding gabbro magma while Mason (1967) who has mapped the gabbro and its immediate metasedimentary envelope has suggested that in part the early folds were bent against the consolidated gabbro. Certainly it seems that a major fold development was earlier than the gabbro.

Lithological sequences through the upper part of the Sulitjelma unit are given in Table II for various sub-areas. In a sense this table is intended as a substitute for a complete map of the upper sequence of the Sulitjelma area for so far we have considerable detailed information from isolated tracts but only reconnaissance data between. The ice-caps of Sulitjelma proper and Blåmannsisen, together with the gabbro, effectively divide the Sulitjelma development of the upper part of the regional structural sequence into two. They are linked in the west between Blåmannsisen and Sisovann (but the ground is unknown to us) and to the east between Blåmannsisen and the gabbro.

The Furulund has been added to the record of the upper sequences in Table 2 to emphasize its presence throughout the region considered here. Table 2 also brings out one of the features of the sequence; that

Table 2. Structural sequences in the uppe

Western Rishaugfjell	*Lappfjell to Blåfjell*	*Skoffedalstind*	*Duoldagop)*
(Nicholson)	(Nicholson)	(Nicholson)	(Sjögren, Vogt, Wilson)
Fauske Marble Gp.	Fauske Marble Gp.	Fauske Marble Gp.	(Links between Duoldagop and Røtind and further west not known in detail)
	Amphibolites and pelitic schists forming thin sequence between fragmental group below and marble above	Pelites, marbles amphibolites Coarse garnet biotite schist	
		Marble-quartzite pelite series	
		Massive pelitic schists	Well-bedded calc semi-pelite
Very thin schist sequence continuous with that of Blåfjell		(Bottom rocks rest conformably on amphibolites above Furulund)	Marble, quartzite and rusty-weathering schist
	Graphitic rocks, no breccias	Not recognized	Fragmental Group as thin rim to Duoldagop structure
	Marble below graphitic rocks	Absent	Absent
Very thin hornblendic schist with some amphibolite	Thin and schistose amphibolites	Amphibolites (some brecciated)	Amphibolites—flaser gabbro above
	Furulund	Furulund	Furulund

part of the rocks of the Sulitjelma region.

Sorjusvann (Mason, Nicholson)	*Sorjusvann* (Kautsky)	*Veiskivann* (Nicholson)	*Our group names*
			Fauske Marble Group
			No regional terminology
	Quartzites	Nodular amphibolitic rocks	
	Mica schists	Phyllitic schists	
Very distinctive staurolite pelite not known to south west	Staurolite mica schist unit		
Kyanite pelite			
Calc-silicate and calc-semi-pelite, some fragmental. Group including granitic gneiss and its breccia and graphitic breccias	Acid effusives. Graphite and other schists. Fragmental rocks with graphite schist. Basement granitic gneiss body	Schist sequence rich in graphitic schist and with some fragmental granite gneiss material	Fragmental Group
	GASAK NAPPE		
Marbles and schists	Marbles and schists	Marbles with schists	Sorjusvann Marble Group
Amphibolites	Amphibolites	Amphibolites	Sulitjelma Amphibolites
	VASTEN NAPPE		
Furulund	Furulund (upper part of Pieske Nappe)	Furulund	Furulund Group

everywhere amphibolites occur above the readily distinguishable Furulund schists although the higher parts of the sequence vary from place to place.

The only certain evidence of age in the rocks listed in Table 2 is afforded by the mid-Ordovician fossils of the Furulund/eastern Sjønstå Group junction of the Lomivann tract (first finds reported by Sjögren, (1900a)). In fact this is a very useful criterion for as we have seen the Furulund level appears in every column of the table. Later finds by Th. Vogt (1927) and Nicholson (1966, 48) have defined and confirmed the original estimates of age but it appears that there is much better evidence of stratigraphic age in as yet undescribed fossils assemblages from the Swedish side of Sulitjelma (O. Kulling, personal communication).

In the east and north of the region there is a marble unit above the level of the main southern development of the Sulitjelma amphibolites which also may be in stratigraphic place with them above the Furulund. Since the unit of marble etc. is well-developed in an east-west zone north and south of the Sorjus lakes it is called the Sorjusvann Marble Group. No equivalent is known south-west of the Sulitjelma gabbro whose lower part (Mason, 1967) is considerably deformed (see below, p 54). As allowed on p. 58 below there may be a thrust at this level, accounting for the absence of the marble to the south and west as well as the other differences between column 5 to 8 and 1 to 4 of Table 2.

a) Developments in north and east Sulitjelma.

On the north side of nedre Sorjusvann and further north and west along Veskivann (fig. 10) the Sorjusvann Marble Group is overlain by a curious and distinctive formation of sedimentary fragmental rocks associated with a coherent granite gneiss body at least 1 km long that Kautsky (1953) considered to be a slice of the basement. The Marble Group below and the granite-gneiss and associated breccias above have been supposed by Kautsky to be separated from one another by a thrust, the Gasak thrust (Table 1 here and Kautsky, 1953, Abb. 94). The writers agree with Kautsky's proposal that the granite gneiss is extremely like the local basement to the Caledonian sequence of the region (as revealed in the massifs of Tysfjord, Rishaugfjell, Trågdal and Nasafjell all now structurally well below the breccia level). However, the detailed relationship between the granite gneiss and its neighbouring and generally fragmental meta-sediments is more complicated than described by Kautsky

(1953). We also agree that the shore section along the north side of nedre Sorjusvann from west to east provides a section through coherent granite gneiss with a western dip to its top which to the east merges structurally downwards into a granite gneiss breccia or conglomerate apparently produced more or less in situ from the gneiss (but not entirely so for it also contains bedded fragments of rather green calc-silicate schist not present in the coherent granite-gneiss).

However, the coherent gneiss does not form the upper part of the whole of the lengthy body of granite gneiss material for this body is fragmental from top to bottom where it leaves the edge of nedre Sorjusvann and swings north. Here more ordinary fragmental sediments ,of pelitic fragments in a pelitic ground mass, lie underneath the granite gneiss breccia as well as above them while in the fragmental sediments above there occur isolated bodies up to 10 m long of breccia rich in granite gneiss debris. Sometimes the granite-gneiss breccias on the margin of such bodies show clear graded bedding when the rocks may be seen here to face sideways to the south-west on the transverse schistosity.

The fragmental sediments above the granite-gneiss lithologics usually have black and slaty graphitic schists between them and the granite gneiss. These schists often themselves are fragmental; sometimes the fragments are rounded pieces of a graphite-rich rock not known in situ here but which does accur on Lappfjell (there associated with such breccias). Above the slaty rock occurs a calcareous and pelitic rock generally rich in muscovite and then semi-pelitic rocks, often flaggy, but with a discontinuous bedding structure composed in cross-section of long elliptical bodies of banded semi-pelitic material in a similar matrix. These too seem to be fragmental rocks although of course the shape of the fragments must owe a great deal to tectonic strain. It seems that these latter rocks are the agglomerates of of Kautsky (1953). We regard them as non-volcanic; they form an easily recognized series that can be traced south-west into Duoldagop and towards Røtind (fig. 10).

The sequence north of Sorjusvann also contains some very beautiful staurolite schists (Kautsky, 1953) which seem to be developed locally at the top of the fragmental semi-pelitic series. They are overlain by a flaggy set of rocks of which the more northern and upper parts contain much granite as discrete sheets as well as more intimately distributed in the obviously metasedimentary fraction. This flaggy unit seems to run into the north-eastern-most lobe of Sulitjelma gabbro (fig. 10) at the west end of Øvre Sorjusvann and although it may be equivalent to similar rocks known on the east side of Duoldagop this is not certain. We do know, however, that the fragmental semi-pelitic rock below is found there. Such a correlation is shown in Table 2.

As Kautsky has shown (1953, Tafel V) no thick granite gneiss fragmental formation exists by the shore of Virijaure in Sweden but a much thinner development of such rocks together with the underlying marble occur on the south side of Veskivann (still further round the Sulitjelma synform to the north and west and in Norway). They are accompanied there by the very distinctive graphite breccia found in the Sorjusvann development and which is well-developed on Lappfjell also (first reported by Holmsen, 1916, 12) where, however, there is no granite gneiss in any form.

From Lappfjell the sequence passes under the Fauske Marble Group on Blåfjell. As it does so the marbles and graphitic members disappear while the granite gneiss unit may be represented by one or two sheets of gneissic material up to 10 m thickness. These can be followed above the thin but distinctive Furulund development south into Kjølvikdal where they are overlain by a very thin schist unit representative of the upper part of the Sulitjelma sequence which itself is directly overlain by the thick and conglomeratic Fauske Marble Group.

The succession above the fragmental group in the ground west of Virijaure (table 2) consists of generally fine-grained and phyllitic schists (some porphyroblastic) whose relation to Kautsky's staurolite garnet mica schist formation etc. (Kautsky, 1953) or the units which we have distinguished is uncertain. They are well displayed in the almost entirely bare country-side south of Veskivann and towards Gasakjaure and Messingmalmvann. Immediately south of Veskivann it is clear that this substantial fine-grained schist or phyllite sequence lies directly over the very thin fragmental group (there topped by a graphite schist) and that there are no rocks there lithologically like the rocks overlying the granite-gneiss breccias and graphitic schists of the tract directly north of nedre Sorjusvann.

On the hills south of Sirkasluokte (itself a bay on the west side of Virijaure) dips in the phyllite sequence are gentle and southerly but change to steep on a northerly strike at the east end in a series of post-schistosity folds of moderate southerly plunge and easterly axial plane dip. These lithological and structural characteristics broadly are those described by Kautsky (1953, Tafel V). Above the phyllitic sequence, however, and south of Messingmalmvann there are nodular amphibolites and not the quartzites and garnet mica schists described by Kautsky in the tract immediately west of Gasakjaure (1953). However, we have done too little work in this sector to be sure of the distribution of lithologies; all we can do here is to agree with Kautsky that there is a thick phyllitic unit above the here very thin fragmental group with higher members still only very imperfectly known to us.

b) Developments in southern Sulitjelma.

Over half the southern development of the upper part of the Sulitjelma structural sequence lies in ground well-mapped by Sjögren and his collaborators (Sjögren, 1900). Much of the Dualdagop or eastern part has been re-examined by Mr. J. E. Larsen, Dr. R. Mason and Dr. M. R. Wilson. As Sjögren's map shows (1900) the Duoldagop area contains some large folds bounded on the east by the Sulitjelma gabbro. As indicated above, in spite of the partial interuption of lithological continuity by the gabbro it is clear from the region between the north end of Duoldagop and Almanajekna that much of the Duoldagop sequence runs directly northwards into the rocks lying above the Sorjusvann Marble Group on the north side of the Sorjus lakes. Since these northern rocks are continuous themselves with those south of nedre Sorjusvann it is clear that the northern end of the gabbro is contained within this sequence (see table 2 for details).

On the south side of the gabbro, north of Lomivann, the gabbro abuts directly into the Sulitjelma amphibolites (Mason, 1967, fig. 2, this paper fig. 10). Dr. Mason (personal communication) has mapped the good igneous contact of the gabbro across various levels of this sequence in the region in Sweden on the east of the gabbro and south of Sorjusvann. Thus the gabbro cuts across the rocks above the Sulitjelma amphibolites and down to their level so that only they continue right round the east side of the gabbro from north to south. Of the rock units above the amphibolites north east of the gabbro, one, the Sorjusvann Marble Group, does not reappear on the west side (table 2). West of Duoldagop, in the region including Røtind, the sheet dip is gentle and apparently here we are in an upper limb of the Duoldagop fold complex. However, our detailed structural work has not been extended yet to this region which to the west joins the sequence described in pt. II.

Kautsky's structural synthesis includes as a necessary part the fairly straight-forward stratigraphic correlation of the structural (and presumed stratigraphic) sequences in his nappes (Kautsky, 1953, Abb. 94). Thus the rocks above the Pieske Marble (our Sjønstå and Furulund Groups) are correlated by him with the sequence from granite gneiss breccias to well above staurolite schist occurrences; since the former contain Ordovician fossils then latter are supposed to be this age also. The writers can see no sufficient reason for this correlation. Similarly we cannot agree with Kautsky's correlation of what is here called the Sorjusvann Marble Group with the Pieske Marble since (see p. 60 below) we doubt the existence of his Vasten thrust. We feel that the Pieske Marble - Furulund sequence may form one tectonic unit whose age is more less well defined by fossil occurrences, but since our judgements must depend upon our structural analysis they are best placed on the section dealing with it (p. 58).

Structure and metamorphism

Introduction

Some elements of the structural pattern of the Sulitjelma region have been described already both here and in part II of the description. Most of this material was of a stratigraphic type or concerned the broad and sometimes late structures which control the overall distribution of rock units. Here, however, we will be primarily concerned with the intimate deformation structures of the rocks viz. folds, schistosity and lineation and their relation to metamorphism. The detailed investigation of the small-scale structures of the Furulund as well as the rocks above is mainly the work of Henley and Wilson, but some aspects have been described by Mason (1966, 1967) and Larsen (personal communication).

Primary structural phases

All the Sulitjelma meta-sediments except the narrow rim of hornfels round the Sulitjelma gabbro (see Mason, 1966, for structures in hornfelses) have a good deformation fabric and even in the hornfelses there is evidence of deformation earlier than their contact metamorphism. The Sulitjelma metasediments commonly are well lineated, the trend of the mineral and fragment lineation generally being east-west or across the deformation belt (Th. Vogt, 1952). The mineral lineation generally is parallel to the linear fabric of highly deformed and elongate fragmental rocks which occur at various levels of the Sulitjelma sequence and it seems that these linear structures reflect general extension.

Early folds (with axial plane fabric) are known in the Furulund Group on a minor or middle scale, the latter being isoclinal folds often with amplitudes up to some tens of metres. No larger scale early folds are known for while the Furulund is well-bedded it lacks clear larger scale variation so that investigation of structures on scales greater than that of individual outcrops is made difficult by problems of correlation. However, the group has a distinctive top and bottom and it is clear as long ago demonstrated by the maps of Sjögren that there is no overall fold within the group.

Henley (1968, Ph. D. thesis) has described the deformation of the metasediments of the area south and east of Langvann as separable into three main episodes, which he labels D_1, D_2 and D_3. He attributes the regional lineation and schistosity to the second suggesting that inclusion trails in garnets, generally trending obliquely across the schistosity of the enclosing rock, represent a schistosity developed during a yet earlier deformation phase now largely obscured by later effects. He also attributes the common early folds of the Furulund to the second phase, the new schistosity (in part a highly modified D_1 schistosity) being parallel to their axial planes. The strong mineral lineation so often developed is oblique to the axes of his supposed F_1 folds but parallel to the axes of his F_2 group. In any event, it is itself of fairly constant orientation through the Furulund schists and Sulitjelma amphibolites. The single most accessible occurrence of isoclinal folds in the Furulund is in Balmielv south of the dam (middle of the bottom of fig. 10), which diverts its water from the natural channel into another course slightly to the east (eventually to reach a power station at Fagerli). This sub-region and that comprising the Duoldagop-Sorjus tract are now described separately.

a) Balmielv area

In the now almost empty water course of this river the isoclinal folds of the Furulund with their characteristic disharmony are well-displayed. The bedding/schistosity lineation trends about 065° and is seen again and again in the wide stream bed exposures. The schistosity is a well-developed and thoroughly penetrative one. Usually there are biotite porphyroblasts in the rock which form the centres of augen-like structures with the schistosity sweeping round them and with quartz-rich zones at either end. In Balmielv there is little evidence of the relative rotation of porphyroblasts and matrix presumably because the flattening plane or extension direction of the phase which produced the augen fabric was about coincident with the earlier schistosity. Within some folds to which this schistosity is axial plane there is the development of a secondary cleavage about parallel with the schistosity and rather like the structure to be found in low-grade cleaved rocks.

The biotite porphyroblasts do not contain trails (nor do the less common garnets of Balmielv) so that it is difficult to judge whether or not they are synkinematic themselves but since they define a fair L-fabric (cleavage poles forming a girdle) they may be synkinematic. If so the sequence of fabric-forming phases in Balmielv may be a follows:

1. Schistosity (exact S-L character not so far known to us), the D_1 episode of Henley, isoclinal folds.

2. Biotite (and garnet?) porphyroblasts formed perhaps in some terminal stage of the first deformation phase — at any rate biotite cleavage poles form a great circle girdle not coincident with the fold axes.

3. Modification of this penetrative fabric as a consequence of a generally symmetrically related phase of deformation. Generally there is little evidence of relative rotation of porphyroblasts but where rotation does occur there is grown a single crenulation set oblique to the early fold axes not parallel to the biotite cleavage girdle. A little quartz-mica differentiation. No known minor scale or larger folds here, D_2 of Henley? (It will be seen that unlike Henley we have not divided the isoclinal folds into two phases). Garnets with S-chaped trails of schistose character are widely distributed elsewhere in the Furulund (Vogt, 1927; Henley, personal communication) so that much garnet may belong to stage 3 above.

b) Sorjusvann-Duoldagop region

At the northern end of the Duoldagop area (fig. 10) Sjögren (1900), has demonstrated the presence of tight folds. These form part of a complex pattern attributed by Vogt (1927) to the deformation of earlier folds by the intruding gabbro. Wilson (Ph. D. thesis) has redescribed these structures and has shown that they have a good schistosity and that they plunge steeply south. At their northernmost Duoldagop development these folds are isoclinal and the core of the major fold may be followed north from the small Sorjus lakes (up on to hill 1265) as a narrow band of marble and rusty red-weathering schists which closes about 3 km north. This takes the Duoldagop folds well towards the Sorjusvann region which generally lies structurally beneath the level of this fold core and in its eastern limb since there no such large folds are known. Indeed clear early folds of any size are rare although bedding/schistosity intersections are not uncommon in the calcareous pelite lying above the granite gneiss and its breccias. This linear structure is varied in attitude but generally about down dip of bedding and schistosity which are close to one another.

Fragment elongation, where marked, also is about down dip but the degree of elongation varies so much with lithology that it is difficult sometimes to identify it (especially for the apparently resistant granite-gneiss fragments). In general, too there is a mineral lineation parallel to fragment elongation. This lineation seems to be the same one as that so well-developed in the Duoldagop tract for it can be observed in all the rocks from Sorjusvann to Duoldagop and where the attitude remains about the same.

As described above, some of the distinctive Duoldagop-Sorjusvann rocks have been identified in the north by Veskivann and on Lappfjell. It is possible that west of Virijaure the structural arrangment is like that to the south i.e. to the west the sheet becomes gentle in the upper limb of Duoldagop-type structures. None have been mapped yet, however, on the north-east side of Blåmannsisen.

There are clear post-fabric folds in the Sorjusvann region and some bend the granite gneiss boundary, the clearest example being the fold in which this boundary swings from its west south-west course to the north-south one which takes it over Sorjusvann and to the west side of Hammaren (about dip amount 44 on south side of Sorjusvann, fig. 10). Thus here too the structural development is divisible into two phases in the first of which the penetrative arrangment was produced, and in the second of which the earlier fabric was highly-modified. Textural evidence suggests (for example from the staurolite schists) generally only moderate small-scale post-schistosity deformation. None of the porphyroblasts shows any synkinematic character nor are the quartz inclusions so common in these staurolites obvious relics of a schistose fabric. This is an observation already made by Henley for the Baldoaivve and Duoldagop representatives of the upper part of the Sulitjelma structural sequence and confirmed by Wilson in his further work in Duoldagop and it seems to fit Kautsky's descriptions. It is thus the common condition at this structural level and is a further distinction from the common synkinematic garnet and hornblende fabrics of the Furulund (both in the type area around Langvann and in the area west of Virijaure). On the whole, all fabrics are simpler to the west where grade is higher. This seems common enough in deformation belts to be considered the usual condition; presumably the difference for the most part results from the effects of increased component mobility in the hotter regions.

The fragmental rocks of the Furulund (and in the east of the rocks of the junction zone between it and the eastern Sjønstå Group below) contain elongate pebbles etc. which trend east-west, and this is true downwards from above the group where conglomerates occur in the metasedimentary amphibolites. In addition there is a well-developed east-west lineation in the deformed region on the southern edge of the Sulitjelma gabbro, and in the highly deformed junction unit (largely made of onetime gabbro) between the gabbro and the amphibolites beneath it (Mason, 1967). The age of development of this east-west lineation of course must be post-gabbro. Since the gabbro is later than some deformation (see above and Mason, 1967), the lineation may be equivalent to the porphyroblast lineation of the Balmielv rocks (above p. 52). This correlation of this linear fabric with that of the Furulund makes it generally of Henley's D_2 type.

Although extension fabrics seem characteristic of the Furulund there is some evidence that there may be variation in amount of extension within it. For example at the east end of Lomivann Nicholson (1967) has shown that there are conglomerates without a strongly linear character and marbles bearing only little-deformed fossils only 300 m across strike from a quartzite-marble conglomerate with very much elongate pebbles; all within the phyllitic rocks of the Furulund/eastern Sjønstå Group junction region.

Since the Sulitjelma region as a whole, and the lower levels of the Tverstifjell synform in particular, are characterized by thick eastern developments and attenuated western ones it would be interesting to know whether there is any correlation between the type of strain at any locality and the thickness there of the various elements of the regional sequence. In part II we noted the possible similarity of Fauske Marble Group pebble shape through the Rishaugfjell antiform and the Tverstifjell synform. The Fauske Marble Group does not seem to thin west from Tverstifjell although the same fragmental carbonate group thins very much in the same relative position in the same structure in upper Saltdal (fig. 13). Unfortunately no fragmental rocks are present beneath the Marble Group on Tverstifjell where thining obviously is very great.

Changes of metamorphic grade

As Sjögren and Vogt first showed there are considerable differences of metamorphic grade between eastern and western Sulitjelma. The first detailed description was by Vogt (1927) and recently Henley has reinvestigated the region. Vogt seemed to have demonstrated that the oligoclase isograd surface near the east end of Lomivann dipped west so that higher-grade rock overlay lower-grade, but Henley has shown that his line merely marks the beginning of easily recognized oligoclase. Henley has shown, in addition, firstly that the biotite isograd is not quite as mapped by Vogt, secondly that his (Henley's) garnet isograd (which as we have seen above extends much further east than mapped by Vogt) also markes the incoming of hornblende and is referred to by Henley as the garnet-hornblende isograd, and thirdly that the true oligoclase isograd is approximately coincident with the garnet-hornblende isograd and marks the peristerite jump in composition (here An_{8-12} and An_{23-31}). However, it still seems that the garnet hornblende isograd of Henley at first dips westwards but becomes more gently dipping to the east until finally along the north shore of Lomivann there is a thin skin of garnet- and biotite-bearing calcareous semi-pelitic Furulund schist under the amphibolites at the top of the group and above apparently lower grade rock. Our work and Henley's has shown that this upper level goes at least as far east as the frontier where only rarely garnetiferous muscovite and often chloritic phyllites lie beneath. As described above it may be that all these schists belong stratigraphically under the amphibolites and not separated from them by a thrust as Kautsky has suggested (1933). However, as discussed below there is a suggested level of thrusting above the amphibolites (Kautsky's Gasak thrust). It might be postulated therefore that the upper units were at high metamorphic temperatures when they were thrust over lower cooler units (at least in eastern Sulitjelma) so as to lead to a reversal of the usual order of the isograd sequence with depth. It is clear that it will not be sufficient to bring in higher grade rocks late in the structural history of the region as the metamophic grade changes have been identified by Henley as being at least as early as the D_2 deformation episode, that is they involve the porphyroblast distribution. This explanation is very like that of Haller for similar isograd sequences in the Greenland Caledonian (Haller and Kulp, 1962, 23). However, we are not confident that such a simple explanation can be straight forwardly applied here.

Secondary structural phases

Although both large and small-scale secondary folds are known their relations to one another are not always clear, and first of all we will discuss the secondary folds of the system which determine the large scale pattern of outcrop and then consider smaller examples.

a). The regional antiforms along Langvann and across Balvann as well as the intervening synform of Skaiti, Baldoaivve and Sulitjelma proper; all apparently related to the Vatnfjell antiform.

In part II of this account we suggest that the great thickness changes in the rocks of the Sulitjelma sequence as they pass out of the Vatnfjell antiform in the west were produced in the early phases of deformation. The antiform and related folds then follow later. There is no doubt, of course, as we pointed out there, that the later folds occur at special places in the early arrangment, a relation that suggests some continuity of development from the early to the later. However, there is a great difference in the relation of the earlier and later fold phases to the penetrative fabric which clearly developed in earlier phases merely to be modified in the later.

The small-scale folds of the secondary phases generally are of a style near to kink-zones. Angular character is best displayed in eastern developments in the lowest grade rocks around Lomivann where the kinks are distinguished by well-developed quartz-mica differentiation but no growth of new types of mineral. In general the folds are not simple conjugate pairs but mainly consist of the member with west-dipping axial plane although some conjugate pairs are known low down in the eastern Sjønstå succession. However, folds of a conjugate motion are developed on a small scale in the mica-rich elements of the kink-zones (Nicholson, 1967) and Henley has reported regions in the eastern Sjønstå Group where only the member with east dipping axial plane is developed (see fig. 12).

Passing westwards from these low grade developments there occur at the west end of Lomivann folds of the same vergence and axial plane orientation as the kink-zones although too broad and rounded to be called kink-zones but which seem to have been produced at the same time. Their axial plane crenulation cleavage, however, carries new biotite along its surfaces and it seems that a metamorphic pattern developed during D_2 persisted long enough to influence mineral development in these later folds (D_3 of Henley). It seems probable that the style of these D_3 structures in the west results from the more coarsely schistose D_2 fabric in which they formed; a contrast with the finely phyllitic fabric around Lomivann and south of that lake.

Such D_3 folds are absent along Langvann where the conspicuous late deformation phase is one of boudinage, sometimes, however, associated with a fine-scale crenulation of boudin nodes. Further west still, in the core of the Sjønstådal inlier, the Sjønstå Group is folded in many secondary folds clearly part of the Vatnfjell antiform (see part II, p. 25) and they too may be contemporary with the D_3 folds of the ground to the east. Their axial planes dip east, however, although their axes still trend to the north and the axial planes are still of northern strike. Between these two fold developments lie the zone of boudinage (fig. 12).

While the D_3 folds have an atttitude across the Langvann antiform and may be earlier than it there are folds whose axes trend just south of east in the ground north of Langvann and between Skoffedal and Duoldagop and which may be of the same age as the antiform; the Røtind phyllitic unit lies in a structure defined by such folds. Like the Langvann antiform they are clearly post-schistosity structures of the secondary phase but may be later than the north-south trending D_3 structures. However, the complex pattern of the major late antiforms and synforms does not really allow subdivision in this way and age differences may be slight. Thus we believe that the cross folds are of the same age as the Vatnfjell antiform. Evidence from the Rishaugfjell region and the ground of the north of it up towards Narvik suggests that the Vatnfjell antiform and related folds are the easternmost undulations of the granite gneiss basement. If this is so then

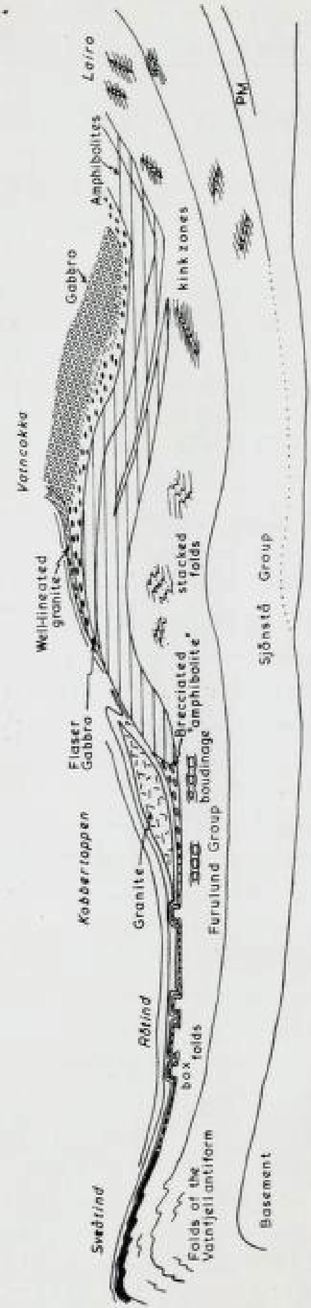

Fig. 12. Cross-section east from Vatnfjell antiform to Lairo diagrammatically showing some of the distinctive late folds and fabric of the Furulund and rocks immediately above it. The east-west trending folds of the Røtind region cannot be shown. Line of section exactly that of fig. 11 of this account but topography omitted.

the north-north-east trend certainly is contemporary with the "cross-folded" one and time distinctions are not reasonable.

b) The Duoldagop structures.

As noted above both Vogt (1927) and Mason (1967) have suggested that the pattern of structures immediately west of the gabbro result from two phases of folding. The gabbro cuts across the early folds of the Duoldagop-Sorjus unit so that part of the pattern is pre-gabbro. It may be that the main result of post-gabbro deformation has been to bend gently an early synform against the gabbro. This region has been studied also by Wilson in connection with his work on the Gasak-Vasten thrust-zone north of the town of Sulitjelma.

Discussion of the evidence of thrusting

It is now essential to make reference to Kautsky's stratigraphic and structural analysis of the region (1953, especially Abb. 94) in which he distinguished, one above the other Pieske, Vasten and Gasak nappes and further north, a fourth nappe, the Salo nappe between the Vasten and Gasak. He considered that each of these nappes had a characteristic lower Palaeozoic content, mostly Ordovician. Some of the evidence for this analysis is local and some is the result of analogies with other areas in the Scandinavian Caledonides and bold extrapolations from them. Here we will consider the local structural evidence only; local stratigraphic correlations are dealt with on p. 50 and regional relations are discussed in part IV.

We have remarked above that the metamorphic evidence does not permit of late large-scale tectonic transport (Mason, 1967). The penetrative fabrics of the rocks both above and below the level of Kautsky's Gasak thrust have been described earlier (pp. 50-54). It was suggested there that the main fabric is in someways compound and that it may be that the deformed character of the base of the Sulitjelma gabbro at its south side (the flaser-gabbro especially) and the linear structure developed there belong to Henley's D_2 phase as he has suggested. However, the zone of concentrated deformation to which the flaser gabbro belongs does not extend throughout the region at the appropriate level (for instance to the east of the gabbro the igneous contact of the gabbro cuts down across it from above without the interuption of any dislocation horizon). We will therefore consider the evidence for D_2 and earlier slides separately from any evidence of late movements.

Evidence of lithological discontinuity

Table 2 clearly suggests variation in structural succession above the Furulund Group. However, work in the Sorjusvann-Duoldagop sector especially suggests that there is a considerable degree of continuity above the level of the Sorjusvann Marble Group even though there are substantial thickness changes through early structures. Thus the problem here is one of explaining the different structural developments above and below the level of Kautsky's Gasak thrust rather than using the notion of a thrust to account for differences of structural succession from place to place. As is emphasized below there is no doubt, however, that the level of his proposed Gasak thrust in the region along Langvann and to the south possesses many curious structures unknown elsewhere, many of which suggest relatively late dislocation.

Further south, in the sequence between the Furulund amphibolites and the Furulund granite gneiss on either side of Langvann, that on the north is much the thicker although similar members are present in each (see table 2). Both the amphibolite and the granite also thin very much to the south of Langvann while both the northern and southern developments thin greatly to the west.

As fig. 12 shows the Furulund granite north of Langvann is in two parts and is is possible that the two were broken from a single body in the D_2 deformation phase. The north-eastern member against the gabbro has a very strong and penetrative lineation probably also of D_2 age. As both Sjögren (1900) and Vogt (1927) have pointed out there apparently is a big difference in the rock types developed above the zone of thinning in which the granite lies for much of the Baldoaivve sequence not been recognized north of Langvann. This possibly is another example of the variation of sequence at about the level of Kautsky's Gasak thrust. There are similar differences between the area immediately south of Langvann (Baldoaivve) and the Skaiti region to the south. However, the evidence of the drastic thinning rather than dislocation of the Sorjus developments towards Duoldagop suggest caution where no detailed work has been done.

Kautsky (1963, Tafel V) supposed that the Sorjus granite gneiss breccias etc. (p. 46) where of high Ordovician age but older than the Furulund because he correlated them with conglomerates in the succession just below the Furulund in the region south of the southern end of Virijaure which contain granite gneiss fragments and where he also reports graphitic rocks. It seems to the writers' that this correlation is not pressing and cannot be used as evidence for thrusting. Kulling's work (1964) suggests an alternative correlation with low Cambrian rocks further east but this too is too loose to be compelling.

In Sweden, in ground to the north-east of Sulitjelma, the supposed thrust at the base of Kautsky's Vasten Nappe is marked by a marble band and is shown by Kautsky (1953, Tafel V) to cut down from its supposed position immediately under the amphibolites well into the underlying sequence. At the same time the trend of the thrust and the marble band is shown to be little affected by the strong relief, indication that they must be a steeply dipping. Our examination does not confirm either the discordance or the attitude. Rather it suggests that there is a continuous concordant and gently east-dipping sequence from the rocks above the Pieske Marble in the east up into the amphibolites above the schists at the east end of Sorjusvann. This evidence does not rule out the presence of an important concordant slide, but as noted above, the Furulund schists and the overlying amphibolites, which are supposedly separated by the Vasten thrust, actually interdigitate on the north side of Lomivann (Mason, 1967). They therefore appear to belong together stratigraphically. Our examination of the same sequence on the north side of Sulitjelma in the Veskivann region also suggests stratigraphic continuity. To the west such evidence becomes less and less useful for in the westward thinning sequence conformity becomes more and more marked. The writers do not accept therefore the existence of the Vasten thrust as a separate disjunctive nappe boundary, a conclusion reached independently by Henley (1968, Ph. D. thesis) and Mason (1967), and confirmed by Wilson (1968, Ph. D. thesis).

Granitic gneiss occurrences

The presence of gneisses at the base of the inferred Gasak nappe is important to Kautsky's analysis and the writers accept his view that these granitic gneisses are basement rocks. Kautsky suggested that they were emplaced (together with the sequence above them) by thrusting and certainly the hypothesis is very attractive for the coherent body of granite gneiss is over 1 km long and covered by its own debris while itself showing cataclastic deformation of Caledonian age. Further to the north of Sorjusvann, as we have described on p. 47, no coherent gneiss is present although its level is continuous with an horizon of granite-gneiss-rich sedimentary breccias with above and below it breccias of other types of rock. Thus to the east it seems as of the coherent granite body is both underlain as well as overlain by breccia-like debris. This breccia series seems to be concordant with the upper rocks of the marble-phyllite group below (the Sorjusvann Marble Group), and there is no evidence of unusual late deformation of their junction. Nor is their any indication of syn-metamorphic thrusting here except that as usual grade falls off east below this level. However if synmetamorphic sliding is not allowed then some earlier transport (synsedimentary?) for this very large unit of basement material is needed. So again, but in a different way the "Gasak level" raises special problems.

Late deformation structures

Evaluation of Kautsky's postulated thrusts is complicated to some extent when late deformation structures are taken into account although these cannot be related easily to a regionally significant phase of tectonic transport. Late deformation structures of a distinctive kind occur on both sides of Langvann in the attenuated sequence between the supposed base of the Gasak nappe and the top of the Furulund schists. They could thus be related to renewed but oddly local movement on a Gasak Thrust or to the initiation of a Vasten Thrust.

On Kobbertoppen the Furulund Granite cuts clearly across the bedding of the enclosing schist and there is some evidence that it lies about along the axial surface of a large fold in them (Sjögren, 1900, and Wilson, 1968, Ph.D. thesis). A little east of Kobbertoppen the granite cuts the gabbro. On Kobbertoppen the granite has a mixed S-L fabric (Wilson) while south of Langvann ground the north and east side of Baldoaivve it is a flaser-gneiss. The granite has a wide regional occurrence at about the same structural and lithological level at which it occurs on Kobbertoppen. It often appears to be concordant, sometimes sufficiently so for its intrusive character to be doubted (Herr N. Raith, Sulitjelma Gruber, personal communication) and it has been interpreted as an extrusive horizon.

The Sulitjelma gabbro (fig. 12) has a well-lineated facies of the granite next to its own well-lineated flaser-gabbro belt on the southern edge of the gabbro. Mason (1967, fig. 2) has shown that this flaser-gabbro runs west under the less well-lineated development of the Furulund granite on Kobbertoppen where it is separated from it by the Duoldagop schist of the sedimentary breccia level. Here it merges with the so-called chloritized brecciated amphibolite of Sjögren (1900, Tafel 11), and Wilson has noted flaser-gabbro-like material at this level 2 km west of the edge of Mason's map. West of Kobbertoppen the whole "amphibolite" unit is made up of the breccia.

The "brecciated amphibolite" of Sjögren often is a greenish biotitic and chloritic rock often containing rounded plagioclase-rich fragments. Kautsky (1953) has suggested that it is agglomeratic but to us most of the fragmentation seems undoubtedly tectonic. The plagioclase-rich material often exists as 10-20-cm. thick but partly disrupted or boudined layers in biotitic and chloritic material. It seems quite different in original character from the gabbro and the two types of amphibolite found to the east (Mason's metaporphyritic amphibolites and schistose bedded amphibolites). The brecciated material is thus distinct in regional character and structure from them although it shares its secondarily fragmental character with the flaser gabbro into which it merges to the east.

Although the brecciation is clear enough there is no crystal strain present now and syn-kinematic (or more likely post-kinematic) recrystallization seems to have eliminated it. In addition there is clear growth of pyrite after all deformation. The breccia contrasts with the flaser-gabbro and its immediately adjacent Furulund granite in not containing a strong lineation. This is an obstacle to ready acceptance of their structural equivalence. However, the two fit so readily in place that such a correlation is very tempting (this is not Henley's view).

East of Kobbertoppen the flaser-gabbro unit has been traced 6 km east of Kobbertoppen by Mason into the area of the Sulitjelma ice cap, but it is not known at the appropriate level to east or north beyond the ice. In this way it matches the brecciated "amphibolites" which also are replaced (but now westwards) by unbrecciated material rather like the schistose bedded amphibolites south east of Duoldagop.

The breccias were omitted by Vogt in his generalized version of Sjögren's map (1927, plate 35); at the time of writing of his memoir Vogt apparently did not regard the brecciation as evidence of thrusting. He did admit in 1949, however, in reply to a question by Kautsky (Vogt, 1949) that there might have been small-scale thrusting in the region although he did not accept Kautsky's view that thrusting was the dominant structural mechanism there. We are able to agree with Vogt on the use of this particular evidence for the brecciation in "amphibolites" and flaser character in gabbro or granite have a limited distribution.

As a further pecularity the brecciation is accompanied by chlorite growth, and both occur in a zone in which linear (D_2?) pyrite bodies are present. The chlorite is developed in a zone of the area earlier characterized by generally high grade assemblages so that brecciation and chlorite growth are found only in higher grade regions being entirely absent to the east where regional grade is lowest. Mason, (1967) has suggested that this chlorite growth occurred at the same time as retrograde effects in the Sulitjelma gabbro.

In the central part of the Langvann region these Sulitjelma breccias (amphibolite breccias) contains folds of a type unknown elsewhere. The folds (which have been studied by Henley in the Furuhaugen region) are late, deforming schistosity etc., and are of a general box-fold or conjugate-pair-style of about north-south axial plane strike and axis. They may be comparable with the smaller conjugate and non-conjugate kink-zone like late folds of regions around the east end of Langvann and further east although the later are not so concentrated in the supposed thrust zone but developed through a considerable thickness of the Furulund etc. The Furuhaugen folds bend the brecciated amphibolites of the sequence whose fragmentation therefore was earlier.

Conclusions on thrusting

It may be clear from the above account that more detailed evidence of the supposed thrust tectonics of the Sulitjelma region is needed for to account for the combination of characteristics found in this structurall sequence still is a problem. We will attempt some answers in part IV of this account, and close this section by emphasizing firstly that the Gasak thrust level of Kautsky is rich in structural peculiarities. None of these seems associated with any substantial post-metamorphic movements. Thus if any important slide is present at this level it must have formed relatively early in the deformation history. As we have seen even the occurrence of the granite-gneiss might require an explanation other than such thrusting. Secondly, most of the structures which may point to late dislocation are absent in the northern development of the Gasak level as well as westwards where it is merely one within a sequence almost reduced to nothing by thining. Thirdly the Gasak level also about corresponds in the east with the junction between lower grade rocks beneath and higher grade rocks above; this could most simply be explained by over thrusting of the higher grade units but as we have seen above relationships are more complex than this simple picture would allow.

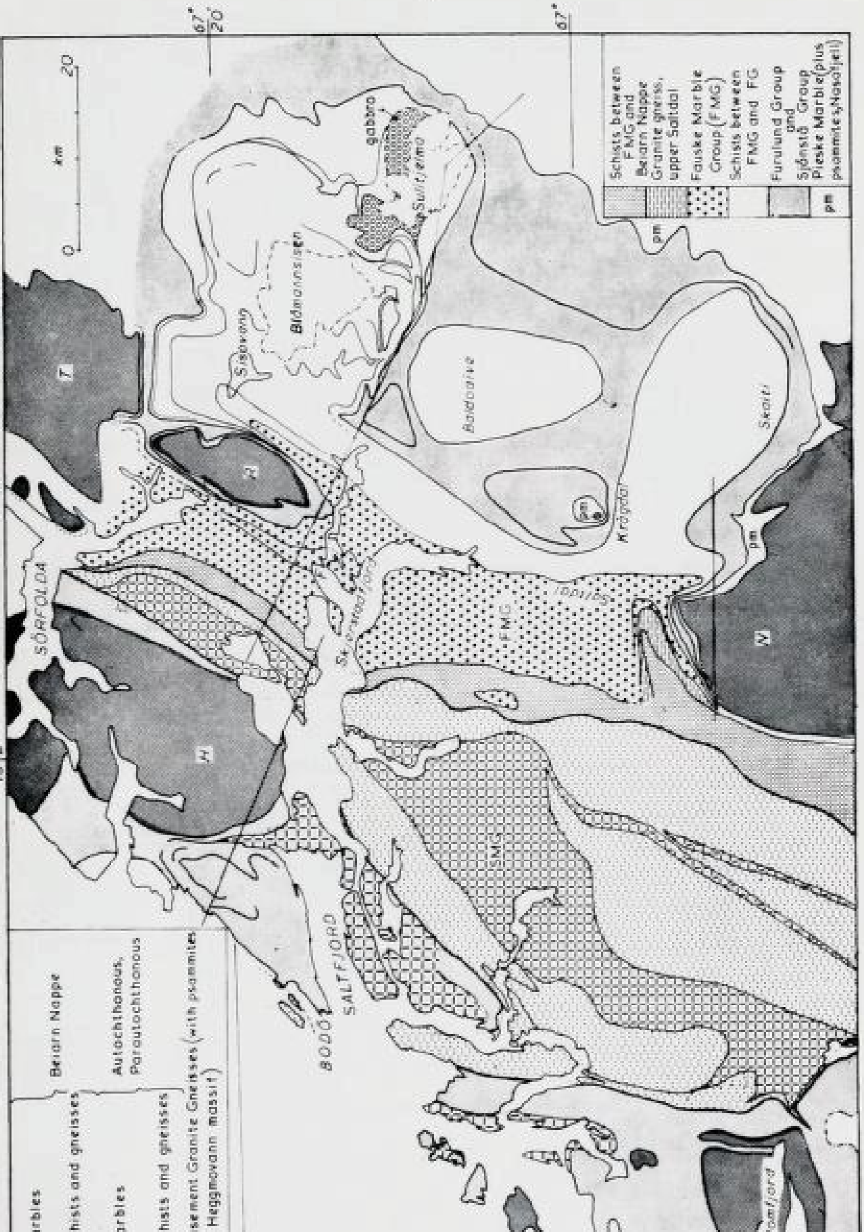

Fig. 13. Map of Bodø—Sulitjelma tract showing major structural-lithological units. Information from our own work and from NGU sources (Rekstad, Vogt), the SGU (Kautsky) as well as Sjögren (GFF, Stockholm, 1900), Steenken (1957) and Mason (1967, NGT).

PART IV:
Synthesis and discussion

Introduction

Figs. 13, 14 and 15 shows on a small scale the regional geology of the section we have described in some detail in the previous parts of this account. As may be seen from them the basal unit of the region is composed of granite gneiss which is exposed in dome-like structures of varying size and shape. The largely meta-sedimentary sequence lying above the granite gneiss is readily divisible into three structural units. The first of these is the thick conjunctive and probably para-autochthonous structural sequence first recognized by us in the west (Hollingworth et al., 1960; Nicholson and Walton, 1963; Holmes, 1966) which has a thin but probably discontinuous partial development around the Nasafjell massif as well as discontinuous developments on the Tysfjord and Rishaugfjell granite gneiss massifs. In the west this conjunctive unit is directly overlain by the disjunctive Beiarn Nappe omplex (Rutland and Nicholson, 1965) while in the east the conjunctive sequence and the Beiarn Nappe equivalent are separated by a considerable thickness of rocks essentially comprising the whole of the Sulitjelma structural sequence as well as the overlying Fauske Marble Group.

Both these eastern units can be seen to thin markedly westwards. The Sulitjelma structural sequence (Pieske Marble to the base of Fauske Marble Group) is reduced to almost nothing on Rishaugfjell while the Fauske Marble Group does not reappear on the west side of the Beiarn Nappe outlier west of Fauske and must thin out under the nappe. On the west side of upper Saltdal (figs. 16 and 13) the Fauske Marble Group can be seen to thin out so that with the underlying Sulitjelma structural sequence it comes to form an apparently simple layer of the meta-sedimentary envelope of the Nasafjell massif.

As we have noted in Part III (p. 60) it has been difficult to accept all the previously defined structural units (nappes) of what is here called

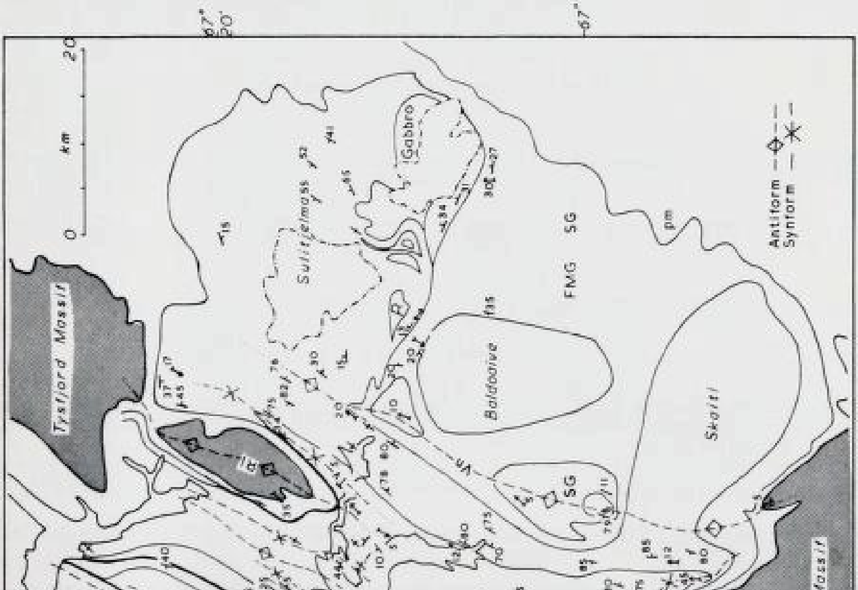

Fig. 14. Structural elements of the tract between Bodø and Sulitjelma.

the Sulitjelma structural sequence, and in some respects this set of rocks behaves as a single unit as does the Fauske Marble Group. Thus though they both thin westwards n the Heggmovann-Hellarmo tract they do so independently. However it is not possible to characterize their junction as a zone of any specially concentrated movement and it does not seem

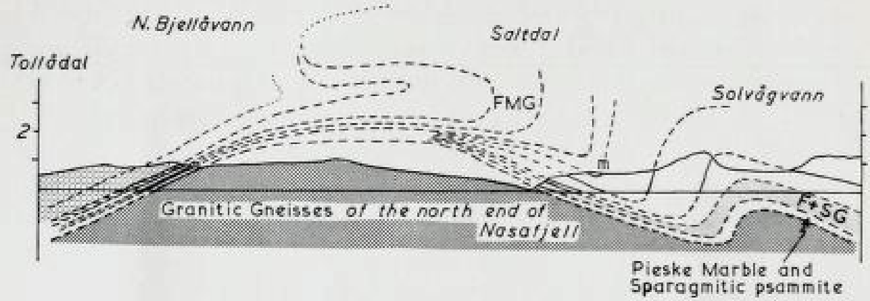

Fig. 16. Upper Saltdal section; from our own work as well as from Steenken (1957).

that we can consider that one unit is the active element and that the other is deformed by it (as in the traineau écraseur and the traineau écrasé of Termier).

The eastern end of our section comprises rocks which have for long been regarded as parts of far-travelled nappes of thrust-slice character and generally have been pictured as extending through the length of the Scandinavian Caledonian and from side to side (see e.g. Magnusson et al., 1960). It is clear however, that the eastern units do not extend to the Norwegian coast in the Bodø latitude but severally thin out so that at the present level of exposure they tend to replace one another as substantial elements of the local structural sequence. Thus as can be seen from the section (fig. 15) the general arrangement is of a relatively thin sedimentary sequence, in the east composed of wedge-shaped units, overlying a regionally developed granite gneiss basement.

Correlation of tectonic episodes between east and west

We have mentioned elsewhere (Rutland and Nicholson, 1965, p. 103) the differences of overall fabric character between the Beiarn Nappe and the rocks beneath it to the west on the one hand and the rocks below it to the east on the other. To the east linear fabrics in conglomerates are common and penetrative mineral lineations are prominent in many of the non-fragmental rocks. In addition large early folds appear to be rare. In the Beiarn Nappe and below it to the west early folds are relatively common and some very large examples occur and the occasional conglomerates (e.g. Saura and Gildeskål marbles) are not strongly linear. This difference is another between the two sequences which underlie the Beiarn Nappe to east and west.

In the Sulitjelma area Henley (Ph.D. thesis, University of London,

1968) has suggested that the elongation of fragmental material and the prominent mineral lineation were produced in a second phase of deformation rather than in the first while Rutland and Nicholson (1965, p. 99) have described the Beiarn Nappe as a first phase structure, recognizing however, that the first phase might itself encompass a complex deformation history. For example, they pointed out (p. 87) that they very large Krokvatn fold, which in terms of its schistosity/bedding relation is of F_2 type (schistosity round the closure and crenulated there) nevertheless belongs to a group of early F_2 folds which do not fold the Beiarn nappe boundary and which may be synchronous with its emplacement. Later F_2 folds affect both the Beiarn Nappe and the underlying Krokvatn fold and thus provide the first demonstration that emplacement of the nappe was complete. There thus seems to be a prolonged early phase of deformation producing the large-scale nappe structures and the regional lithological sequences which were then disturbed by the later phases, whose effects tend to dominate local outcrop patterns, particularly in the east where the earlier episodes produced fewer zones of steep dip than in the more strongly folded west. These later phases include the granite gneiss tectonics that may be examples of density-controlled gravity structures. In the west such structures are much more extreme than in the east (Nicholson & Walton, 1963, p. 16; Rutland and Nicholson, 1965, p. 80) and while there is some suggestion that they are not part of the earliest deformational phase in which granite gneisses and cover reacted in the same way, they certainly appear in the closely linked F_2 phase (e.g. the Svartisen Nappe) which in our analysis succeeds the main period of porphyroblast growth. In the east the granite gneisses and their meta-sedimentary cover (there largely allochthonous) only become folded together in the late phase of broad folds after what Henley has recognized as D_1 and D_2 episodes. Since the main fabric-forming phases of east and west are both earlier than granite gneiss dome development they may themselves by broadly synchronous. However, this would mean that Henley's D_2 phase is earlier than the western F_2 phase since F_2 is related to the development of the granite gneiss structure and D_2 is not. This may be too rigid a division since it is not certain that the whole of the development of the domes etc., on the west is contemporaneous with the gentler eastern gneiss dome structures and it may be that the eastern domes represent only the late part of the development of the western domes. Thus the eastern domes etc. may be contemporaneous with the western F_3 folds e.g. the later Sokumvatn Synform rather than the earlier Fondal

Synform (see Rutland, 1959, Nicholson and Watson, 1963, and Rutland and Nicholson, 1965).

There is an apparent exception to the general very late character in the east of folds of granite gneisses and cover in the very limited development of sparagmitic psammites at the south end of Rishaugfjell antiform, where the psammites are involved with the granite gneisses in tight isoclinal early folds. This interesting occurrence is in the north-south zone noted below in which psammites seem to be absent for the most part (Gustavson, 1966, Table III). Their general absence may be a result of the stripping of the immediate cover of the granite gneisses by the overlying allochthonous units.

In summary then, the sequence of structural styles in the deformation episodes is similar in east and west. There are however, quantitative differences in the importance of comparable episodes which reasonably can be related to differences in geothermal gradient between east and west. The smaller and less prolonged temperature increases in the east have limited the degree of development of some structures there. Strict contemporaneity of comparable structural phases cannot therefore be expected.

Age of deformation and metamorphism

a) In Part III we made some attempt (largely based on Henley's work) to discuss the relationships in the Sulitjelma region of mineral growth and deformation. Earlier discussion of the same topic for some of the western rocks is available (Ackermann et al., 1960).

In the west there is a static phase of porphyroblastesis (especially staurolite) overgrowing an early schistosity (Ackermann et al., 1960). This schistosity is deformed by some very tight major folds which have a crenulation cleavage rather than an axial plane schistosity of their own. The porphyroblasts are clearly earlier than this crenulation cleavage except in areas of late granitization (Ackermann, 1960, Ph. D. Thesis, University of London).

In the east, there is a synkinematic phase of porphyroblastesis in the Furulund schists of the Sulitjelma region. Si is generally confluent with Se but is finer-grained and, according to Henley, the main mica schistosity may be compound D_1-D_2 structure. Thus the porphyroblasts are again later than the fine-grained schistosity but earlier than the coarsening of the main schistosity. In the east there appear to be no tight folds affecting this schistosity in the way it is affected in the west although there is a late crenulation cleavage.

The 'inversion' of metamorphic zones at Sulitjelma is best explained, in our view, by thrusting of hotter rocks over colder (part III, p. ??) and thus an earlier phase of metamorphism must be postulated in the west. Thus the western post-F_1 but pre-F_2 porphyroblasts may be earlier than the eastern D_2 types.

Sturt et al. (1967) report that in the Caledonian of Sørøy the main high grade minerals were produced between the two main deformation phases, thus confirming and extending our own results.

b) The only palaeontological evidence of the time of deformation is afforded by the supposedly middle Ordovician fossils of the Furulund-eastern Sjønstå Group boundary of eastern Sulitjelma and other roughly comparable fossil finds from about the same horizon in northern Scandinavia. As indicated in Part III and in Nicholson (1966) the fossiliferous rocks seem to have undergone all the deformation episodes indentifiable in the higher grade Furulund rocks to the west. Also the whole Furulund unit itself seems to contain evidence of the same sequence of deformation phases as is present in the structurally higher rocks from which they may be separated by a thrust. (Kautsky, 1953; Nicholson & Rutland, Part III). In Västerbotten, Silurian rocks are involved in the Køli section of the Seve-Køli unit (Kulling, 1956), that is, broadly in the tectonic unit in which the Furulund and Sjønstå Groups are found. So regionally at least the rocks concerned range well into the Silurian.

The principal translation of the thrust masses are quite evidently post-Furulund and therefore at most middle Ordovician in age. Moreover, these translations were accomplished prior to or during the main metamorphism, which is therefore also no older than middle Ordovician.

In Northern Ireland and Scotland the main deformation and metamorphism appear to be pre-Llanvirn since lower Llanvirn sediments (Skevington and Sturt, 1967) contain detrital metamorphic minerals and lie more or less directly on the Dalradian. Recently Sturt et al. (1967) have published results from potassium argon age determinations of minerals (and one whole rock) from West Finnmark in the high grade section of the Scandinavian Caledonides. There is evidence there of two main phases of tectonic activity the earlier of which is said to be about basal Ordovician in age and the later end-Silurian. The latter is correlated by them with the main nappe movements of Scandinavia but the former has up to now not been distinguished as a major phase there. Sturt et al. suggest hat such a phase should be recognized in Scandinavia on unconformities etc. in the stratigraphically known sequence. As we have described in parts II and III of this account we have not been able to separate any Caledonian structural events in which the middle Ordovician Furulund are involved from any that affect only the older rocks such as the basement or its sparagmitic cover. However, the main nappe complexes of the Scandinavian Caledonides often carry gneissic rocks at their bases; these rocks were clearly metamorphosed before the emplacement of the nappes and perhaps before the main metamorphism of the overlying meta-sediments. The age of these gneisses is unknown but some could conceivably be attributed to a pre-Llanvirn and Caledonian metamorphism. If so, then a period of uplift and denudation would need to be involved prior to the deposition of the main marble group. This appears to be an extravagant hypothesis for the present region though isotopic studies to test it would be welcome. The writers accept however that metamorphism may have begun earlier in the interior of the orogenic belt and, in appropriate tectonic environments (e.g. N. Ireland) it may have been terminated earlier. Conversely metamorphism may have persisted longer elsewhere and Haller has pointed out that in Caledonian Greenland the main nappes are post-Wenlock (Haller and Kulp, 1962).

Moorbath and Vokes (1963) have reported a lead isotope model age of 390 ∓ 70 million years from a galena from a mine at Jakobsbakken on the east side of Baldoiavve.

Shape and westward extent of allochthonous units recognized in the eastern part of the Nordland-Norrbotten Caledonides

The direct extrapolation from Sweden into Norway of what we have called disjunctive nappes (Rutland and Nicholson, 1965) has been a central part of Swedish-Norwegian correlation (see Kautsky, 1963; Kulling, 1964, and illustrated most comprehensibly by Lindström in Lundegårdh et al., 1964). We have demonstrated in Part III that such extrapolation is in error for the Sulitjelma structural sequence itself which thins dramatically west until it is so longer recognizable as a distinct unit. Examination of Foslie's maps of the Tysfjord district (1941, 1949) show that a similar westward thinning of the eastern sequences occurs there also so that the east and west limbs of the Håfjell synform are very different in thickness. This is true, as we have seen on the smaller scale of the Tverstifjell Synform itself at Sulitjelma (Part III) where again the east limb is the thicker, a character both it and the Håfjell Synform share with the much more westerly Sokumvatn (Rutland, 1959) and Fondal Synforms (Nicholson and Walton, 1963). The writers have inferred that this characteristic thinning of the western limbs of major late synforms is of early tectonic rather than original depositional origin (see for example Rutland, 1959, p. 309, and Part II of this account).

The Sulitjelma structural sequnce also thins very greatly over the antiformal Nasafjell massif south of Sulitjelma in a continuation of the Tverstifjell structure. However, in this southern area the Fauske Marble Group is also thin in the continuation of the Tverstifjell synform relative to the comparable structural position further north on our traverse (fig. 16). In other words the thinning does not take place everywhere at the same structural position in these late fold structures: structural isopachs trend NW-SE across the N-S trending fold axial traces. The thinning evidently antedates these folds. Nevertheless the principal thinning normally occurs in the western limbs of the major late synforms which are also of course the eastern limbs of the major late antiforms where these are present. There is therefore some correlation in space between the siting of the late structures and the earlier thinning and it may be that the late structures were initiated at a very early stage. It should also be noted that throughout this part of Norway the principal marble groups have their greatest thickenesses in the tectonic depressions. They form prongs on either side of the granite gneiss massifs of the principal culminations and are often eliminated there. Such elimination is sometimes due to the plunge of an F_2 fold closure (e.g. Nicholson and Walton, 1963, for the Navervatn synform) but is sometimes a tectonic thinning unrelated to a fold (e.g. the Saura marbles west of the Heggmovatn massif in Part I of this account).

It seems from maps of Norrbotten (even on a scale of one to one million) that similar thinning occurs further east still in the lower part of the Seve-Køli unit which is rich in greenstones. Fig 17 summarizes this relation with evidence from Kulling (map of Norrbotten, 1964, plates 1 and 2; see also his section through the Torneträsk-Ofoten area, fig. 65). The thinning of the Seve greenstone unit does not take place through a fold as thinning does at Sulitjelma but in a more or less flat lying tract; this is further evidence that the thinning and late folds are of different age.

Køli/Seve distinction is a confused matter and it might be better in some respects to drop the use of these terms (at least until the significance of the various criteria used to separate them have been rigorously examined). Here we use the two terms broadly as the names firstly of the sequence between the Pieske Marble and its supposed equivalents and our Sulitjelma sequence, the Køli, and secondly of the rocks below this marble and above the level of Kulling's Middle thrust rocks, the Seve (1964, fig. 65). We are aware that this is not as they are used by Kulling himself (op. cit.).

It seems from Gustavson's map (1966, fig. 1) that the Seve unit is absent north of Torneträsk (fig. 17) although Kulling (1964, plates 1 and 2) marks it as present. According to Gustavson the middle nappe unit (there his Storfjell Group of sparagmitic psammites) is immediately overlain by his Narvik Group which (see Table 3) may be equivalent to our Sulitjelma structural sequence and the upper part of the Køli (Furulund-Sjønstå) below with no Seve between it and the Storfjell Group. Correlation is difficult as different investigators have differently linked the various members of the regional structural sequence.

In our account of some Nordland structures we suggested (Rutland and Nicholson, 1965) as noted above, that the Fauske Marble Group in the region west of Fauske also thinned to the west like the rocks beneath it, in this way contriving to explain its absence underneath the Valnesfjord Marbles on the east flank of the Heggmovatn massif (see also Part I and Part II of this account). This pattern of thinning therefore, may be a regional characteristic and the complete disappearance of units through such thinning lends support to the view that direct extrapolation westwards of all Swedish tectonic-lithological units is mistaken. It also points to an answer to the question of the structural character of the granitic gneiss rocks of the massifs from Tysfjord and Nasafjell westwards to Glomfjord and Svartisen.

Structural character of the Norwegian granite gneiss massifs

There have been two views on the general structural character of the granite gneisses of the Tysfjord area which lie just west of the Norwegian-Swedish border and not far west of undoubted autochthonous Pre-Cambrian granite gneisses. The first regards them as basal and autochthonous (advocates T. Vogt, G. Kautsky and at times Foslie) while the other regards them as allochthonous (principal advocate, Kulling). This latter interpretation follows from Kulling's correlation of them with the sheet of granitic and syenitic rocks which make up part of this Middle thrust units on the eastern side of the Caledonian belt (Kulling, 1964, and Table 3 of this account). The Middle thrust units in Sweden undoubtedly are allochthonous for they tectonically overlie nappes of Cambrian strata and sometimes even autochthonous Cambrian itself. However, detailed work is lacking over the region of supposedly direct continuity from the Middle

Table 3. Structural sequences and suggested correlations over northern Nordland and Norrbotten.

Western coastal areas	*Sulitjelma*	*Structural divisions,* Kautsky (Sulitjelma)	*Narvik region* (Foslie, Gustavson, Vogt)	*Sitasjaure area* (Kulling)	*Structural divisions,* Kulling (Norrbotten)
Beiarn Nappe (Thick marbles and pelitic schist groups — some volcanics)			Schists of Niingen Group		
Meta-sedimentary sequence including the Bodø Schists, Marble Groups (some conglomeratic) and the immediate cover to the western granite gneiss massifs; this cover rich in sparagmitic psammites (Meløy and Vågen Groups)	Fauske Marble Group (Fe ore in Fauske area and Dunderlandsdal)		Thick marbles, etc. Elvenes conglomerate Mica schists Sedimentary iron ore Melkedal marble		Stipok and Viri Nappes
	Sulitjelma schist sequence - with Sulitjelma Gabbro	Gasak Nappe	Schists with norites	Gicce gneiss	(more or less equivalent to the Rödingsfjäll Nappe)
	Amphibolites	Vasten Nappe	Some amphibolites	Patta greenstones	
Granitic gneiss of basement character	Furulund Group Sjønstå Group Pieske Marble Juron Quartzite	Pieske Nappe	Calcareous schists, etc. of Furulund aspect Rombak Group including the Rombak Marble	Schists Schist complex with Nuolja marble Thin quartzite of conglomeratic aspect	Main Seve-Køli Nappe
	Graphite schists (N.E. Nasafjell) Granitic gneisses of Tysfjord culmination		Granitic gneisses of Tysfjord culmination and Rombak window	Sequence of schists and gneisses with greenstones, marbles and quartzites	
				Psammites on granitic rocks, themselves allochthonous	Middle and Lower Nappes
				Allochthonous low grade rocks or autochthonous	
				Hyolithus series rocks	Autochthon
				Pre-Cambrian autochthon	

thrust units to the granite gneisses of the Norwegian side of the border. Thus while Kulling suggests complete continuity along this tract (the Akkajaure valley) Kautsky (1953) has suggested that this is an imbricate zone in which there are several thrust units of granite, all thin and of relatively small east-west extent so that the mass of granitic gneisses beyond the frontier in Norway is basal and autochthonous.

To Kulling, the Nasafjell granite gneisses are autochthonous while those of Tysfjord are allochthonous. However, the two massifs are built of the same rock types and lie below very similar rock sequences both forming the substructure of the Sulitjelma meta-sedimentary succession. In addition we have discovered an inlier in Krågdal, one third of the way from Nasafjell to the southern end of the Tysfjord massif (fig. 13) with the Sulitjelma sequence above the granitic gneisses. This inlier is in the core of the Vatnfjell antiform (see Part II) and a similar sequence (although not exposing the succession as far down as the granitic gneiss) occurs in the Sjønstådal inlier further north still. Thus there is good direct connection between Nasafjell and Tysfjord which suggests that what is true for the one is true for the other (and also for Rishaugfjell). Similar although less comprehensive arguments can be formed concerning correlation between Tysfjord and Heggmovatn and then the other granite gneiss units further southwest. Thus we have proposed that the substantial granite gneiss areas south and west from Tysfjord (Rishaugfjell, Heggmovatn, Glomfjord, Svartisen and Høgtuva), plus some smaller bodies associated with them, are all basal and autochthonous, in the sense that they are not separated by tectonic discontinuities from the basement to the Caledonian Geosyncline, although the western massifs in particular have suffered comprehensive plastic deformation (Rutland and Nicholson, 1965).

As we have described from the west of Sulitjelma and as described by Foslie (1941) from regions to the north, granitic rocks are exposed in marked domes with tight synforms of sediment around and between them. Such tectonics are not displayed in the Akkajaure region nor on the east side of Nasafjell and it may be that dome tectonics is developed only where the Køli sequence (at Sulitjelma mainly the Sjønstå and Furulund Groups, Part III) is high grade to the base. Such a metamorphic limit more or less corresponds in the Sulitjelma region with the eastern limit of domes. Thus it may be supposed that, where the rise of temperature has increased the ductility the density-controlled advance of the gneisses has been able to take plase. Certainly there is no good evidence that the eastern limit of domes is the limit of occurrence of a widespread highly granitic basement (Vogt, 1941, fig. 2).

Kautsky has suggested (1946, and 1947) that the western granitic rocks of Nordland (then generally regarded as Caledonian intrusives) were derived by melting from an autochthonous Pre-Cambrian basement so that the rocks that in the east had been thrust eastwards were rendered mobile in the west (somewhat similar arguments were published a little earlier by Holtedahl, 1944, p. 13). Although detailed work in the south-west has shown that the suggestion of intrusive character is mistaken, there is considerable truth in the idea of changing reaction of the basal rocks from east to west.

In the east (see for example, Kautsky, 1953, Kulling in Magnusson et al., 1960, Brown and Wells, 1966) a relatively undeformed and unmetamorphosed autochthonous sequence rests with strong unconformity on Pre-Cambrian crystalline basement which has not been Caledonised. This sequence is then overlain by metamorphic nappes. In the west (e.g. Nicholson and Walton, 1963) the basement massifs are Caledonised so that they are structurally concordant with their envelopes of meta-sediment. No penetrative structural or metamorphic characters allow the distinction of an autochthonous cover from allochthonous nappes. In intermediate areas such as the southern end of the Tysfjord massif the basement is not Caledonised, but all the metasediments above the granitic basement have similar metamorphic and structural characters so that the distinction between autochthonous and allochthonous cover (which both may be present) is not readily made.

Stratigraphic correlations

The correlation of most of the schist units is much more dependent upon proven continuity or upon certain knowledge of discontinuity than is the correlation of the granite gneiss massifs but Table 3 gives the successions of various regions in summary form, the sources of the information used, and also indicates our view of the major tectonic correlations.

Hernes (1967, p. 461, also 1966, p. 455) has claimed that a "considerable" part of the Nordland rock sequence is late Pre-Cambrian while Hollingworth et al. (1960) have suggested such an age for only the psammitic basal part of the meta-sedimentary envelope to the granite-gneisses of Glomfjord and other massifs (see also Nicholson and Walton, 1963). To that degree only can we agree with Hernes but as we have written above (p. 70) the rocks of Nordland are not well enough known to justify very firm views on the stratigraphy; where detailed work has been published there is no evidence in favour of the view that extensive parts are late Pre-Cambrian although this could be true of the high-grade region south of Ranafjord which is hardly known as yet.

Table 3 clearly shows the difference between the eastern and western developments. The westward thinning of the eastern allochthonous units explains the presence of the disjunctive Beiarn Nappe in the west on top of a sequence which we have described as conjunctive while in the east it overlies a sequence largely made up of a disjunctive pile of allochthonous sheets.

Although the detailed composition and structure of the western sequence in the Svartisen and Glomfjord areas have been described elsewhere (Nicholson and Walton, 1963, and Holmes, 1966) we summarize their general character here to allow the adequate development of our argument. Thus the metasediments marginal to the Svartisen granite gneisses (about 100 km south-west of Sulitjelma) are made up of a structurally lowest unit rich in sparagmitic psammites together with marbles followed by pelites, calcareous schists and marbles which can be matched in a general way with the sequence around Høgtuva as well as Glomfjord although the thickness varies considerably from place to place. These rocks are overlain by the Beiarn Nappe and while the sequence between granite gneisses and the Nappe has been strongly deformed it does not seem to contain either the structures or the lithological members of the Sulitjelma sequence with which on the broadest structural terms it might be compared.

The Glomfjord granite gneiss massif has a cover similar to that of Svartisen in both lithology and structure. The covering of the Heggmovatn massif is less well known to us than the others but is lithologically similar and similarly does not contain the structural units known in the east. The highest structural unit, the Beiarn nappe, separates these western successions from the successions to the east. The eastern succession falls naturally into two parts, the Fauske Marble Group and the succession below the Fauske Marble, which we have called the Sulitjelma schist sequence.

The Fauske Marble Group, which is so widespread to the east, does not occur immediately to the west of the Beiarn Nappe where it might be expected, viz. between the structurally higher marbles of the Beiarn Nappe and the Heggmovatn granite gneisses and their psammite cover etc. although it may reappear on the west side of the Beiarn Nappe further to the south-west as the Saura Marbles (Rutland and Nicholson, 1965). It is clear also that all the meta-sediments involved lie on top of the granite gneiss so that the Fauske Marble Group cannot be supposed to extend eastwards underneath the gneisses. The Sulitjelma sequence has a thick development east of the Tverstifjell synform but is largely eliminated on Rishaugfjell. The units of this sequence cannot be recognized further west in our section.

Thus accepting that the granite gneisses of Tysfjord and Nasafjell as well as those further west are basal and autochthonous there are a number of allochthonous units in the east which are not represented in the west. The disappearance of the eastern tectonic units need not mean, of course, that there are no stratigraphic equivalents in the west of rocks forming the eastern nappes; and there are some possible correlations both between the eastern nappes themselves and between them and the west (Part III, p. 59, and Table 3).

We have previously suggested (Rutland and Nicholson, 1965) on lithological grounds firstly the stratigraphic correlations of the Fauske Marble Group with the marbles of Gildeskål, Sokumfjell and Saura to the west and possibly with the Pieske Marble to the east and secondly of the Furulund Group with the Bodø Schist Group. These correlations are consistent with the observed structural successions around the Heggmovatn massif and south-east of Sulitjelma but not with the structural succession in the intermediate Fauske area. Thus around the Heggmovatn massif the succession of basement, Meløy Group (sparagmitic), Saura Marble Group, Bodø Schist compares with the south-east Sulitjelma succession of basement, graphite schist, Juron Quartzite (sparagmitic), Pieske Marble, Sjønstå-Furulund Schists.

At the north-west termination of the Nasafjell massif, however, the Pieske Marble forms a thin member of the envelope to the massif and is separated from the structurally higher Fauske Marble Group by the attenuated Sulitjelma succession and the Furulund and Sjønstå Gorups (see Part II, p. 38). Thus in the Fauske region the Fauske Marble lies above the Furulund Schists. If the correlation of the marble groups suggested above is accepted therefore, the Fauske Marble Group and the overlying rocks must represent a tectonic duplication of the succession. Even if the stratigraphic correlation is rejected however, the Fauske Marble Group remains an allochthonous unit since it rests on the allochthonous Sulitjelma schist sequence.

The above discussion leaves open the question of the possible autochthonous character of some of the lithological units of the eastern structural succession. That is to say the recognition that the succession is apparently conjunctive (i.e. preserves the original stratigraphic order) does not demand that the units be autochthonous; stratigraphic sufaces may have been utilized as slides. The psammites of the margin of the Nasafjell granite gneiss (Steenken, 1956, and Part II, p. 27) may be taken as an example. They are similar in character to the "hardskiffer" of the Middle thrusts of Kulling (1964) in the Torneträsk area of Sweden. Gustavson (1966) has suggested that the psammite unit of the neighbouring southern Troms area of Norway is para-autochthonous or allochthonous. Such psammites apparently are largely missing from the basement junction in the west of Gustavson's area; they are represented only thinly, and with breaks, around the Rishaugfjell antiform which lies along the general strike trend from this part of Gustavson's ground, although they form a thin but continuous cover to the Nasafjell massif. Reconnaissance mapping by the authors on the north-east side of Nasafjell has shown that graphitic schists only separate the Juron Quartzite of the Seve-Køli complex from the basement and that the Juron Quartzite is apparently continuous with the other marginal psammites of the Nasafjell massif. Thus the psammites are structurally equivalent to part of the Seve-Køli complex but there is no direct evidence that they are allochthonous. Acceptance of the Kulling analysis however, would suggest that the allochthonous sequence of "Seve" together with the Lower and Middle nappe units have been eliminated. Detailed mapping from Nasafjäll into Sweden might demonstrate the validity of this hypothesis.

Status of the Rödingsfjäll Nappe

Table 3 shows that the upper part of the eastern Caledonides in Southern Norrbotten (that part of Sweden due east of Sulitjelma) is referred by Kulling (1964, p. 138) to an upper Stipok and a lower Viri nappe which are equivalent to a lower Storfjäll and upper Rödingsfjäll nappe in Västerbotten further south in Sweden. The Stipok and Viri nappes of Kulling correspond broadly with Kautsky's Vasten and Gasak nappes (Kulling, 1964, p. 165). As we have described in Part III we do not distinguish a tectonic unit equivalent to the Vasten nappe but suggest that there is one major thrust level between the Furulund etc. below and the Sulitjelma schist sequence above. We have correlated this upper tectonic unit (which corresponds with Kautsky's Gasak nappe) with the Rödingsfjäll Nappe as originally defined by Kulling (1956) broadly following Strand (1961) in this matter.

In our earlier work (Rutland and Nicholson, 1965, p. 102) in addition to describing the rocks west of Fauske, we attempted also to fit the major nappe structure there to the generally accepted scheme of structural correlation for the whole of the Scandinavian Caledonides (Strand, 1961). In that account we proposed that the Beiarn Nappe was to be correlated with the Rödingsfjäll Nappe, the former being an outlier of the latter between the Heggmovatn and Glomfjord culmination (a view with which Strand disagreed, Rutland and Nicholson, 1965, p. 108). The two nappes appeared to contain similar rock units; they lie in similar disjunctive positions at the top of their respective structural successions; and the published maps of the intervening ground seemed to allow their forming part of a once continuous unit.

In the section now under review however, the Gasak nappe, which has also been correlated with the Rödingsfjäll Nappe, dips westward under the Fauske marbles, which in turn dip under the Beiarn Nappe. It is probable therefore that the Beiarn nappe-complex is a separate and higher structural unit than the Gasak-Rödingsfjäll Nappe Complex. The Beiarn and Gasak (or Rödingsfjäll) Nappes could only be regarded as originally part of a single nappe complex if a subsequent thrust or isoclinal fold is invoked to explain their present structural separation. There is no evidence of such structures and, as noted above, the Gasak-Rödingsfjäll unit, like the lower tectonic units in the east, apparently thins beyond recognition onto the conjunctive and pseudo-autochthonous cover of the Heggmovatn more western massifs. The fact remains however that the Beiarn and Gasak Nappes are of similar character and lie disjunctively above similar successions for as noted above the Saura Marbles and Bodø Schists in the west could be the correlatives of the Pieske Marble and Furulund Schist in the east.

It may therefore, that different tectonic units contain similar stratigraphic successions, a suggestion already made by Kautsky (1953). In elaboration of this point it may be noted that the Beiarn Nappe has been divided into a group of meta-sediments above and a group of gneisses below (Rutland and Nicholson, 1965). These units might be broadly comparable stratigraphically (but not structurally) with the Køli and Seve divisions of the Seve-Køli Nappe Complex.

We have shown above (p. 37 and p. 65) that the Sulitjelma schist sequence and the Fauske Marble Group to some extent behave independently but for simplicity however, and with acknowledgment that further work may necessitate modification, we will use the term Rödingsfjäll Nappe for all rocks between the Beiarn Nappe above and the Gasak thrust of Kautsky below. In eastern Nordland Strand (1961) has described two tectonic units of major scale (an eastern and generally low grade one below a western high grade one) and has correlated their junction with the Rödingsfjäll Nappe base. The lower grade rocks beneath belong to the Køli unit of Swedish geologists (which contains the Furulund and Sjønstå Groups of Sulitjelma). The correlation seems very reasonable on the evidence available but there too perhaps the Rödingsfjäll Nappe is surmounted by other major tectonic units as in the ground west of Sulitjelma.

Detailed work on the rocks of the Rödingsfjäll Nappe near the type area seems to have demonstrated a sequence of development not unlike that described by us in Part III from Sulitjelma although as the results have been described only in abstract as yet detailed comparisons cannot be made (Ramberg, 1965, p. 154). Ramberg does distinguish a major tectonic unit south of Nasafjäll above the Rödingsfjäll Nappe and it is just possible that this upper and western unit corresponds to our Beiarn Nappe which would thus have a wide occurrence in southern Nordland south of the main area of granite gneiss massifs (Heggmovatn to Høgtuva).

Conclusions on spatial relationships

While it is easy to see that there are differences of structural sequence above the granite gneisses from east to west it is difficult to decide whether any rocks found in the east except the granite gneisses and the sparagmitic psammites are represented in the west. Some structural and stratigraphic correlations have been offered above.

In Sweden the Seve-Køli nappe complex shows higher grade metamorphism and more plastic deformation than the underlying low grade fracture cleaved autochthonous sediments of Hyolithus type (e.g. Kautsky, 1953, p. 151). In extrapolating into Norway it has consequently been assumed that all the nappes have been translated across a basement retaining an autochthonous cover so that the root zones of all the nappes must be far to the west.

At first sight the present work may seem to give some support to this view for the basement culminations are characteristically overlain by a sparagmitic succession which appears to be conjunctive and could be essentially autochthonous though there may have been major relative translations of stratigraphic units without disturbing the overall succession. Therefore it is described below as pseudo-autochthonous.

The most notable facts which emerge from our own and other studies however, are that the major tectonic units are thick and demonstrably disjunctive on their eastern edges, but that they thin westwards so that they become indistinguishable from the conjunctive and possibly autochthonous cover of the western basement massifs. The disjunctive character of the leading edges is often emphasized by the presence of sole rocks which must be interpreted as slices of Archean basement. Thus, even in the absence of fossil evidence, there is no doubt that large scale repetitions of the stratigraphy do occur. Westwards however, such evidence is lost and although deformation is intense the broad stratigraphic relations appear to be original.

In summary, the evidence of Swedish workers shows that the Seve-Køli complex is thick in Sweden, where it contains on its eastern edge high grade metamorphic rocks (which may be Archean) and these overlie lower grade rocks of the Middle Caledonian Bedrock Nappes of Kulling. Westwards in the north Nasafjell area we have found that the Pieske Limestone and Juron Quartzite of the Køli sequence lie close to the Archean basement and there is no evidence of disjunctive character. Westwards again the Seve-Køli Nappe is a structurally indistinguishable part of the conjunctive cover of the Rishaugfjell massif.

The upper part of the Sulitjelma succession (the Gasak Nappe of Kautsky) is thick and disjunctive at Sulitjelma. It thins abruptly westwards where it passes under the Fauske Marble Group. The Fauske Marble Group in turn passes under the Beiarn Nappe but seems to be represented stratigraphically in the Heggmovatn culmination as part of the conjunctive cover (the Saura Marble Group). The attenuated portions of the Gasak (Rödingsfjäll) Nappe may thus be indistinguishable from the conjunctive cover of Heggmovatn massif.

It therefore seems possible that the original site of deposition of the Seve-Køli nappes was in Nordland and not further west. The local occurrences of Archean and sparagmitic rocks on the sole of the nappe complex could be derived from local stripping of the Archean basement as is known to occur for example on the Rishaugfjell massif. In general however, the principal movement horizon appears to have been above the basement and its immediate cover.

The Gasak (Rödingsfjäll) Nappe has clearly been derived from further west than the Seve-Køli but it appears that the stratigraphic units which originally lay above the Heggmovatn massif can have contributed to it. The main part of the nappe may be derived from further west still however, as is clearly the case for the Beiarn Nappe.

This interpretation does not depend on the correlation of the marble groups within the three main nappe complexes but it gains strength from that correlation and provides reciprocal support for it. The main nappe complexes display great internal complexity with isoclinal folding but on the largest scale they appear to contain the major stratigraphic units in their correct order. The genesis on the largest scale can be described as a plastic imbrication which was accompanied by great internal strain of the thrust units. The section of fig. 15 shows the situation clearly.

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Finally we must record that this work grew from the late Professor Hollingworth's project in the Glomfjord region. We are very sorry that he did not live to share our interest in the relationships now obvious between those western rocks and the relatively well-known sequences of Sulitjelma and adjacent Sweden.

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Abbreviations:
NGU = Norges Geologiske Undersøkelse
NGT = Norsk Geologisk Tidsskrift
GFF = Geologiska Föreningens Forhandlingar
SGU = Sveriges Geologiska Undersökning.

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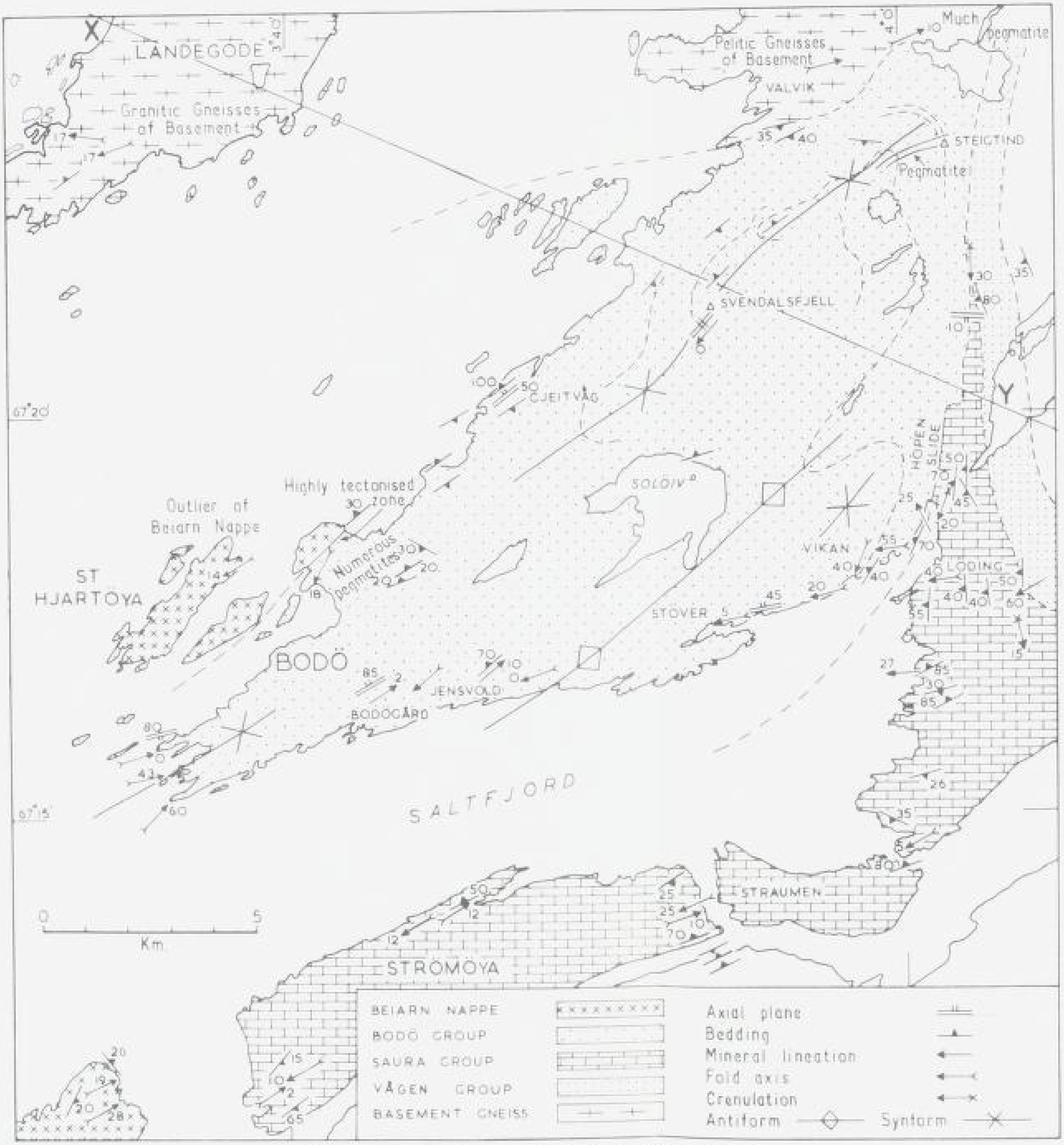

Fig. 2. Structural sketch-map of the Steigtind Synform.

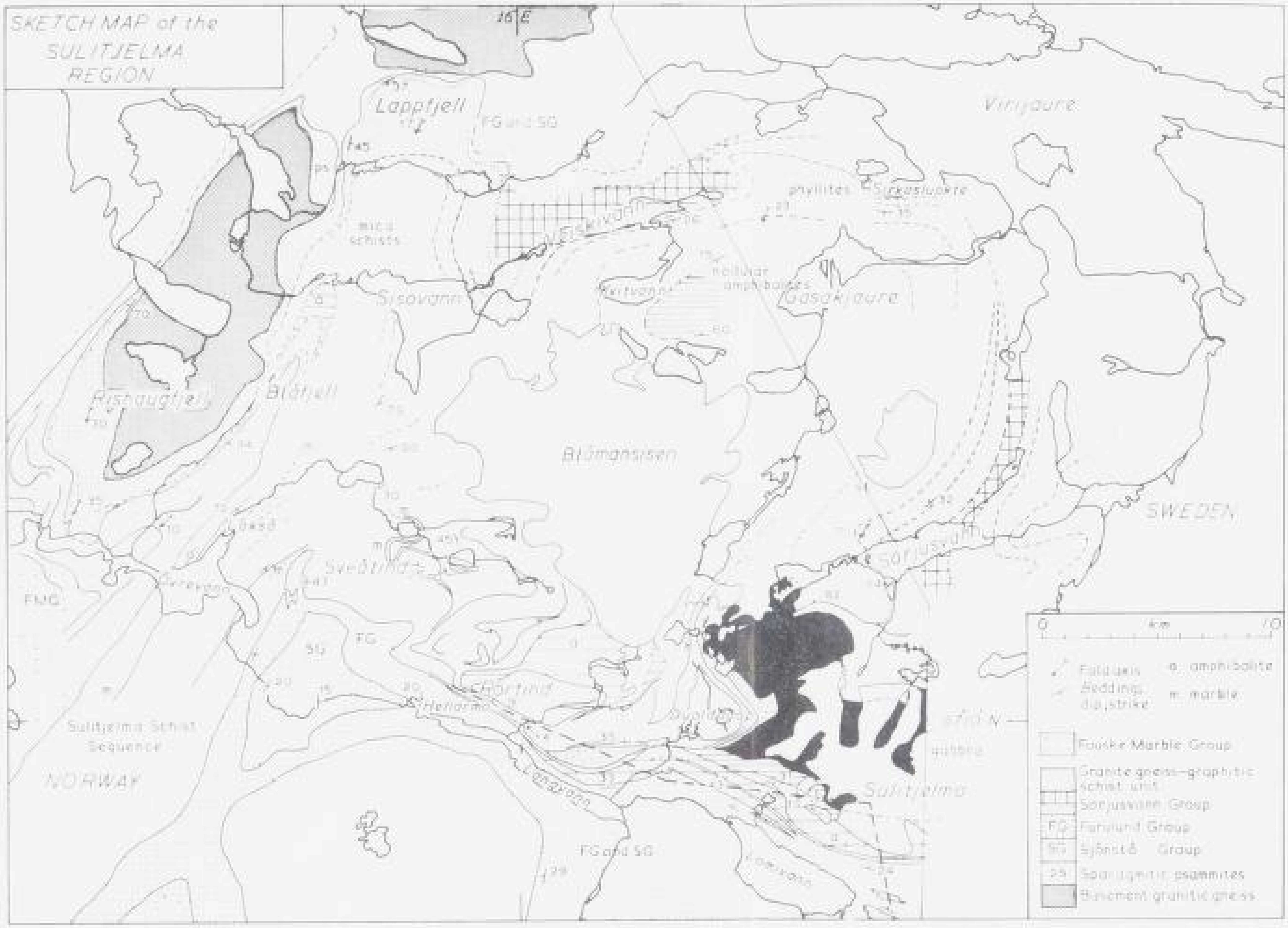

Fig. 10. Sketch map of the Sulitjelma region. Heavy dashed line shows position of section fig. 11. (The mountain Røtind is incorrectly labelled. R ø r t i n d). Information on Duoldagop from Sjögren (1900b) and on the Sulitjelma gabbro from Mason (1967).

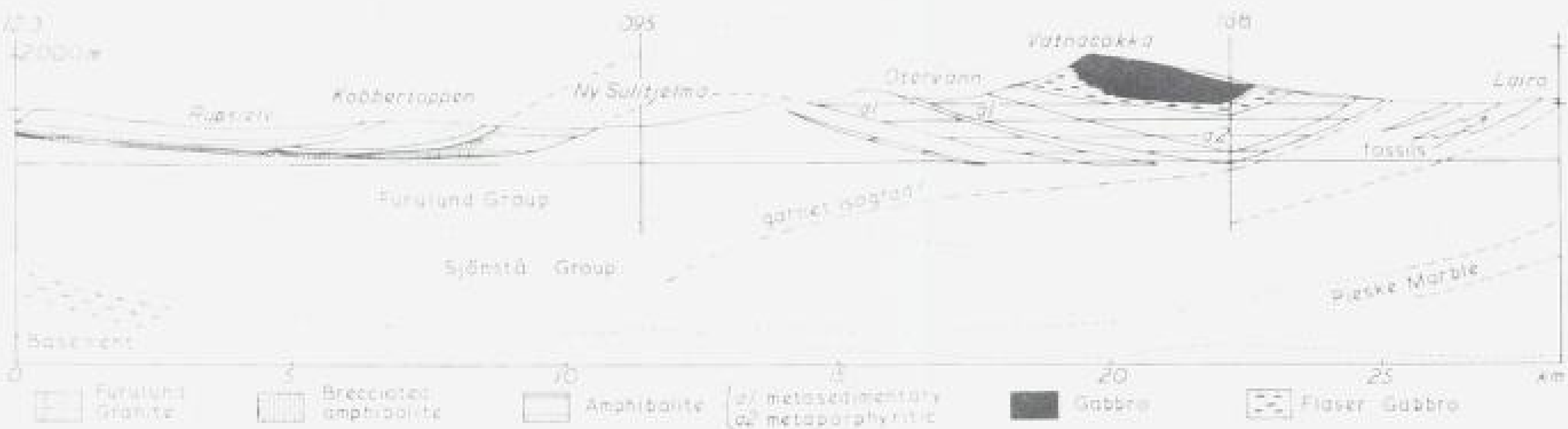

Fig. 11. Cross-section of Hellarmo-Lairo region (fits directly on to fig. 7).

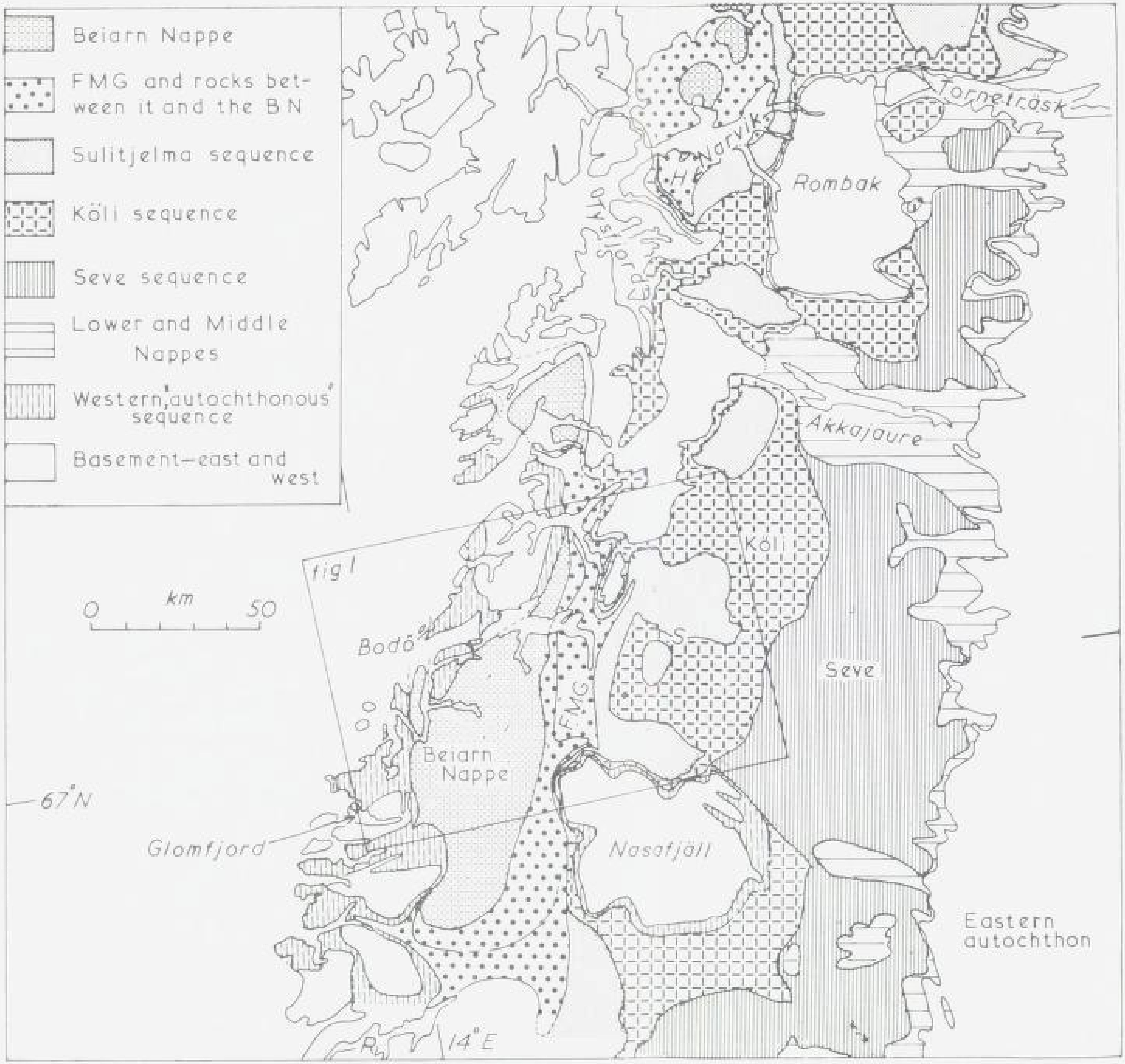

Fig. 17. Map of the Rana-Narvik region showing suggested lateral continuity of structural-lithological units. Information from various sources but principally the SGU for Sweden (G. Kautsky and Kulling), and the NGU (Gustavson and Foslie) and Steenken and our own work for Norway. The Seve sequence is defined as broadly that below the level of the Pieske Marble and its proposed equivalents (e.g. the Nuolja Marble) and above the Middle thrust units, and the Køli as that above the marble level but beneath the rocks of the Sulitjelma schist sequence (or their supposed lateral equivalents). This separation seems to fit Kulling's regional map (fig. 1, p. 152, in Magnusson et al. 1960) in southern Norrbotten but not in northern Norrbotten. The Seve/Køli distinction is not a simple or, perhaps, always a desirable one although it has its use here.

Fig. 15. Section, Bodø—Sulitjelma; position indicated on fig. 13.

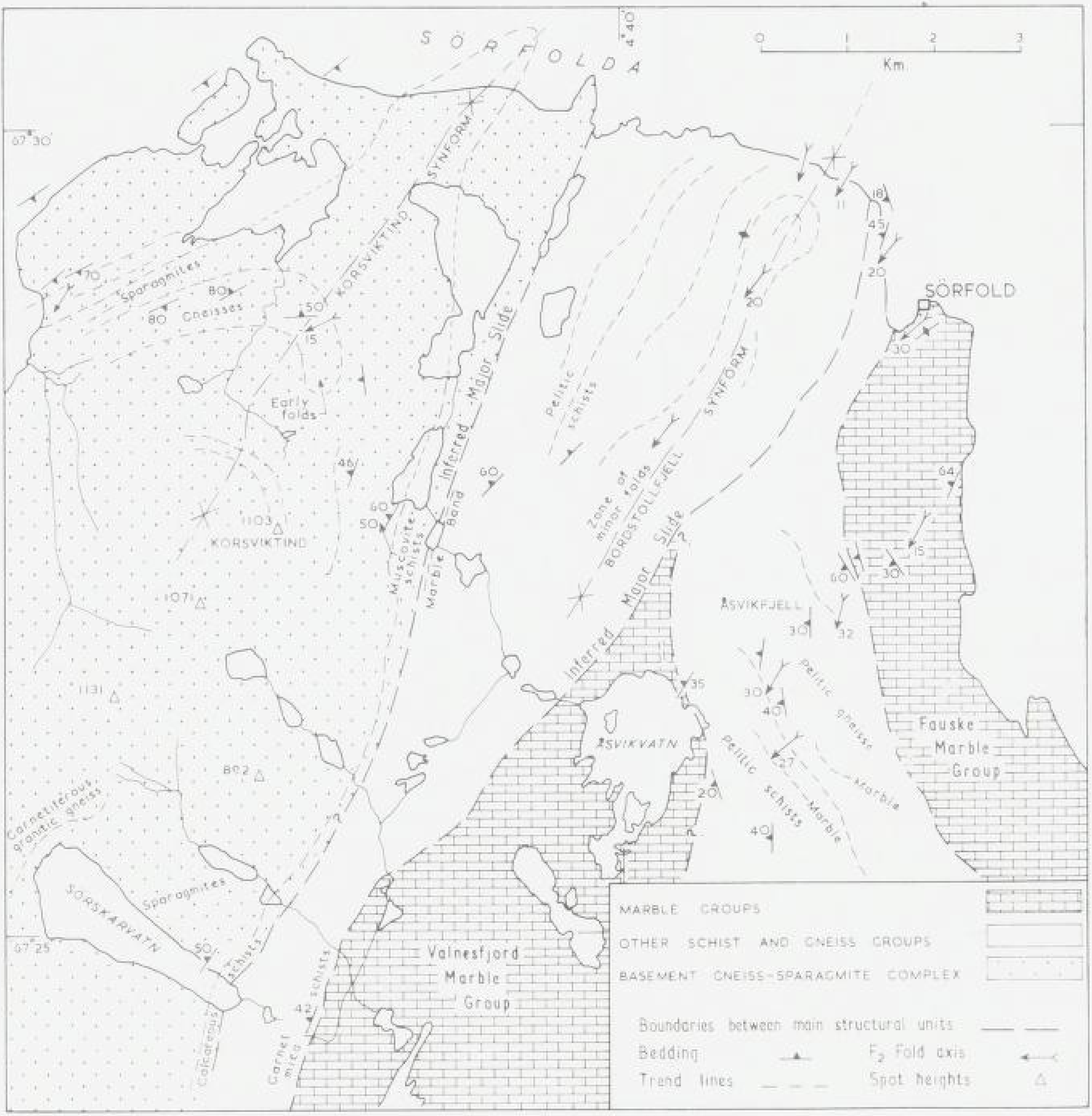

Fig. 4. Structural sketch-map of the Sørfjord area.

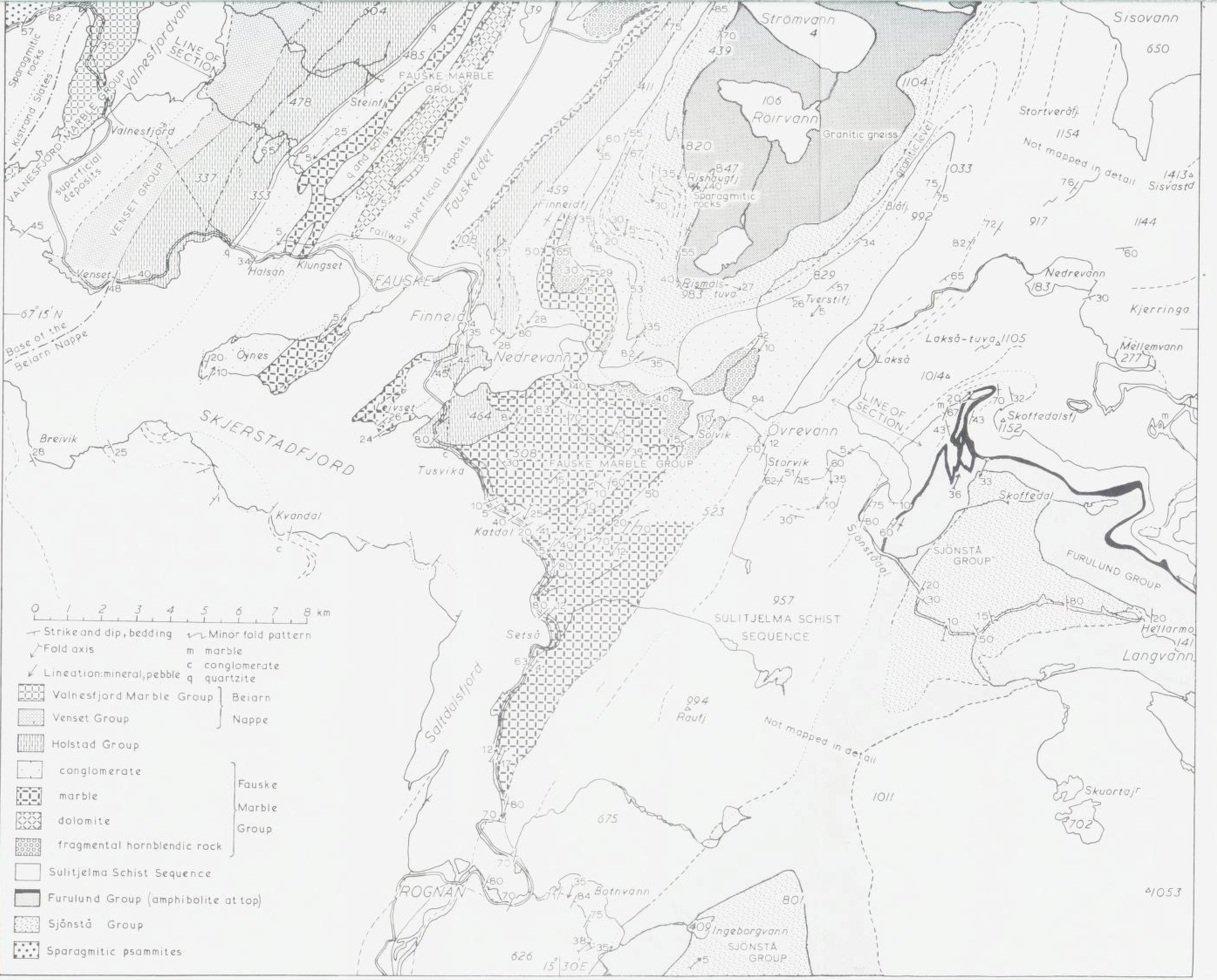

Fig. 6. Geological map of the region between Valnesfjordvann and Hellarmo. Information on western parts of the Fauske Marble from M. R. Bradshaw, University of Bristol.