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Sammendrag

Undersökelser med tanke på å bevise Kautsky 's skyvedekketeori Sulitjelmafeltet. Alt arbeide utfört i Nordgruvefeltet og viser at de to nederste enhetene - Furulund skifrene og Sulitjelma amfibolittene - ikke er skilt med et skyveplan. De består av en kontinuerlig serie av metasedimenter og -vulkanitter. Breksjering i amfibolittene er ikke entydig relatert til overskyving. Viktigste bevis for skyvedekketeorien er metamorfe skilnader mellom enhetene. Inverterte metamorfe isograder i de lavere enhetene kan forklares ved overskyving av varme bergarter. Geologi. Kartlegging.

AN INVESTIGATION OF SUPPOSED NAPPE STRUCTURE ON THE NORTH SIDE OF LANGVANN, SULITJELMA, NORTH NORWAY.

Thesis presented for the degree of Ph.D.
at the Victoria University of Manchester
by M.R.Wilson.

Department of Geology
July 1968

Present Address :-
Department of Geology and Mineralogy,
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Since obtaining my first degree at the University of Manchester in June, 1965, I have been engaged in research work in the Department of Geology at the University of Manchester. Results and conclusions obtained during the course of this work are presented in this thesis. No portion of this work has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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ABSTRACT

Since the work of Törnebohm in the 1880s it has generally been accepted that thrusting has played a major part in the structural development of the Scandinavian Caledonides. In 1953 Kautsky correlated the succession in Sulitjelma (Nordland, North Norway) with three major nappes mapped by him in adjacent parts of Sweden. In this thesis the evidence concerning the possibility of thrusting in part of Sulitjelma is examined.

An area of 40 sq.Km. has been mapped in detail noting the characteristics of the two horizons which Kautsky postulated to be thrusts and comparing the structural history of the adjacent units. The work has confirmed Mason's observation that the lower two units are not separated by a thrust but consist of one series of meta-sediments and meta-volcanics. Study of the second postulated thrust horizon has not revealed any special features such as mylonites or strong lineation fabrics as might be found in a thrust zone. There is unusual brecciation in one unit, but it is not readily related to thrusting. Investigation of the structural history of each unit, relating different phases of deformation to mineral growth and igneous intrusion has suggested that one unit has had a longer history than the others, though this is not necessarily proof of thrusting. The strongest arguments in favour of thrusting concern metamorphic differences between the units. The metamorphic isograds within the lower units are apparently inverted, a fact which can be explained by over-thrusting of relatively hot rock. East of the thesis area high-grade rocks overly low grade rocks.

While thrusting has not been proved, several features are best explained by a thrust hypothesis.

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CHAPTER 1

GENERAL INTRODUCTION

1.1 The project

The project is entirely based on field-work, being the description of the structural geology of a 40 sq.km. area of metamorphic rocks in the Norwegian Caledonides. The work is part of a larger project in the Sulitjelma area in which the senior investigator is Dr. R.Nicholson. This has grown from the project initiated by Professor S.E.Hollingworth in 1953 in the Glomfjord region, some 75 km. west of Sulitjelma, an earlier extension of which was described by Rutland and Nicholson (1965).

Sulitjelma is well known for its important copper mines, and the mine concession area was initially mapped by Hjalmar Sjögren at the turn of the century. The area is the subject of the classic N.G.U. memoir "Sulitelmafeltets Geologi og Petrografi ", 1927, by Thorolf Vogt. The structural importance of the Sulitjelma area lies in its critical position near the eastern edge of the Caledonian orogenic belt where metamorphic and structural characteristics change rapidly from Norway towards the eastern tract in Sweden. Thus rocks in the village of Sulitjelma are of high metamorphic grade and contain kyanite, while some 15 km. east rocks at the same structural and stratigraphic level contain fossils, and are of low grade. To the east side of Sulitjelma and in Sweden, Gunnar Kautsky (1953) has described a sequence of post-metamorphic nappes which have been thrust eastwards, and has correlated three of them with lithological units in the Sulitjelma area. Until recently the nappe hypothesis was rejected by Norwegian workers, but now it has some broad acceptance, although for the most part the region is poorly known.

Modern work on the area, apart from studies of the copper deposits sponsored by the Sulitjelma mining company, has been by Dr Robin Nicholson, Mr Keith Henley, and Dr Roger Mason. Henley has investigated an area mainly south of the lake Langvann, describing the structures and, particularly, the chemistry and mineralogy of the metamorphic rocks. Mason has described the Sulitjelma gabbro complex, which lies immediately east of the thesis area and his work there continues. Nicholson has provided a correlation with the known succession to the west and is now working to the north of the area. Nicholson's work has demonstrated extreme thinning of the Sulitjelma rocks to the west. Neither the nappes, nor the supposed thrusts between them can be traced as far west as previously thought.

The present study, designed to complement the above work, has concentrated on a small area containing the two horizons which Kautsky described as tectonic contacts betweennappes. The detailed nature of these levels has been examined, and the structural history of the adjacent rock units compared, as an examination of Kautsky's nappe hypothesis.

1.2 Position of the Area

The Sulitjelma area lies astride the Norwegian-Swedish border within the Arctic Circle, (fig.2.1). It is known for the Sulitjelma mountains, the highest of which, Suliskongen (1914m.), is the highest mountain in mainland Norway north of Trondheim, but the area is particularly famed for the copper mines, centred around the lake Langvann (67°10' N., 16°5' E.). The area described in this thesis lies north of this lake and the Norwegian topographic maps at 1:100,000 of Saltdal (L13) and Sulitjelma (M13) cover parts of it.

1.3 Topography

Fig. 1.1 is a topographic map of part of Sulitjelma, with the thesis

FIG. 1.2 VIEW WEST FROM SULITJELMA TO BODÖ

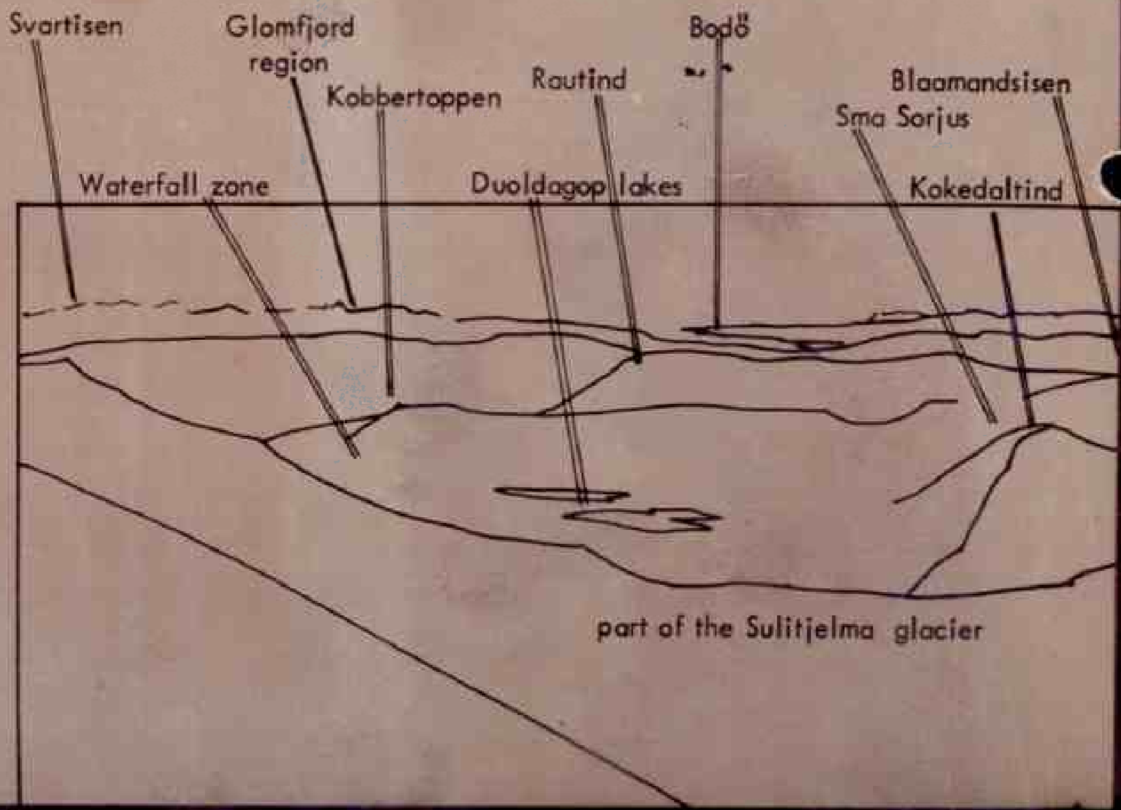


FIG. 1.3 THE NORTHERN SHORE OF LANGVANN (EAST FROM GRONLI), VIEWED FROM FURUHAUGEN

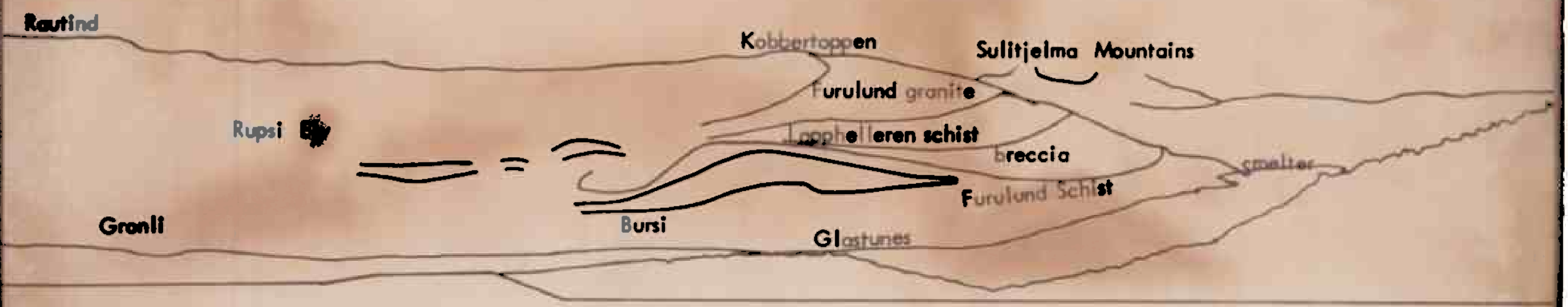
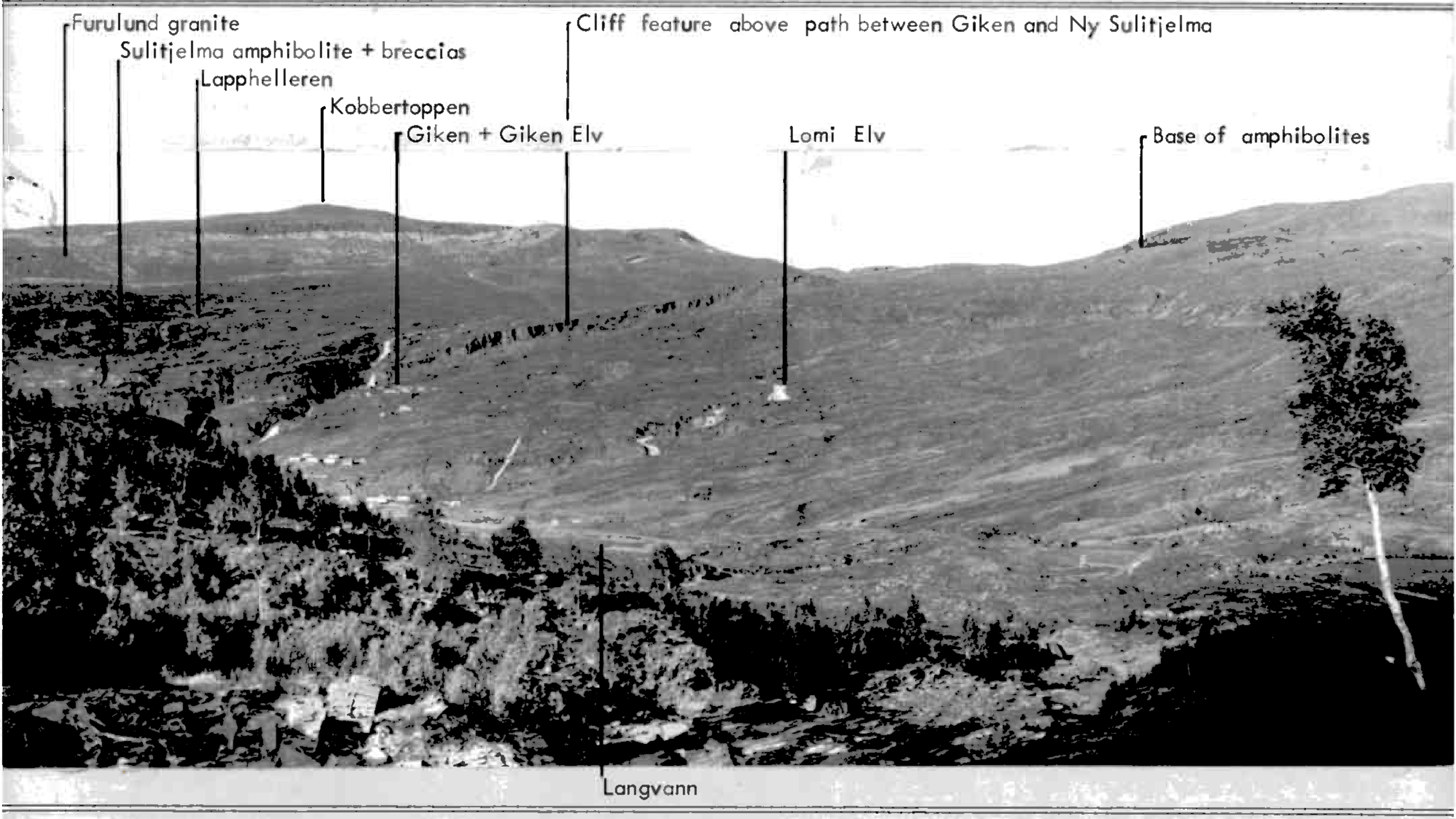


FIG. 1.6 THE SOUTH-EAST PART OF THE THESIS AREA - VIEW NORTH FROM BALMI ELV



area indicated. The northern part of the area covered by the map comprises two large basins at about 800m. height, draining south-west, separated by a north-south ridge reaching 1160m. (Fig. 1.2). At the southern end of this ridge is an east-west ridge, the highest point of which, Kobbertoppen, reaches 1012m. The westerly basin, drained by Rupsi Elv is bounded to the west by Rautind, and to the north by the large icecap Blaamandsisen. The easterly basin, Duoldagop, is drained by Giken Elv and is bounded to the east and north-east by the Sulitjelma mountains, particularly Vardetoppen (1722m) and Sorjustcokka (1702m.). To the north lies a series of lakes at near 1,000m. known as Sma-sorjus. The centre of Duoldagop contains two large lakes.

South of these basins the dominant feature is a long narrow steep-sided valley running WNW-ESE, in the bottom of which is the lake Langvann, (141m.), Fig. 1.3 . Relative to this the westerly basin is a hanging valley, and Rupsi Elv cascades down the steep valley side in a series of spectacular waterfalls, (Fig. 1.3). Giken Elv does not flow directly into Langvann on leaving Duoldagop, but first drops into a short secondary valley at about 550m. height running ENE-WSW, Fig 1.5 . The head of the valley is very steep and there is a large waterfall which has cut back along a fault to form a gorge. The area around the head of this waterfall is referred to in this thesis as the " Waterfall zone ", (Map 4). This secondary valley is a hanging valley relative to the main valley; Giken Elv descends rapidly to Langvann over a series of waterfalls, as shown in Fig. 1.6, a view north across Langvann from Balmi Elv.

A second lake, Lomivann (719m.), larger than Langvann lies to the east of the thesis area. It is joined to Langvann by Lomi Elv, which forms the southern boundary to the eastern part of the thesis area.

South-west of Langvann lies a plateau at 800m.-900m. known as Baldaoive. To the south of the eastern end of Langvann is a relatively broad valley drained by Balmi Elv, Fig. 1.6. This river does not drop quite so steeply into Langvann as do the rivers on the north side.

Fig. 1.4 View west over Giken. In the distance can be seen the lake Langvann and the church. The prominent white rock on the hillside above Giken is the lower part of the Tectonic Breccias.

Fig. 1.5 View north over Ny Sulitjelma. In the distance can be seen Giken Elv. In the cliff feature rising east of Ny Sulitjelma the lowest rocks are Furulund Schist, the highest, amphibolite.

It is quite clear that glaciation has had a considerable effect on the area. The cross section of Langvann, and the hanging valleys are all glacial erosion features. Large surfaces of rock are glacially smoothed and scratched; some of the surfaces of the Furulund Granite still bear a very fine polish. Deposits of moraine and other glacial and fluvial materials are common.

1.4 Settlements and Communications.

Sulitjelma is a village some 6km. long and less than 100m. wide strung along the road and railway which run by the shore (fig. 1.3). The total population is about 2,500 and is entirely dependant on the copper mines for employment. The copper is mined from a number of localities north and south of the lake and settlements originally grew up at each mine. In recent years it has been the policy of the mine company to concentrate housing and facilities along the north shore of Langvann, the outlying mines being connected to the main settlement by tunnels.

The railway connects Sulitjelma to Fauske, which is on the main line to Trondheim. The road in Sulitjelma is at present only a local one within the village, and linking it with the outlying mines.

Two particular settlements north of the village are Giken (fig.1.4) part-way up the hill behind Sulitjelma, and Ny Sulitjelma (fig. 1.5) which lies on one side of the small valley containing Giken Elv. Ny Sulitjelma was abandoned in 1965 but has been used for accomodation during the field-work. It is linked by footpath to Giken, from where there is a road to the village. From Ny Sulitjelma a cairned path leads into Duoldagop, where it divides, one path crossing Duoldagop between the lakes, the other skirting its eastern limit. These both cross into Sweden and are much used. A third path leaves the Giken.- Ny Sulitjelma path leading to Lomivann and on to Sweden.

1.5 Vegetation and Standard of Exposure.

Up to 500m. the ground is usually covered with small birch trees etc. the larger trees having been used in the old smelter. In the west of the region the vegetation is thick enough to hinder work considerably but in the east the sulphurous smoke from the copper smelter has killed off all but the hardiest plants. Between 500 and 1,000m. the soil is covered with typical upland plants - grass and heathers, and above 1,000m. there is virtually no vegetation at all except mosses.

Exposure in the lower ground where it is not covered by birch scrub is good, but far from continuous (Fig. 1.3). In the central part of the area above the Church and the mine office the combination of steep hillside and heavy vegetation makes mapping extremely difficult.

Fig. 1.4 illustrates the typical standard of exposure around Giken and Fig. 1.5 the same for Ny Sulitjelma. Large patches of moraine can be present on higher ground and in Douldagop much of the central area is extremely badly exposed. On the highest ground, on the other hand, it is possible to follow rocks without a break for considerable distances.

In the early part of the season snow cover hindered work on the highest ground, but by August Douldagop was fairly clear of snow. Fig. 1.2 was taken in mid August 1965, a bad year for snow. The climate allows a good three months in the field.

1.6 Method of Work.

Three field seasons totalling 23 weeks were spent in the field. The area was mapped using Kodatrace overlays on aerial photographs, the photographs being supplied by Widerøes Flyveselskap A/s., Oslo. During the first season photographs at 1:15,000 were used, this being the standard scale for that run, but more space was needed to plot data onto the photographs directly so for the subsequent work enlargements of the photographs at 1:7,000 were obtained from Widerøes. The central and northern parts of Douldagop were mapped using 1:15,000 scale photographs.

The map of Sjögren (1900) indicates very well the broad distribution of lithologies over the area and the map of Carlson at 1:5,000, a private map belonging to the mine company gives details in the zone of copper mineralisation, an important area in this study. Sjögren's and Carlson's maps, however, contain no structural information, not even dips and strikes, and a complete structural mapping was necessary. The method employed was first to examine traverses across all the lithological units and then to map the contacts between them. Three particularly critical areas were then selected and mapped thoroughly, every outcrop being visited. Finally the remaining areas were covered to investigate the structures of the rock units as a whole. The main part of Duoldagop was only examined in some detail in the last field season, since it had until then been reserved for a Norwegian student.

Topographic maps at 1:10,000 (parts at 1:5,000) were constructed from the aerial photgraphs using the slotted template method on equipment at Salford University. The ground control for this was taken from the 1,100,000 Norwegian topographic map. These topographic maps are the basis for the geological maps accompanying this thesis.

On the 1:10,000 geological map - Map 1, are marked all the schistosity and lineation measurements, except where the density of observation was too high. Representative fold axes are also marked. The colour patches approximate to the areas examined in detail, the size of the outcrops being slightly exaggerated. The colour does not indicate all outcrops. Where contacts were seen, or there was very good evidence for their location they are marked with a solid line, and where inferred with a dashed line. Within the Furulund Schist, occasional dashed lines indicate particular levels which could be followed for short distances. The finished map indicates the density of observations and the reliability of contacts.

CHAPTER 2

THE REGIONAL CONTEXT

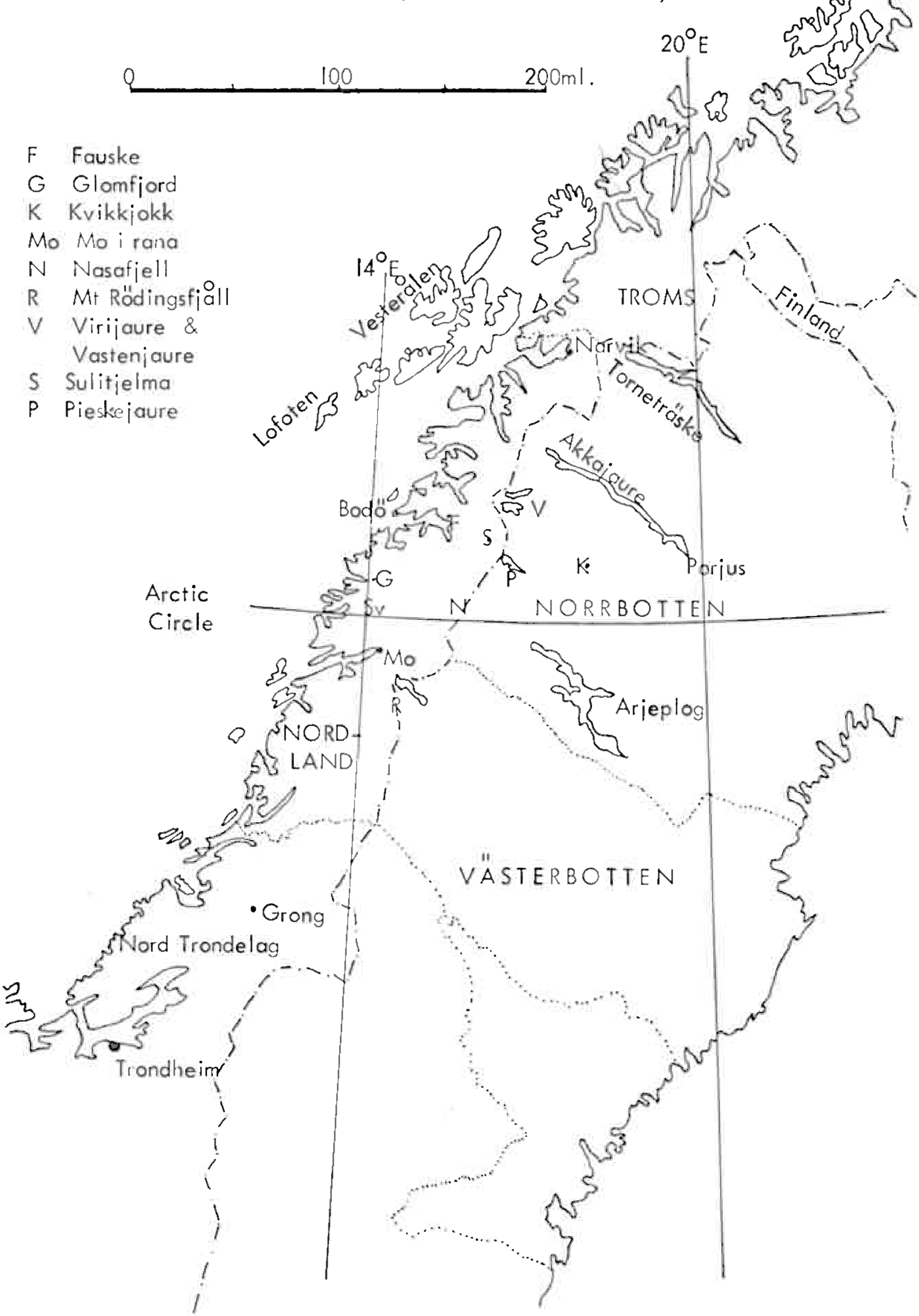
2.1 Origin of the nappe hypothesis in Scandinavia.

The dominant feature of the eastern margin of the Scandinavian Caledonides is the presence of metamorphic rocks overlying fossiliferous Cambro-Silurian sediments. This feature has become known as the Scandinavian " mountain problem ". A.E.Törnebohm in 1888 and more fully in 1896 suggested that the overlying metamorphics were of Pre-Cambrian age and had been thrust into their present position. This was not accepted without opposition as is summarised by Holtedahl (1920). Firstly there were workers such as Brögger (1893) who supposed the metamorphism of the overlying rocks to be contact metamorphism, no tectonic contact being present, and secondly there was much discussion as to the actual age of the overthrust rocks. Clearly some of the lower nappes could be correlated with the 'sparagmites', a thick series of feldspathic sandstones of Eocambrian age. Many early workers were on the other hand convinced that some if not all the metasediments were of Cambro-Silurian age. It is now known that both Eocambrian and Cambro-Silurian sediments are present, but the problem of the age of sedimentation and deformation is still debated, as in the discussion following the account of Rutland and Nicholson(1965, page 106), and as in Sturt et. al.(1967).

2.2 The adjacent regions of Sweden.

The Swedish part of the Sulitjelma region lies within the county or "län " of Norrbotten, Fig. 2.1 . Kautsky, working between 1945 and 1947, mapped the part of Norrbotten which lies adjacent to the frontier between Swedish Sulitjelma and the lake Akkajaure, an area some 80Km by 30 Km.

FIG. 2.1 Northern Sweden and parts of Northern Norway



The whole of Norrbotten is at present being mapped by Kulling, who has already mapped Västerbotten, the county south of Norbotten, (Fig. 2.1). Accounts for Västerbotten and North Norrbotten are already published, (1955 and 1964, respectively), and there is in addition an introductory account of the two counties, (1960).

Kulling (1964) divides the Caledonides of Västerbotten and Norbotten into four tectonic units which overlie the Archæan basement and its autochthonous ("hyolithus zone") sediments, (Fig. 2.2). These four tectonic units he terms the Lower, Middle, Upper and Uppermost thrust rocks. The Lower and Middle units are exposed as narrow zones some 50Km. to the east of the Norwegian-Swedish border. They are sparagmitic in character and the Middle unit, the Stalon nappe complex, is of higher metamorphic grade than the Lower unit, the Blaik complex. The Upper thrust rocks form the Seve-koli complex and occupy a wide area in Sweden and Norway. The Seve-koli complex and the Stalon complex together form the Large Seve nappe of Tornebohm. On top of the Seve-koli rocks in Vasterbotten lies the Uppermost thrust unit, the Rödingsfjåll nappe. In 1955 Kulling suggested that the "Rödingsfjåll nappe has its main extension in Norway and it comprises there most probably the coast area with its abundant salic Caledonian intrusive rocks extending from Nord Trondelag in the south to Vestfjorden in the north" (pg. 290). As will be mentioned below, recent work between Bodo and Sulitjelma shows that the probable structural equivalents of rocks of the Rödingsfjåll nappe thin to nothing when traced to the west, and lie very close to the basement granites of Rishaugfjall and Nasafjall (Fig. 2.5).

2.3 Kautsky's work in Swedish Sulitjelma.

Kautsky published a full account of his work in 1953, but several

FIG. 2.2 MAIN TECTONIC UNITS (from Nicholson & Rutland)

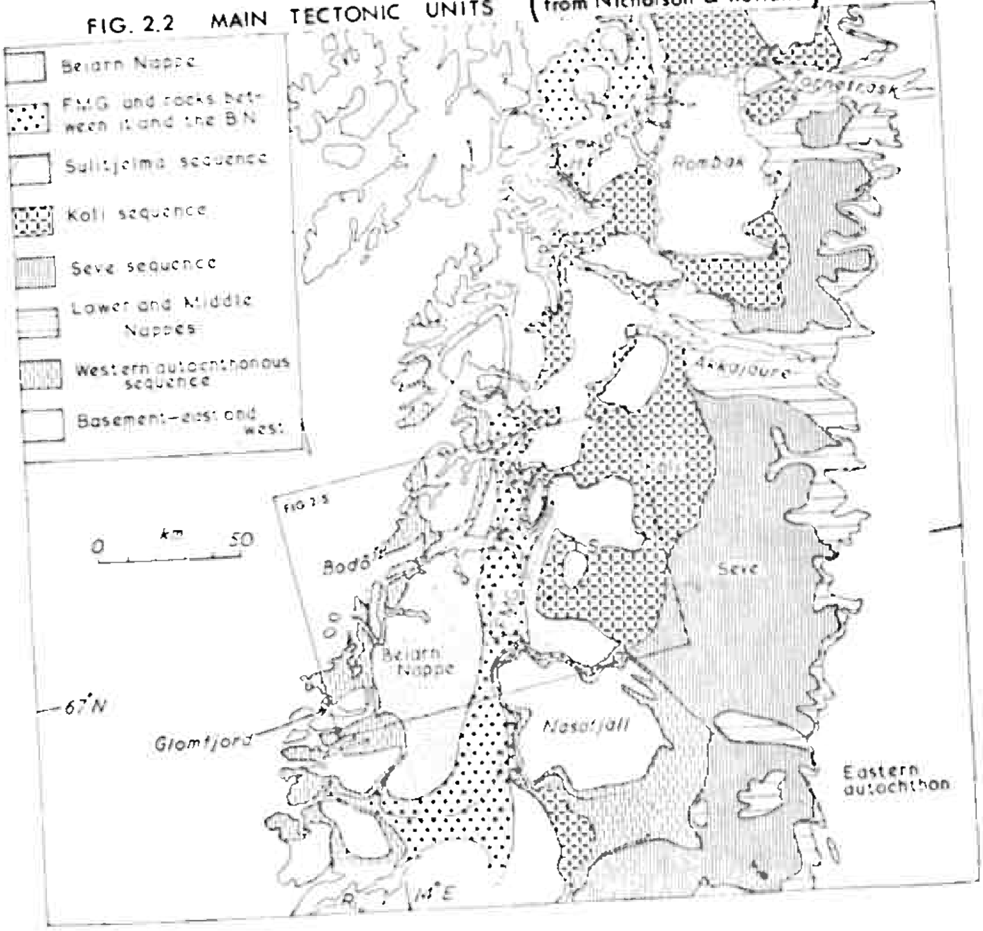
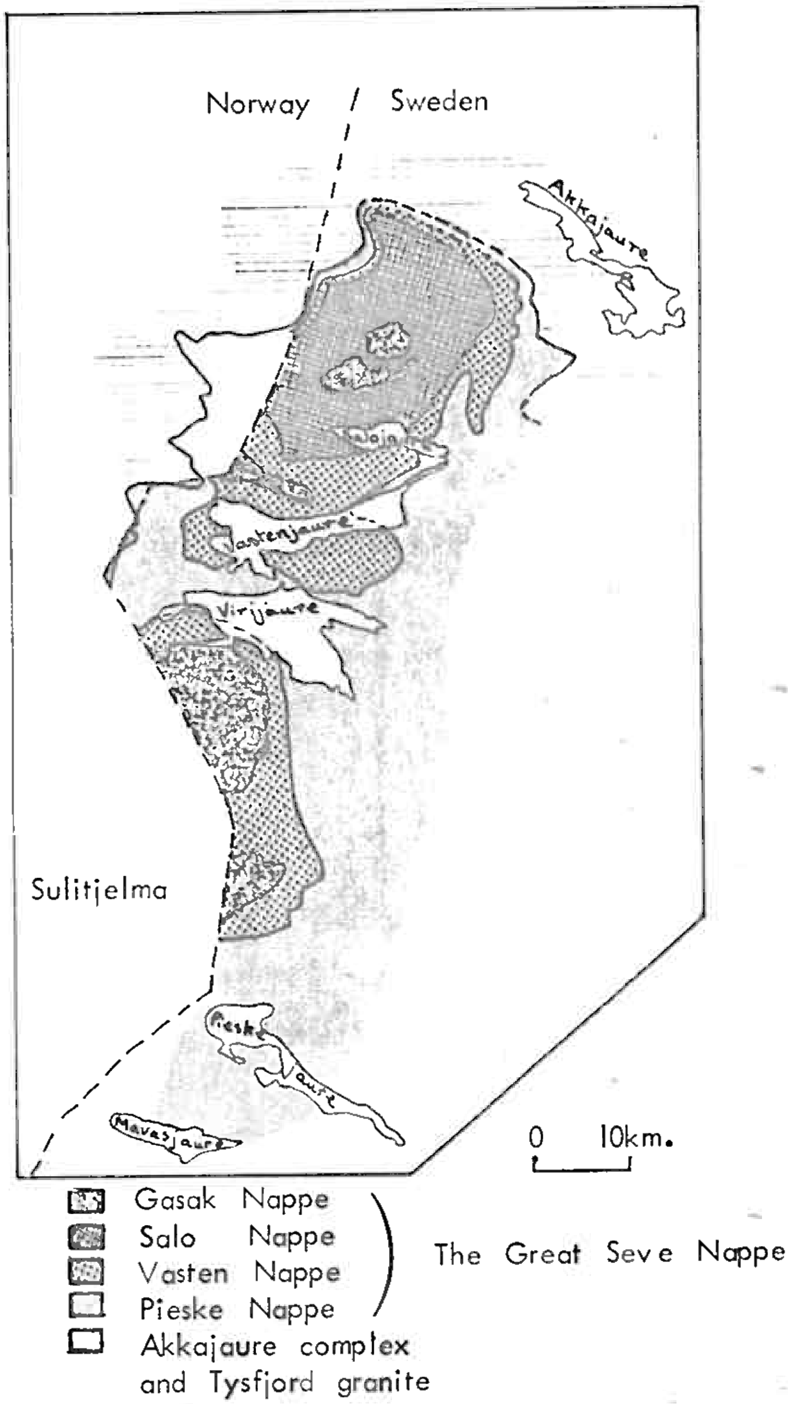


FIG. 2.3 Sketch map of the ground mapped by Kautsky, showing his divisions into nappes. After Kautsky (1953).



summaries were published earlier, in 1946, 1947 and 1949. Kautsky described his area (referred to in Fig, 2.1), as being composed of two major tectonic units, the lower one being known as the Akkajaure complex and the upper one as the Large Seve nappe. He describes the Akkajaure complex as being allochthonous, comprising several thrust slices of Archæan basement with overlying "hyolithus zone " sediments. In the west the Akkajaure complex overlies the Tysfjord granite, which Kautsky describes as Archæan basement. The Large Seve nappe Kautsky divides into four smaller nappes, named from the bottom, the Pieske nappe, the Vasten nappe, the Salo nappe and the Gasak nappe, (Fig. 2.3). In the Sulitjelma area the Salo nappe is missing.

Kautsky's reasons for supposing the presence of nappes are firstly the metamorphic differences between the high-grade rocks of the Gasak nappe and the low-grade rocks of the Pieske and Vasten nappes, secondly ,the supposed stratigraphic equivalence of the different structural levels and thirdly the discordances between stratigraphic units . Kautsky does not have much evidence for his stratigraphic correlations between nappes. In the Pieske nappe a quartzite conglomerate is correlated with a similar conglomerate widespread in the Caledonides which is of Upper Ordovician age. Yet fossils in the Pieske nappe at Sulitjelma are thought to be of Middle or Lower Ordovician age (Vogt, 1927 , Nicholson 1966). Serpentine bodies in the Vasten nappe are overlain by serpentine conglomerates which are considered to be of Lower Ordovician age. The agesof the various conglomerates and distinctive lithologies are discussed in Kautsky(1949). Kautsky(1953) correlates the marbles of the Vasten and Salo nappes with the Pieske marbles in the Pieske nappe, and considers that there is sufficient similarity between the lithologies of the Gasak nappe and the Pieske nappe to place the Gasak nappe in the Upper Ordovician. These are very tenuous correlations. There is more discussion of this in Chapter 3.7 and 3.8 .

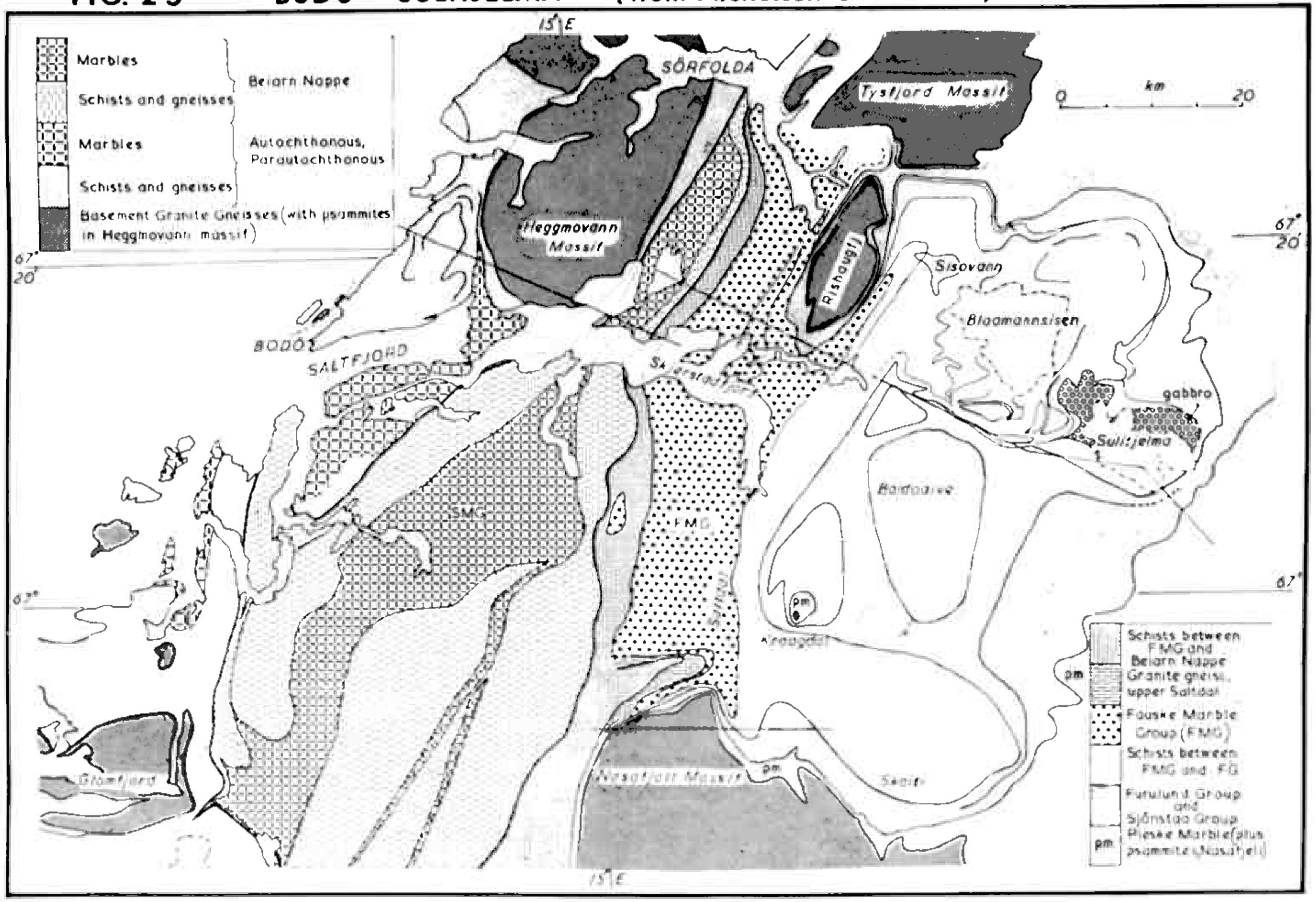
It is not yet clear how Kautsky's nappes fit in with Kulling's divisions for Norrbotten and Västerbotten, as is shown in Fig. 2.4 . In 1955 Kulling considered that the Gasak nappe was part of the Rödingsfjäll nappe. In 1960 Kulling makes the same correlation in the map which forms Fig. 1 of that paper, and in addition marks on that map the Akkajaure complex as being slices of Archæan in the Middle thrust unit, analogous to the Stalon nappe, though Kautsky implied that the Akkajaure complex was structurally equivalent to the underlying Blaik nappe. Kulling's map also marks Kautsky's Pieske, Vasten and Salo nappes as representatives of the Seve-köli nappe. Kulling's map divides the Seve-köli nappe into an underlying unit of high-grade rocks (the Seve schists) and an upper unit of low-grade rocks (the Köli schists), though Kulling does not use these terms. This division on Kulling's map lies within the Pieske nappe of Kautsky, coming below the Pieske marble, so all the Sulitjelma rocks lie within or above the low-grade Köli schists. In 1960 and 1964 , Kulling expresses doubts about Kautsky's tectonic interpretation, and in 1964 (Pg. 138) he includes the Gasak, Salo and Vasten nappes in the Uppermost thrust rocks, equivalent to the Rödingsfjäll nappe, only the Pieske nappe lying within the Seve-köli nappe complex. Kulling states that he intends to give the evidence for this correlation in a later publication. Fig.2.4 opposite, is a table to indicate the alternative correlations of the rocks in the Sulitjelma succession.

The allochthonous Akkajaure complex lies structurally above the autochthonous Tysfjord basement granite according to Kautsky, (Fig. 2.2). The Tysfjord area was mapped by Foslie (1941) who considered that the granite was a Caledonian intrusive. Foslie reported finding no thrusts in the area , (pg. 285). Kautsky (1946) traces the basal thrust of the Large Seve nappe across

FIG. 2.4 DIFFERENT INTERPRETATIONS - NORRBOTTEN SUCCESSION

<table>
<tr><th>Nicholson & Rutland (in press)</th><th>Kautsky (1953)</th><th colspan="2">Kulling (1960)</th><th colspan="3">Kulling (1964)</th></tr>
<tr><td>Fauske Marble Group
Sulitjelma Schist Sequence</td><td>Pieske Marble (incorrect)
Gasak nappe</td><td rowspan="3">UPPER CALEDONIAN NAPPES</td><td>Rödingsfjäll nappe</td><td rowspan="2">Upper most thrust rocks</td><td rowspan="2">Rödingsfjäll nappe</td><td rowspan="2"></td></tr>
<tr><td>Sulitjelma amphibolites</td><td>Vasten nappe</td><td rowspan="2">Seve-köli complex</td></tr>
<tr><td>Furulund Group
Sjönstå Group
Pieske Marble Group
---------------------</td><td>Pieske nappe</td><td>Upper thrust rocks</td><td>Seve-köli complex</td><td rowspan="2">MAIN SEVE NAPPE</td></tr>
<tr><td rowspan="3"></td><td>Akkajaure complex (according to Kulling)</td><td colspan="2">Middle Caledonian Nappes, eg. Stalon nappe</td><td colspan="2">Middle thrust rocks</td></tr>
<tr><td>Akkajaure complex (according to Kautsky)</td><td colspan="2">Lower Caledonian Nappes, eg. Blaik nappe</td><td colspan="3">Lower thrust rocks</td></tr>
<tr><td>Autochthon</td><td colspan="2">Autochthon</td><td colspan="3">Autochthon</td></tr>
</table>

FIG. 2·5 BODO - SULITJELMA (from Nicholson & Rutland)



Foslie's map , locating the thrust by its position relative to stratigraphic horizons. These arguments have recently been revived by Oftedahl(1966).

Strand (1961) in a review of the Caledonides of Norway marks the Akkajaure complex as autochthon, and this interpretation is followed by Oftedahl who describes that area as the 'Tysfjord culmination'. Since Kautsky (1953) maps slices of 'hyolithus zone' sediments within the granitic gneiss of the Akkajaure complex, it is difficult to know on what basis the Norwegian interpretations have been made.

A characteristic of the Caledonides of Sweden is that the rocks generally are flat-lying, there being very little large-scale folding, as is shown in Fig. 2.6. This characteristic also extends into the Sulitjelma region almost as far west as Sjönstå. To the west of Sjönstå all the rocks are involved in major post-schistosity folds with the result that correlation is more difficult than in Sweden. Kautsky(1953, pg.226) interpreted similar folding north of Sulitjelma as being later than the thrusting.

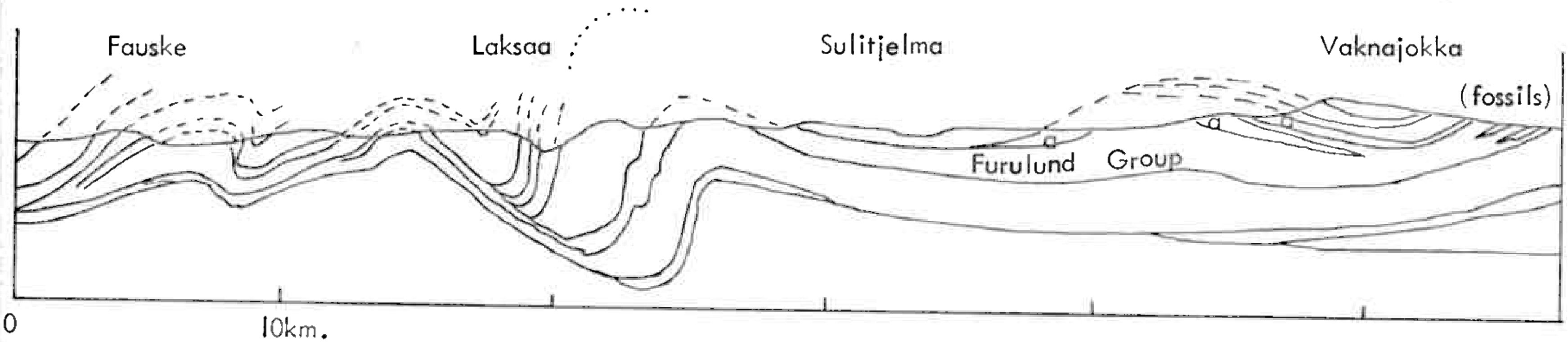
2.4 Regional work to the west of Sulitjelma.

The Sulitjelma area was mapped by Sjögren and fellow-workers in considerable detail (1:20,000) in the 1890s because of the copper deposits, and in the 1920s this work was revised, summarised and extended by Vogt. Until recently none of the adjacent areas of Norway had been mapped in detail, though there had been recconnaisance surveys by the Norwegian survey, and a few isolated studies by individual investigators.

Between 1953 and 1959 about 1,000 Sq. Km. in the Glomfjord region, south of Bodö were mapped at 1:16,000 by a number of workers from University College, London using modern structural techniques, (Fig.2.1). This work was extended by Rutland and Nicholson, who published a synthesis of the Bodö - Svartisen area in 1965. Since 1962 work has concentrated on the Sulitjelma area, (Nicholson, Henley, Mason and Wilson) and on linking the

FIG. 2.6 Section between Fauske and Sulitjelma. (From Nicholson and Rutland, in press).

Line of section is indicated on Fig. 2.5.



(a : Sulitjelma amphibolites)

Sulitjelma area to the Bodö - Svartisen area ,(Nicholson, and up to 1964, Rutland). An account of the profile from Sulitjelma to Bodö is in press (Nicholson and Rutland).

A major feature of the coastal areas of Nordland is the presence of large bodies of granite gneiss. Rutland and Nicholson (1965) put forward strong evidence that the Glomfjord and Svartisen "granites" are autochthonous basement, strongly deformed in the Caledonian orogeny. Previous views had been that they were magmatic or metasomatic in origin, or were highly deformed thrust slices of Archæan (Kautsky 1947, Skjeseth and Sørensen 1953). Extensions of the Glomfjord work have suggested that the Heggmovatn and Rishaugsfjall granites are also basement(Fig.2.5). Rutland and Nicholson demonstrated that there is an autochthonous and parautochthonous meta-sedimentary succession on top of the Western basement granites and on top of this succession, a separate tectonic unit, the Beiarn nappe, Fig. 2.2 . In 1965 it was suggested that this Beiarn nappe could be correlated with the Rödingsfjåll nappe, but this is now known not to be so.

2.5 The Sulitjelma area.

The entire succession at Sulitjelma lies between two marble groups, the Pieske and Fauske marble groups, Fig. 2.5 . The succession as recognised by Nicholson and Rutland is :-

Fauske Marble Group
Sulitjelma Schist Sequence
Sulitjelma amphibolites
Furulund Group
Sjönstå Group
Pieske Marble Group

These are different divisions in the main from those of Sjögren and Vogt, and the structure of the region is known to be fundamentally different from the interpretation of Holmquist, (1900). The critical area is just east of Sjönstå, where Holmquist's map is incorrect. Holmquist's interpretation is that the Sjönstå group overlies the Fauske Marble Group, and can be correlated with the Venset Schists on the west side of Fauske. Nicholson demonstrated in the summer of 1965 that the Furulund Group and the Sulitjelma Schist Sequence pass over the Sjönstå Group, then dip steeply on the limb of a major monoclinal fold, passing under the Fauske Marble Group, as in Fig. 2.6. A similar large-scale fold from further north is illustrated by Kautsky in his section XV, table 9, 1953, but Kautsky did not realise the regional significance of this folding.

There is only a very thin succession of rock between the basement at Rishaugfjall and the Fauske Marble Group, yet the whole Sulitjelma succession must lie within this succession, as in Fig. 2.5 . This map shows a similar situation on the northern margin of the Nasafjall basement complex; the westward thinning of the Sulitjelma units.

Kulling's estimate of the extent of the Rödingsfjäll nappe is clearly incorrect; the units mapped by Kulling and Kautsky cannot be traced very far across Norway. The large-scale correlations and interpretations of Kautsky , Kulling and also Holtedahl, and Strand are useful in defining problems for further work, but the present state of knowledge of the geology of the Norwegian Caledonides is insufficient to allow much weight to be placed on them. Statements such as Oftedahl(1966) - " the Seve nappe attains tremendous dimensions and may be considered as one of the large thrust units of the earth. Its length along the tectonic axis is about 1,100Km. and it seems that the proven stratigraphic displacement in the Tysfjord culmination is 120Km, with a displacement of 160Km. likely and of 240Km. or more possible" - are most misleading, especially to geologists without further knowledge of the Scandinavian Caledonides.

2.6 Previous work in the Sulitjelma area.

The Sulitjelma area was first mapped systematically by P.J.Holmquist, O.Nordenskjöld and Hj.Sjögren under the leadership of the latter. The results of this survey were published in a series of papers in the 1890s, (Sjögren 1893, 1894, 1895, 1896, 1900, 1900a, Holmquist 1900, and Nordenskjöld 1895). All this work is notable for its careful observation. The map prepar ed (Sjögren 1900) is , according to Vogt 1927, compiled mainly by Holmquist, and is of a very high standard. Holmquist, in his paper, describes a section across the Caledonides, from Kvikkjokk in Sweden to Bodö.

In 1917 accounts were published by Rekstad and by Holmsen for the Norwegian Survey, filling in gaps between earlier maps.

In the 1920s Thorolf Vogt (son of J.H.L. Vogt, who wrote about Sulitjelma and its region in 1890), commenced investigations in the Sulitjelma area, publishing a paper on the copper ores in 1921 and one in 1922 on the stratigraphy and tectonics, followed by the 1927 memoir. This memoir was intended to be part of a two-volume account of the geology of Sulitjelma, the second part of which, dealing with the copper ores, was never published. The account is therefore sadly deficient of description of the ore and adjacent rocks. Since these are the specific levels at which Kautsky suggests that there are thrusts, the deficiency is all the more regrettable. The memoir is based on Vogt's own field-work, (19 weeks) and much work by Sjögren, and particularly Holmquist, which had not been previously published. The map is an unfortunate simplification of Sjögren's (1900) map. It covers a greater area, but there is not so much detail, and

Vogt here did a great disservice to Sjögren and to Holmquist. In the memoir Vogt deals firstly with the succession and stratigraphy, secondly with the metamorphism of the sedimentary rocks and of the basic igneous rocks, and with the petrology of the granites, and thirdly, with the tectonics of the area. In the section on stratigraphy, Vogt knits together the observations of Sjögren et al. in a most useful manner, but his classification is here rejected. In particular he failed to recognise that the Sulitjelma amphibolites are a series of metamorphosed lavas and sediments, considering them , as did J.H.L.Vogt and P.J.Holmquist , part of the syn - tectonic " Sulitjelma phacolith ". In addition he correlated together distinctly different rock groups and was therefore obliged to postulate folding which is not present.

The sections on metamorphic petrology are well known as an early study of mineral facies and their relationship to synthetic systems and it is for this that the memoir is still quoted (as in Turner and Verhoogen, Igneous and Metamorphic Petrology, 1960, pg.492). Vogt's work on the Sulitjelma gabbro has recently been revised by Mason (1966, 1967), his work on the metamorphism of the meta-sediments by Henley,(eg. Harte and Henley , 1966).

The sections on tectonics, and mechanisms of igneous intrusion are best ignored. Because of incorrect assumptions regarding the stratigraphy of Duoldagop, Vogt's structural analysis of Duoldagop must be discounted. His suggestion that the intrusion of the gabbro magma could cause the strong folding seen in Duoldagop cannot be accepted. His long discussion (pages 101 to 105) of the formation of the Langvann'anticline' is based on a crude mechanical conception of anticlines moving together as if they were rigid masses. Nowhere in any of his structural descriptions does Vogt refer to the relative age of folds, and only rarely does he mention the axis of a fold, and then in the most general terms.

Other reference to the work of Vogt and Sjögren will be made in relevant places in the thesis. Virtually all the other work in Sulitjelma up to 1961 has been concerned with the copper ores, and very little of this work has been published. One notable piece of work is a map of the ore horizons and surrounding rock at a scale of 1:5,000 excecuted by Fr. Carlson between 1924 and 1930. This map is extremely accurate, but suffers from two deficiencies, No indication of the attitude of bedding or schistosity is made, and secondly the map is not an outcrop map, as a map at that scale should be. Consequently there is an element of subjectiveness in this map. Despite this the map in no place appeared to be inaccurate, and was of great value in the present study. The map is a private map belonging to the Sulitjelma mine company. Several theses have been written by Diploma students at the Trondheim Technical University. These have been mainly concerned with the geology of the ore deposits, but it is naturally impossible to consider the ores out of their context. Of particular interest are the following theses :-

Christoffersen, T., 1960, (on the Bursi - Charlotte area).

Mellingen, T., 1961, (on the Charlotte - Giken area).

Hofseth, A., 1934, (on Furuhaugen, south of Langvann, S.W. of Bursi).

Dybdahl, I., 1951, (on the Sjönstå-Botnvatn-Knallerdalen area, south of Langvann. In this thesis the ore horizon, the Furulund granite and amphibolites are traced round the Baldaoive synform).

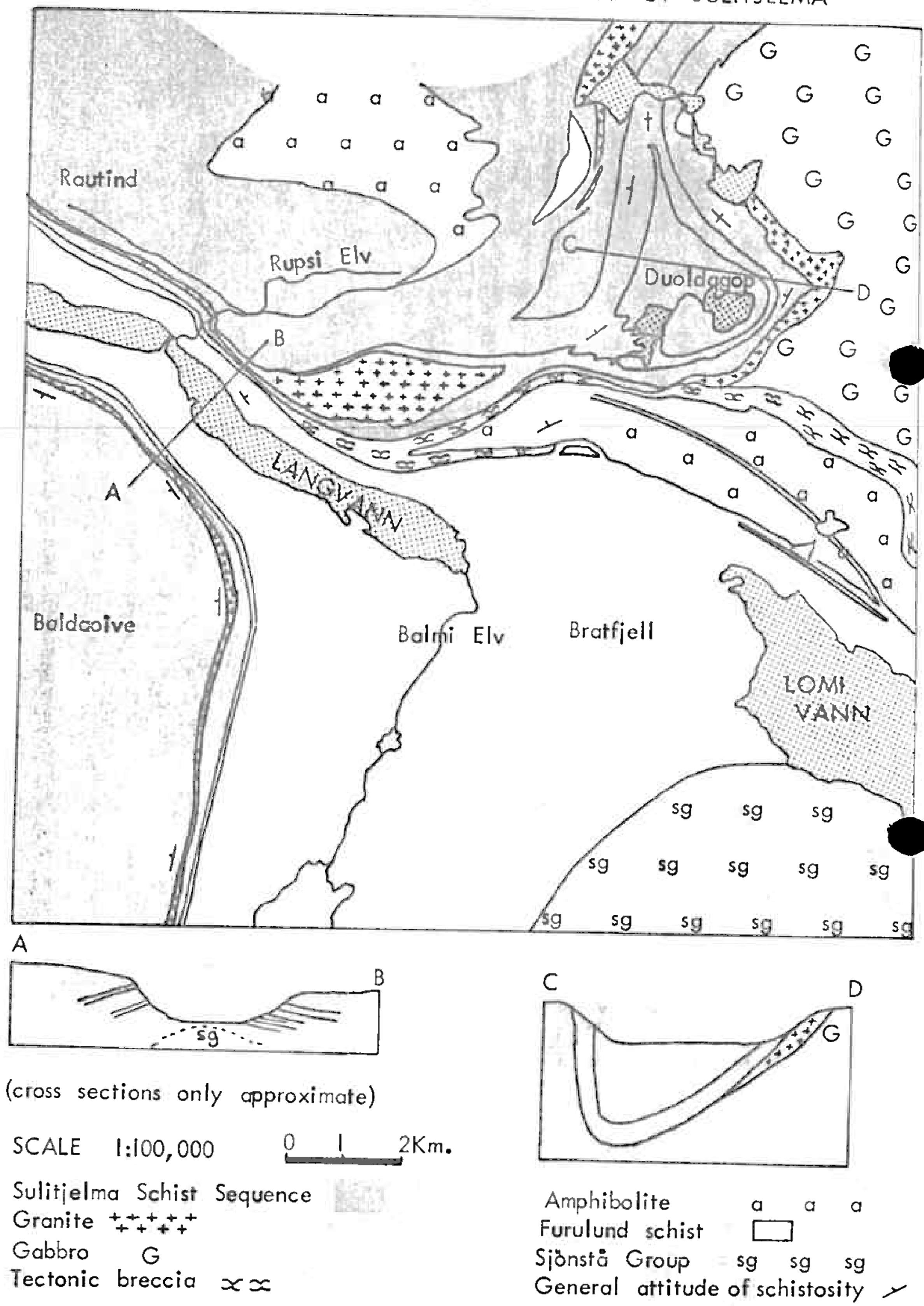
2.7 Kautsky's interpretation of Norwegian Sulitjelma.

Kautsky(1953) suggests a correlation of the succession in Sulitjelma with the nappes he found in the east. He places the Furulund schist and underlying rocks in the Pieske nappe, the Sulitjelma amphibolites in the Vasten nappe and the Sulitjelma gabbro in the Gasak nappe. He does not include a map to indicate exactly where he supposes the Vasten- Gasak nappe boundary to be, and his text is not perfectly clear about this. He suggests on page 208 that some of the greenstones may lie in the Gasak nappe, and that most of the schists around the Sulitjelma gabbro are within the Gasak nappe. The copper ore at Sulitjelma he describes as lying in the thrust plane between the Pieske and Vasten nappes, or in minor thrusts which developed simultaneously with that overthrust. He therefore suggests that the ore was deposited during or after the thrusting.

FIG. 3.1 ALTERNATIVE INTERPRETATIONS OF THE SUCCESSION AT SULITJELMA

Sjögren (1900)		Vogt (1927)	Kautsky (1953)	Henley (1968) (south of Langvann)	Mason (1966)	Nicholson & Rutland	Wilson	
west of Kobbertoppen	east of K'toppen						west of Kobbertoppen	east of Kobbertoppen
Rusty y black k schist st	normal Sulitjelma schist	Furulund Group	Gasak Nappe	Upper Unit	Calc-silicate Group of Duoldagop	Sulitjelma Schist Sequence	Coarse mica schist	Duoldagop Banded Group
					Micaceous Psammite with marbles.		Rusty Psammite with marbles	
le plus quartzite (marble)							Marble-Psammite Group	
Normal Sulitjelma schist					Kyanite schist group		Lapphelleren schist	
Coarse and brecciated amphibolite		Sulitjelma phacolith	Spilitic effusive greenstones of Vasten Nappe	? Junction Unit	S u l i t j e l m a		a m p h i b o l i t e s	
Normal Sulitjelma Schist		Furulund group	brown and green schist of the Pieske nappe	Furulund	schist	Furulund Group	Furulund schist	

FIG. 3.2 GEOLOGICAL SKETCH MAP OF SULITJELMA



CHAPTER 3

GENERAL GEOLOGY OF THE THESIS AREA

3.1 Lithological units and their distribution.

Nicholson and Rutland (in press) have erected the following succession for the Sulitjelma region :-

Fauske Marble Group
Sulitjelma Schist Sequence
Sulitjelma amphibolites
Furulund Group (referred to in this thesis as 'Furulund schist').
Sjönstå Group
Pieske Marble Group

In the thesis area the middle part of this succession was examined, being the top of the Furulund schist, the Sulitjelma amphibolites and the lower part of the Sulitjelma Schist Sequence. The lithologies mapped can be generalised as two series of schists separated by a series of amphibolites, the upper schist series containing intrusions of granite and gabbro. The relationship between the above interpretation of the Sulitjelma succession and previous interpretations is shown on the table opposite, Fig. 3.1 .

The sketch map and sections in Fig. 3.2 , on the next page illustrate the distribution of lithologies and the basic structure of the area around Langvann, with the thesis area indicated. The rocks are arranged in a saddle-shape , first described by J.H.L.Vogt in 1890. An antiform with a WNW - ESE trending axis crosses the area, so that the structurally higher rocks are found in the north and south-west, and the lower rocks are found in the south east and west. Rock units on the north side of Langvann dip gently to the north or north-west, except in the north of the thesis area where as a result of the interference of two phases of major folding the lithological units within the Sulitjelma Schist Sequence are folded into a basin shape.

3.2 Problems.

The main problems in the thesis area concern the relationships between the three main units, particularly the possibility that the units are separate nappes as suggested by Kautsky. The main discussion of this possibility is in Chapter 16. A further problem which is introduced below is the relationship between the various amphibolitic rocks in the area.

3.3 Problems of the amphibolitic rocks in Sulitjelma.

The amphibolitic rocks in the Sulitjelma area can be divided into three groups as is shown in Fig. 3.2. Firstly there are the metamorphosed derivatives of the Sulitjelma gabbro, coarse-grained massive amphibolites which occupy the south-west corner of the gabbro complex as is shown by Mason in his Fig. 2 (1967). Secondly there are the Sulitjelma amphibolites, a series of fine-grained meta-volcanic and meta-sedimentary amphibolites with associated mica schist bands, quartzite bands and conglomerates, which lie south of the gabbro complex and extend eastwards into Sweden. The problems of correlation concern certain bands of coarse-grained amphibolite and quartz-feldspar rock which constitute the bulk of the material involved in the third group, the tectonic breccias. It is demonstrated in Chapter 9B that much of the fragmentation of this melange is tectonic in character, being boudinage or pinch and swell or other types of fracturing. Some of the constituents of the breccia are clearly derived from

FIG. 3.3 The distribution of Sulitjelma amphibolite and tectonic breccia in the thesis area.

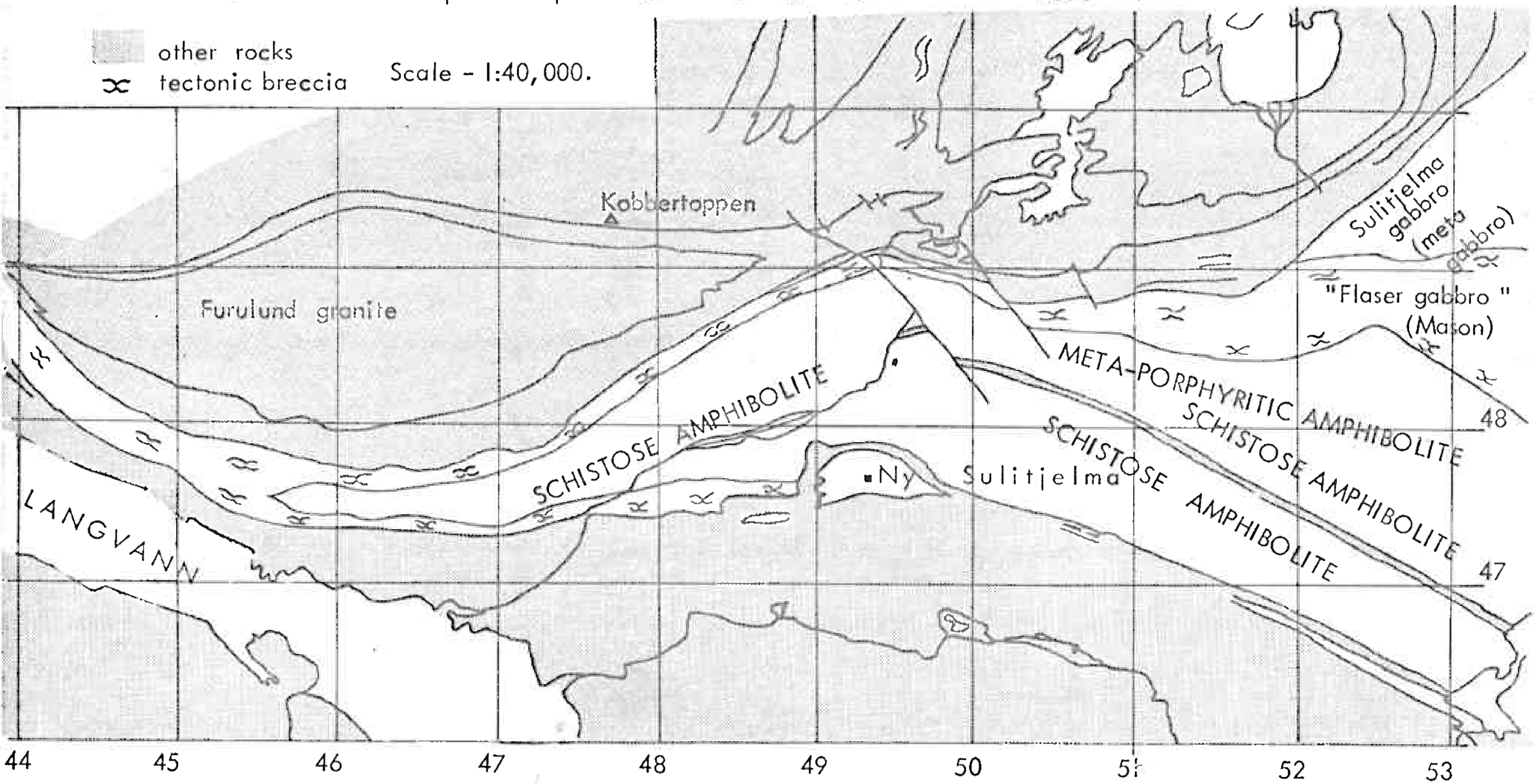
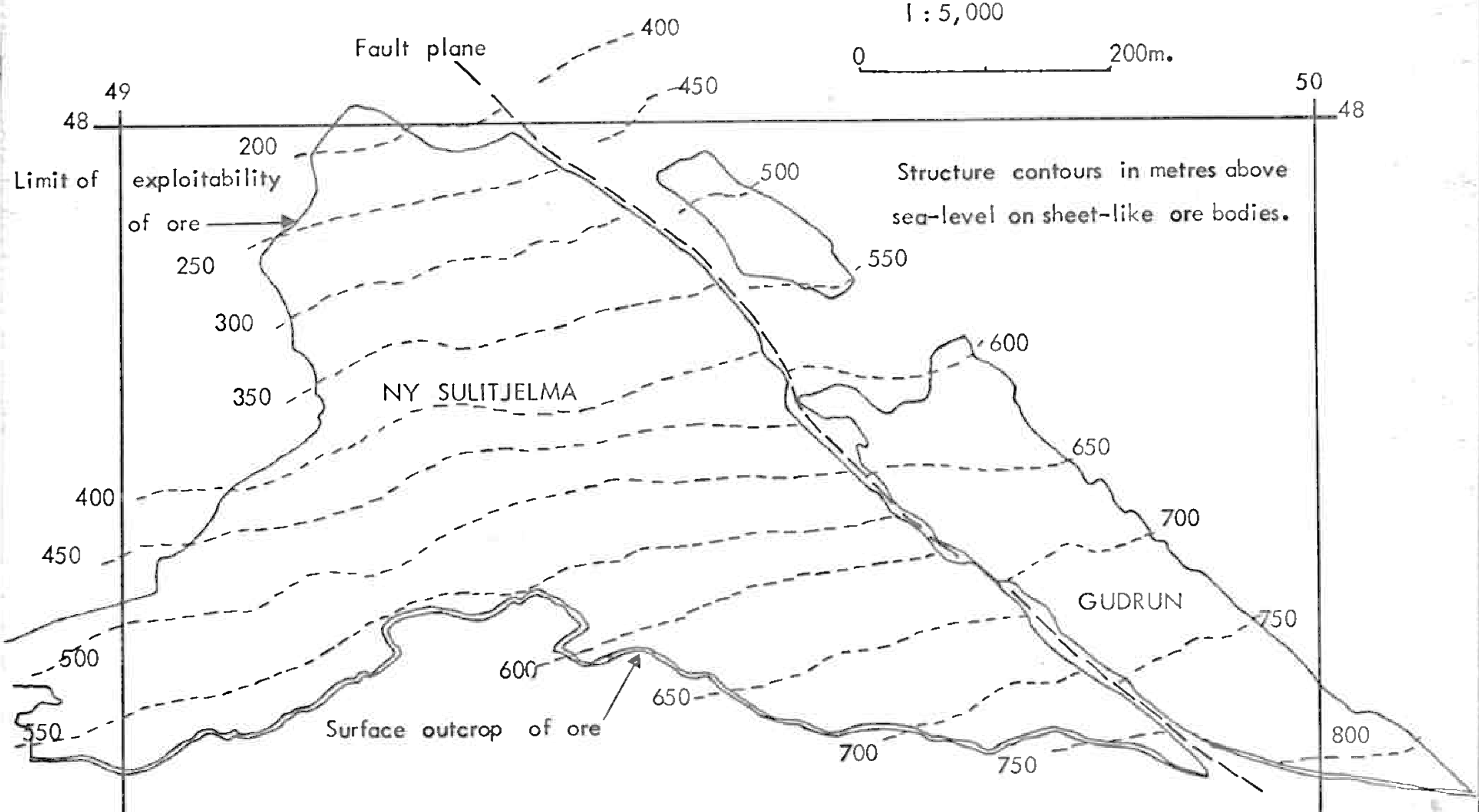


FIG. 3.4 THE NY SULITJELMA AND GUDRUN ORE BODIES



Based on maps by Sulitjelma Grube A/s - Redrawn from Mason (1966, Fig. 2.7) the Sulitjelma gabbro, some clearly from the Sulitjelma amphibolites, but the derivation of most of the rock is not obvious and cannot be ascertained without detailed mapping and petrology. The area of outcrop of this tectonic melange is shown on Fig. 3.3 opposite. In the east it lies between the gabbro and the Sulitjelma amphibolites and continues west above the amphibolites. The unbrecciated part of the Sulitjelma amphibolites tails out to the west, where the tectonic breccia lies immediately above the Furulund schist. A strip of breccia also lies at the base of the Sulitjelma amphibolites, extending from the main part of the breccia above the Church nearly to Ny Sulitjelma. Above Bursi the breccia becomes very thin and is strongly folded. Breccia at this structural level can be seen south of Langvann and also west of Bursi.

The origin of the constituent lithologies is not the only problem with these breccias, for some explanation must be given of their structural character. These matters are discussed further in Chapter 9B.

Vogt and his predecessors regarded all the amphibolitic rocks as one unit. Since north of Ny Sulitjelma (as Mason , 1967, points out) there is no marked break between the breccias and the metamorphosed gabbro, and in most places schistose amphibolites can be seen within the breccia, this mistake is understandable. The modern interpretation is the result of the mapping by Kautsky of the Sulitjelma amphibolites in his area where there is no close geographic relation with the Sulitjelma gabbro.

3.4 Relation between the amphibolitic rocks and the Furulund schist.

Kautsky suggested that there was a major thrust between the Sulitjelma amphibolites and the Furulund schist,(though he did not use those stratigraphic terms). Mason (1967) demonstrated that there is no major tectonic break at this level and in the section below, Mason's evidence is reviewed and confirmatory evidence from the thesis areais presented.

Mason (1967, Fig. 2) has mapped a thin band of schistose amphibolite below the base of the main amphibolites which runs several kilometres to the east.

Mason's map, and Fig. 3.2 also, shows that the bottom 500m. out of a total of 750m. of schistose amphibolites thin to nothing over a distance of 7km. eastwards. A band of Furulund schist several metres thick can be followed from the main body of Furulund schist to a position near the top of the amphibolites north of Ny Sulitjelma.

Map 5, of the Ny Sulitjelma area, shows some details of the complex relations at the base of the amphibolites. There is at Ny Sulitjelma a lense of amphibolite within the schists. Its eastern margin is probably faulted in part, though there is no evidence for this on the surface in the way of discordance or fault breccia. Maps belonging to the mine show a fault here with a throw of between 200m. and 50m. Fig. 3.4 is redrawn from mine maps and illustrates the displacement of copper ore by the fault. The western edge of the lense is marked by a deflection of schistosity with shearing of the rocks in the zone of deflection. Specimen 401 from within this shear zone contains garnet and hornblende porphyroblasts which have been fractured and biotite porphyroblasts which have been kinked by the late shearing. This is shown in Fig. 7.4

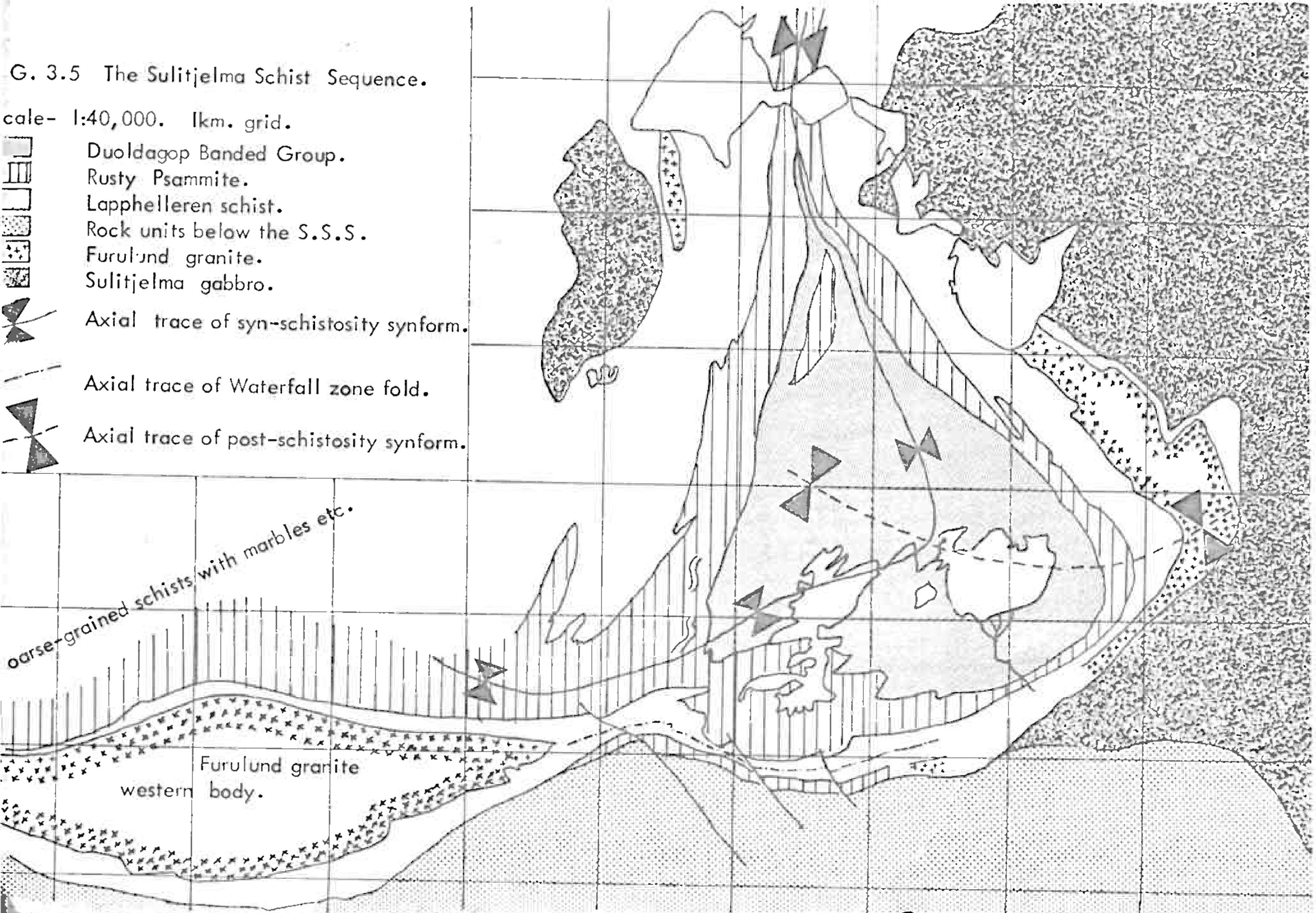
The succession within this lense is of interbedded quartzites, (some conglomeratic), and fine-grained amphibolites. Copper ore has been mined out beneath this lense, and Fig. 3.4 indicates the extent of economic ore at the level which outcrops below the lense. The thickness of the lense on the map is considerably exaggerated by the topography, for the ground surface west of Ny Sulitjelma dips to the north-west almost as steeply as does the bedding. The lense outcrops for some 275m. along the stream west of Ny Sulitjelma but the true thickness of the lense is only about 120m. The sharp right-angle bend in the base of the main amphibolite on the map west of Ny Sulitjelma is purely an erosional effect, the schist band being the site of a north-dipping gulley.

It is suggested in Chapter 9A.2, page 84 that some of the basal schistose amphibolites at Ny Sulitjelma are sedimentary in origin. There is, however, no continuous variation between the true amphibolites such as specimens 329, 340, 439, 379, 387 or even 427 (which appears to be sedimentary , see page 84) and those rocks adjacent to or within the amphibolite which certainly are sedimentary.

Further evidence of the close relationship between the Furulund schist and the amphibolitic rocks is that at Bursi (Map 6) there are three strips of mica schist some tens of metres thick lying within the tectonic breccias. These are marked on Map I and Map 6 as strips A, B and C. The section in Fig. 6.32 shows their position clearly. Strip B is the largest and is probably connected to the main body of Furulund schist at its eastern end. Strip B is disharmonically folded into an antiform and into a recumbent fold with near-horizontal axial plane. Strip A lies adjacent to strip B, separated by a metre or so of ore impregnated material. Strip C lies apparently unconnected to the other strips though its western continuation is not exposed and is therefore unknown. It is possible that it may once have been joined to strip B. This is further discussed in Chapter 6.9 on page 53.

3.5 Copper ores at Sulitjelma.

No special attempt has been made to study the copper mineralisation at Sulitjelma. Nevertheless, since the ore is a rock occuring in the thesis area it was not ignored. In this text the word 'ore' does not imply any specific economic concentration, but merely the presence of copper sulphide group minerals in sufficient abundance to catch the eye. The zone of mineralisation could usually be distinguished by its rusty or blue-black staining. These zones are marked in black on Maps I,5 and 6. The ore is developed in lenses, according to Vogt(1944 and 1952) parallel to the regional lineation, and lie at the contact of the Furulund schist with the amphibolites or just below. Slight mineralisation occurs as far east as mapped, though there it is of no commercial value. In places



G. 3.5 The Sulitjelma Schist Sequence.

the ore is folded by post-schistosity folds and in others the ore cuts across the schistosity, notably at Ny Sulitjelma. At Ny Sulitjelma it is seen on both sides of the lense of schistose amphibolites within the Furulund schist.

Slight mineralisation occurs on the upper margin of the Sulitjelma amphibolites, associated with the brecciation. This is best seen at Fjeldsgrube, a trial mine (484 478) and at Lapphelleren (472 479).

Apart from the main exposures of ore marked on Map I, small discontinuous patches of ore impregnation are quite common near the top of the Furulund schist.

The origin of the ore is a matter of great debate, and a few of the many papers on the subject are Holmsen (1917), Carstens (1944), Bugge (1954), Krause (1956) and Kautsky(1953). It has been asserted (Christoffersen, pers.comm.) that after emplacement, the ores have been remobilised and recrystallised several times.

3.6 The succession within the Sulitjelma Schist Sequence.

The upper part of the succession in the thesis area, the Sulitjelma Schist Sequence, occupies the northern part of the area and comprises several distinct lithological groups. These are the Lapphelleren schists, grey well-banded medium to coarse-grained schists, the Rusty Psammite, fissile quartz-rich rocks with characteristic rust-coloured weathered surfaces, and the Duoldagop Banded Group, extremely regularly banded grey rocks with a pelitic mineralogy, but little preferred orientation of micas. Between the Lapphelleren schists and the Rusty Psammite there lies a thin series of marbles, psammites and calc-silicate rocks known as the Marble-Psammite series.

The map opposite, Fig. 3.5 indicates the areas of outcrop of the individual members of the Sulitjelma Schist Sequence and indicates the pattern of the major folding.

Intruded into the Lapphelleren schists are two lenses of granite, the eastern and western bodies of the Furulund granite, and a large gabbro complex, the Sulitjelma gabbro.

3.7 The age of the Sulitjelma rocks - palæontological evidence.

Fossils have been described from the area east of Lomivann, some 8km. east of the thesis area. They are members of an Ordovician assemblage. They were discovered by von Schmalensée in 1898 during the investigations led by Sjögren (Sjögren 1900a) and the fossiliferous area was mapped in detail by Vogt (1927, plate 38). The area has been recently re-mapped by Nicholson (1966) who has re-interpreted the stratigraphy of the area.

The fossils occur in bands of marble which lie in chloritic phyllites which themselves are local facies variants of a black muscovite phyllite. This black muscovite phyllite is correlated by Nicholson with the Furulund schist further west. Vogt considered that the chloritic phyllite represented the Muorki groups, a series of massive chlorite-muscovite schists which underly the Furulund schist group, and are part of the Sjonstå group of Nicholson and Rutland.

The fossils consist of crinoid fragments, lense-shaped bryozoa colonies and gastropods. Descriptions are in Vogt (1927, pp. 185 to 192) and in Nicholson (1966). The bryozoas were identified as Dianulithes petropolitanus, and the gastropods as immature Maclurites. This is said to indicate an Ordovician age, most likely Lower or Middle Ordovician, particularly Trentonian (Vogt, pg. 192).

3.8 The age of the Sulitjelma rocks - lithological evidence.

Kautsky (1953) suggests analogies with lithologies elsewhere which are of known age in order to determine the age of the rocks in his area. He correlates the microcline gneiss at the base of the 'Pieske nappe' with the Archæan and the overlying feldspathic Juron quartzite with the Eocambrian sparagmites. A quartzite conglomerate high in Kautsky's Pieske nappe is correlated by him with widespread conglomerates of uppermost Ordovician age (stage 5b in Oslo). The age of the Vasten nappe is suggested to be Lower Ordovician since similar splitic lavas occur beneath similar serpentine conglomerates in rocks which can be dated (Kautsky, 1949). Some slight similarities between the successions in the Gasak and Pieske nappes suggest to Kautsky an Upper Ordovician age for the former.

3.9 The age of the Sulitjelma rocks - radiometric evidence.

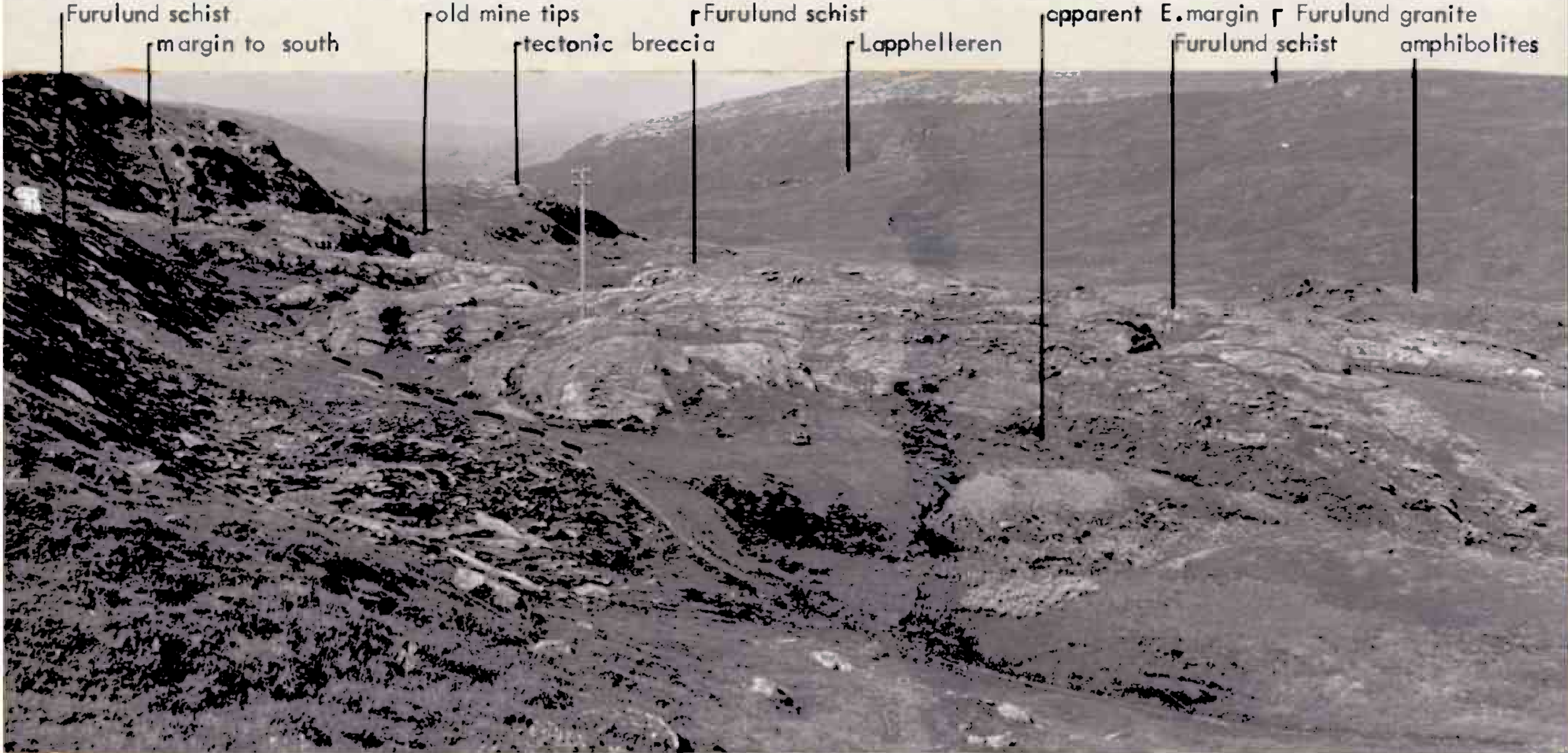
Only one radiometric determination has been made from Sulitjelma rocks (Moorbath and Vokes 1963). This is a lead isotope measurement on a galena specimen from Jakobsbakken (south of Langvann). The galena rich mineralisation at this mine occurs in the hanging wall schists of the pyritic copper-zinc ore body, and is considered by Ramdohr (1938) to be younger than the main ore at Jakobsbakken. The sample of lead yields a concordant Caledonian model age of 390±70m.y., a late or end - Silurian event.

Other Norwegian age determinations up to 1964 are listed by Broch, (1963). Later published ages are by Sturt, Miller and Fitch (1967). Determinations on Caledonian rocks listed by Broch are by the K/Ar method on biotites and muscovites and give ages between 350m.y. and 400m.y. These are probably cooling dates and do not penetrate the 'metamorphic veil' (Armstrong, 1966).

Sturt, Miller and Fitch publish K/Ar dates on nephelines, biotites and muscovites from W.Finnmark, some 250km. north of Sulitjelma, which cluster around 384-420m.y. and 450-491 m.y. Sturt et al suggest that the oldest dates approximate to the date of the intrusion of the plutonic nepheline syenites, the last major event in the structural history. This would indicate a substantial early event around the Tremadoc or Arenig. Sturt et al review stratigraphic evidence for such an event from other parts of Norway. One such event is the Trondheim Orogeny (Strand, 1960) which on the latest evidence (Skevington 1963, Skevington and Sturt 1967) probably occured fairly late in the interval between the occurance of the Dictyonema flabelliforme and Didymograptus hirundo zones of the standard British Ordovician graptolite zonal sequence. This correlates well with the major deformation of the Dalradian in Britain, which is now known to be earlier than the Lower Llanvirn (Skevington and Sturt 1967, Dewey 1961).

No evidence for such an event in seen in the Bodö - Sulitjelma region and it is clear that the large-scale folding of the Sulitjelma rocks in the Sjönstå - Fauske area (and by extension, the major post-schistosity deformation of the rocks further west) is later than mid-Ordovician. If the Sulitjelma Schist Sequence is a separate tectonic unit it could be older than the Furulund schist and perhaps have shared in a pre- Lower Llanvirn event. Further speculation on this subject must await a geo-chronological study of the Bodö-Sulitjelma area.

FIG. 4.1 THE AMPHIBOLITE BODY AT HANKABAKKEN - VIEW WEST



Body of massive coarse-grained amphibolite within Furulund schist at Hankabakken. View from position marked on Map 5. Note the contrasting appearance of the massive amphibolite and the fissile schist. Photo. shows how the outcrop of amphibolite terminates abruptly in the east.

PART TWO - FURULUND SCHIST

CHAPTER 4

INTRODUCTION

4.1 The stratigraphic position of the Furulund schist, discussed in Chapter 2, is above the Sjönstå Group and below, but interdigitating with the Sulitjelma amphibolites and Tectonic breccias. The total thickness of the Furulund schist at Sulitjelma is not accurately known but is of the order of 1,000m. (At the east end of Lomivann the thickness is about 1,000m. as derived from Fig.3, Nicholson 1966, and near Sjönstå the thickness is about 700m. as derived from a map in Nicholson and Rutland (in press). For this thesis the top 300m. of the schists have been examined. Since the area mapped was so small and was limited to the top part of the succession, the excellently exposed Balmi Elv stream section south of Langvann(Figs.1.1, 1.6,3.2) was briefly examined to provide a comparison with lower parts of the succession.

4.2 Lithologies.

The most usual development of the Furulund schist in the thesis area is as a fine-grained biotite schist with porphyroblasts of either garnet or hornblende, or both. Schistosity surfaces are characteristically extremely smooth. The rocks are well layered, and are rich in quartz segregations. Boudins are common. The general character of the rock is illustrated in Figures 8.1, 8.2 and 4.4. There are several photomicrographs of Furulund schist specimens in Chapter 7.

Calcareous bands occur frequently, more especially in the lower parts of the succession visited north of Langvann. They can contain up to 20% calcite

(as in specimen 314) and are richer as well in quartz.

Near the top of the succession east of 460 (grid easting as on the thesis maps) are two levels of soft rusty-weathering phyllitic schist, marked on Map 1 and Map5. Carlson maps these as " rustskiffer". Because of their softness cliff features have formed in the overlying rock. The lower of these two features is particularly well-marked, lying above the road from the Church to Giken (Fig.1.4) and above the path from Giken to Ny Sulitjelma (Fig. 1.6).

In the far east of the region (grid reference 502 470) is a conspicuous band of hard white rock about 10m. thick showing slight layering. Specimen 586 shows it to be medium-grained, composed mainly of quartz with about 10% each of chlorite and calcite and about 5% plagioclase. It is possible that this rock has an igneous origin, perhaps having been an acid tuff. The band cannot be traced east or west of the outcrops marked on Map 1.

The three strips of schist at Bursi which were described in Chapter 3 (pg.22) as lying within the amphibolitic tectonic breccias which overlie the Furulund schist show some unusual features. Strips A and B show all gradations between schist whose fabric is identical to that of the main body of Furulund schist, and a schist with a strong penetrative second cleavage. Specimens 460 and 599 show a non-penetrative crenulation cleavage and specimen 630 shows a penetrative second cleavage. Strip C is a coarse schist similar to specimen 630 but is in part chloritised, (specimens 613 and 614). Garnets in specimen 614 overgrow small crinkles of a former fine-grained schistosity. Coarse-grained chloritised schist is common at Furuhaugen , south-west of Bursi, on the south side of Langvann, where Hofseth has described the development as " Furuhaugen schist ". Strip B is also notable for thin bands (1-3cm. thick) of relatively competent rock which have controlled the type of deformation of these rocks, as is discussed in Chapter 6.7, page 49, with Fig. 6.41 of hand-specimen 634. Thin section of this specimen shows that the bands are composed of hornblende, quartz and clinozoisite

Fig. 4.2 Part of amphibolite mass within Furulund schist at Gikem,((south of the road , west of the bridge). The rock is in an advanced state of brecciation.

Fig. 4.3 The lower part of the amphibolite lense ar Giken mentioned above. The amphibolite, in the top left of the photograph, is massive in contrast to the schist below.

in equal proportions, with small quantities of muscovite, chlorite, apatite and garnet.

The schist strip marked on Fig.3.2 which runs within the Sulitjelma amphibolites from Otervann (east of the thesis area) to Giken Elv (at least) is a fine-grained well-layered rock with extremely good schistosity. Specimen 334 is typical, containing quartz, calcite, muscovite, biotite and the odd grain of tourmaline. The contortions of this banding are shown in Fig.4.8 and also in the hand-speciman 344, but it is not known if these are sedimentary in origin.

At Hankabakken (Map 5,) and at several localities between Giken and the mine office (Map I) lie lenses of amphibolite which possibly represent boudined parts of one basic sill. The Hankabakken body, illustrated in Fig.4.1, (opposite), is 50m. by 300m. and is composed of coarse-grained feldspar-amphibole rock of massive appearance. The rock has a slight foliation, which is parallel to the contacts at the north and the south, and to the schistosity outside. The lenses at Giken and above the village are smaller, with tapering ends and more variable lithologies than at Hankabakken. Fig.4.2 and 4.3 (on the next page) show the character of the rock at Giken. This lense is of coarse-grained green and white amphibolite with a slight banding parallel to the schistosity outside. The top metre or so is fine-grained light-green rock, the bottom metre or so is a soft chloritic schist.

The schist in Balmi Elv is similar to that north of Langvann, being mainly biotite- muscovite schist with bands of highly calcareous schist. One notable difference is that the biotites are relatively large, up to 0.5mm. across and they have a strong L tectonite fabric. The muscovites, considerably finer-grained, are compressed around those biotites which lie at a high angle to the schistosity, as is shown in Fig.7. 2 . The fabrics are further discussed in Chapter 7. Specimens 706 to 713 are from Balmi ELv.

Within the succession in Balmi Elv is a conspicuous fragmentary rock,

Fig. 4.4 The banded character of the [illegible]und Schist.

Photograph taken near Lomi Ely. [illegible] of cliff - Er.

Fig. 4.5 The small scale banding of the Furulund Schist.

This outcrop has the appearance of inverted graded bedding, but this cannot be substantiated in thin section. While small parts of the Furulund Schist may be inverted because of local folds it is suggested that the bulk of the area is the correct way up.

shown in Fig.4.7. Henley has traced the outcrop of this rock across the area south of Langvann.

4.3 Bedding and other sedimentary features.

Bedding is clearly visible in nearly every outcrop of Furulund schist. Except in the closures of early folds the schistosity is everywhere parallel to bedding. Figures 4.4, 4.5, and 4.6 illustrate the appearance of bedding on various scales.

Other sedimentary structures were searched for. At one locality (498 471) there was some possible graded bedding suggesting that the sequence was inverted. Fig.4.5 shows this outcrop, from which specimen 608 was taken. The lighter parts on the photograph are of coarser rock but there are no really sharp contacts between coarse and fine-grained bands. The Furulund schist as a whole is considered to be the right way up on regional grounds. The rock unit is of large extent and furthermore is the top part of a thick succession which does not show any structural sign of being inverted. General stratigraphic clues suggest that the sequence is right way up since the lower parts are'sparagmitic' in character (Eocambrian), while the Furulund schist contains supposed Mid-Ordovician fossils. If this one locality is inverted it could be that it is on the short limb of an early minor fold.

The structures within the strip of schist inside the amphibolites at 504 483 mentioned above on page 29 and illustrated in Figures 4.8 and 4.9 may be sedimentary in origin.

4.4 Lithological differences within the Furulund schist.

The lithological differences within the Furulund schist do not suggest large-scale folding, apart from gentle regional warps. The only obvious marker bands are the two strips of rusty phyllite; these are not folded. Other lithological changes are more grad ual and cannot be marked on the map. It is possible, however, to discern a succession. This is best seen between Giken and Hankabakken.

Fig. 4.6 The banded character of the Furulund Schist near the top of the succession. The rock has suffered a considerable amount of hmx boudinage. Photograph taken about 1km west of Giken. Hammer shaft is marked in inches.

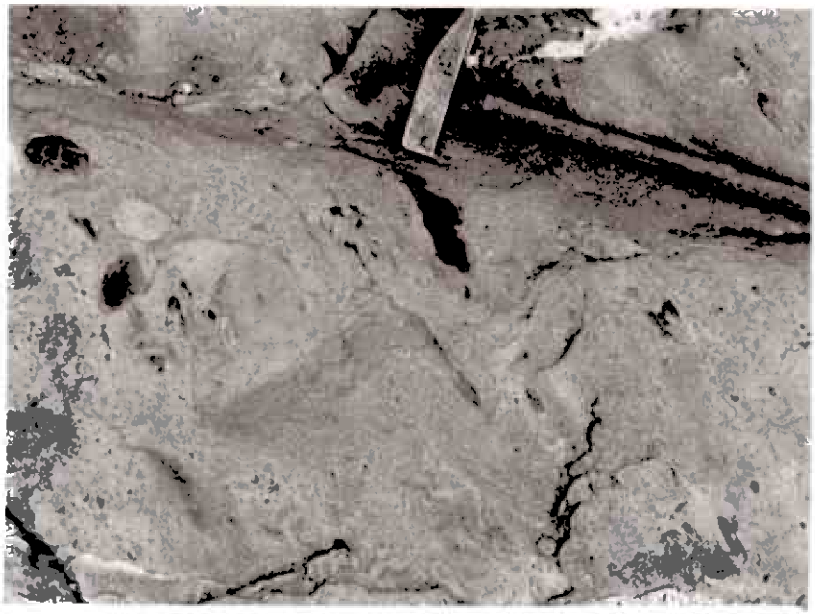


Fig. 4.7 Conglomerate in the Furulund schist in Balmi Elv, south of Langvann.

Succession within the upper part of the Furulund schist

Base of amphibolites - tectonic breccias with quartzite bands at base.

Rusty phyllite (Carlson's rustskiffer)

Non-porphyroblastic Furulund schist (with occasional garnets and hornblendes)

150m.		Zone rich in garnets - extends across area. A few hornblendes.
	Cliff	Plain Furulund schist, only occasional porphyroblasts. Very thin calcareous bands as in Fig. 5.2.
	feature	Rusty phyllite - forms base of cliff feature
150m. visible		Hornblende bearing schists. Concentration of hornblende varies - can be as rich as in specimen 701, (Fig.7.8)Garnets only occasionally present, none east of grid easting 490, even though whole area is within the garnet-hornblende isograd of Henley. Calcareous bands common.

4.5 Summary of the structural and metamorphic history of the Furulund schist.

The following structural and metamorphic events are recognised, but the position in the list does not indicate strictly the order of occurance:-

Biotite schistosity-lineation fabrics - coeval minor folding

Emplacement and folding of quartz segregations

Growth of garnet and hornblende porphyroblasts

Ore emplacement at unknown time

Boudinage of amphibolitic bodies and of quartz veins

Several phases of post-schistosity minor fold generation

Development of shear zones near Ny Sulitjelma

Jointing over the whole area

Faulting north-east of Ny Sulitjelma

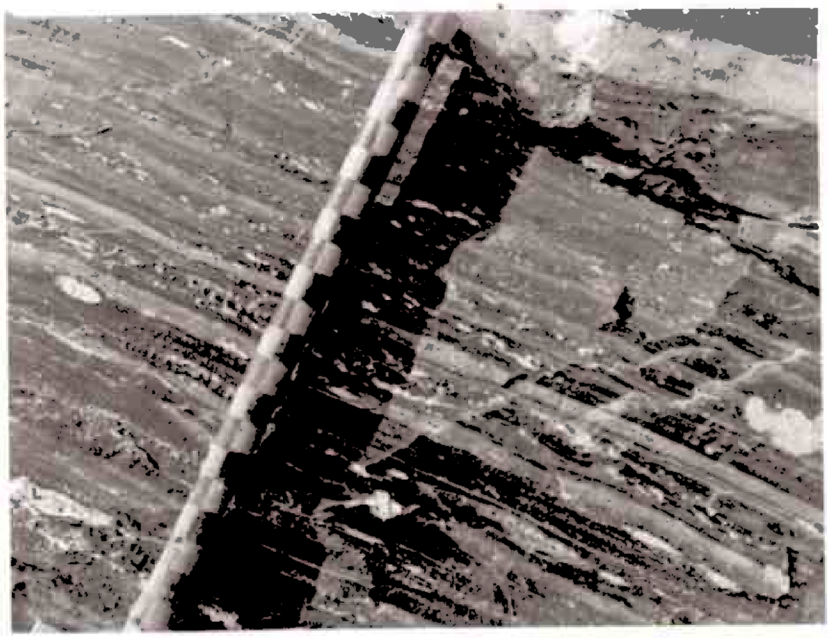
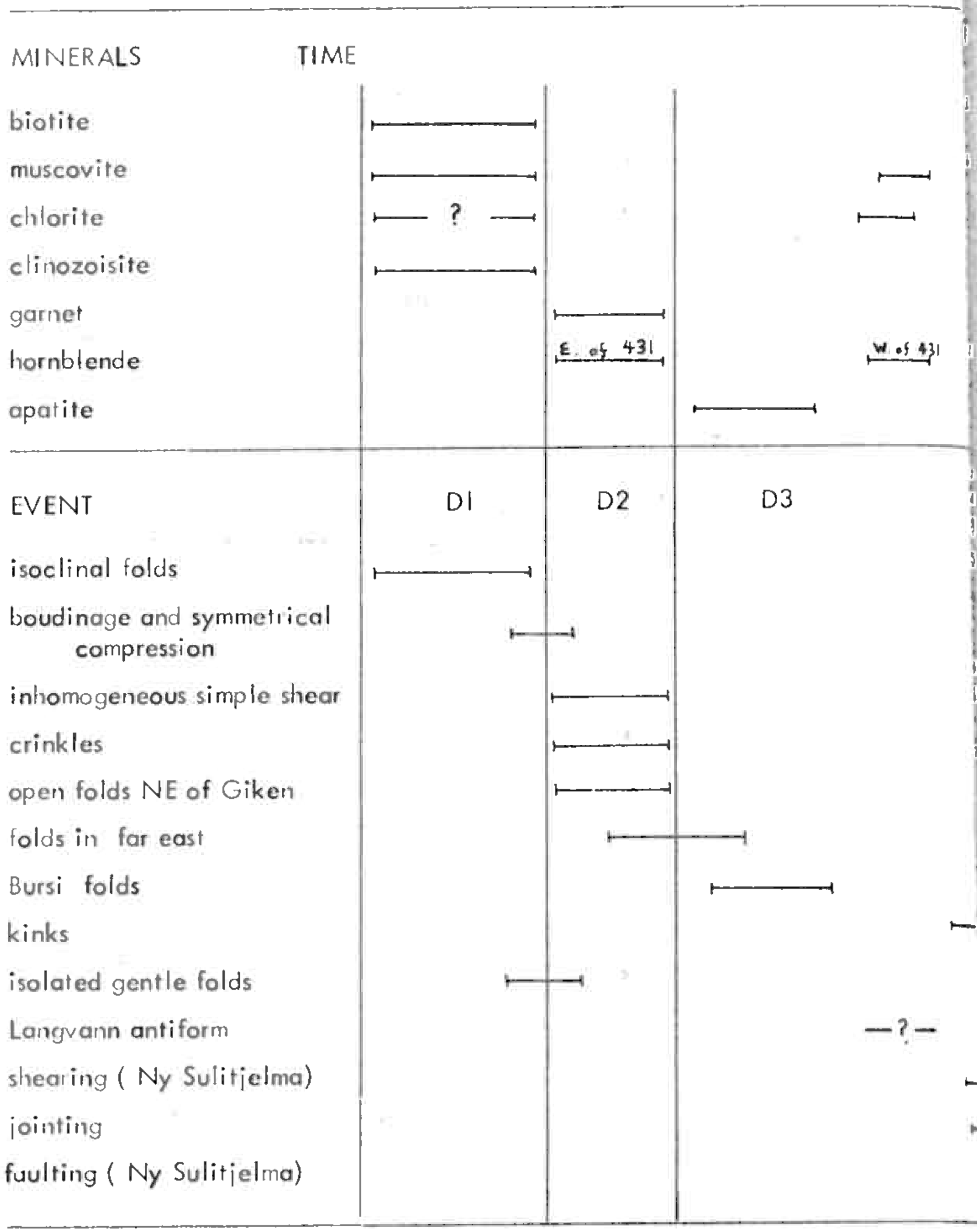


Fig. 4.8 The banded nature of the strip of Fumålund schist which lies within the Sulitjelma amphibolites in the east of the thesis area. Locality grid reference :- 504482

Fig. 4.9 Same rock and locality as Fig. 4.8. - Below the hammer can be seen contortions of the bedding.

FIG. 4.10 STRUCTURAL AND METAMORPHIC HISTORY - FURULUND SC



The following section is a summary of the facts known about the above events. An attempt is made to synthesise the observations in the table opposite (Fig. 4.10).

Schistosity-lineation fabrics, defined by the preferred orientation of biotites (and in places muscovite and chlorite), are found with the schistosity parallel to the axial planes of tight or isoclinal folds. These folds are considesed to belong to one group, named FI, a different interpretation from that of Henley (1968). The formation of schistosity was followed in Balmi Elv, south of Langvann by a tightening of micas around those biotites which are particularly oblique to schistosity. This was a deformation in which the plane of maximum flattening of the strain ellipsoid was parallel to schistosity, since the flattening is perfectly symmetrical, there being no rotation effects. A similarly orientated deformation takes place at some time north of Langvann, since boudinage occurs, again usually without rotation. The boudinage caused folding by flowage of rock into the boudin scars, some of this folding possibly being on quite a large scale. Previous to the boudinage quartz veins had been emplaced. These are folded or boudined according to their original attitude relative to the stress axes. Some quartz veins may be earlier than the FI folds, some are definitely later.

Garnet and hornblende growth occured after a good schistosity had become established. Some garnets grew without rotation, but most,(and all the hornblendes) grew during deformation. The character of this deformation can be deduced(in part) from a study of the inclusions within the porphyroblasts, as is discussed in Chapter 7. It is suggested that the garnets grew during a deformation in which there was a strong element of simple shear. Garnets and hornblendes grew at approximately the same time ,(except in the far west). The hornblendes, elongate parallel to their z crystallographic axis have the preferred orientation of a L-S tectonite fabric. The lineation of the hornblendes is parallel to the lineation of the biotites. This latter lineation is the product of the early F1 strain, the strain during garnet growth and strain following garnet growth, and does not necessarily lie parallel to the longest axis of the strain ellipsoid for any one of these deformations. But since the biotite lineation (the product of three deformations) is parallel to the hornblende lineation (the product of the two latter deformations) it is possible that the early deformation lineation was parallel to the longest axis of the strain ellipsoid for the two latter deformations.

In Balmi Elv there is an example of the folding of calcite bodies which cross schistosity, the schistosity itself not being folded, the deformation apparently having taken place by simple shear parallel to the schistosity. This deformation is tentatively correlated with the deformation during garnet growth north of Langvann and the event termed F2. Minor crinkling is associated with the growth of garnets, and it is possible that other crinkling about the same axes and also limited open folding which occured at this time all form part of the F2 event.

Post-schistosity minor folds in various parts of the region can be classed within the general category of F3 folding, though it is unlikely that folds in different areas are exactly coeval. In the east of the thesis area there are minor folds overturned to the east. The axes of these folds lie parallel to the axes of rotation of garnets in these rocks, and it is possible that folding began during garnet growth, though most of the fold deformation is later than the garnet growth. In the west of the thesis area there is post-schistosity minor folding on axes normal to the axes of garnet rotation. This folding affected all the rocks at Bursi on a minor scale, but the schist strips A, B and C were thrown into major disharmonic folds, which must have necessitated limited sliding in the underlying ore and amphibolite. During this folding crenulation cleavage developed which in parts becomes penetrative.

West of Bursi there is a separate phase of post-schistosity folding which is later than garnet growth, but is earlier than hornblende growth since hornblende grains grow over the tightest microfolds. It is assumed that these post-fold hornblendes did not grow at the same time as hornblendes further east. This minor folding has a different orientation of axes and axial planes from the folds immediately east, at Bursi.

In addition to the post-schistosity minor folds introduced above there are very gentle open folds of schistosity. One such fold is the gentle Langvann antiform, which is illustrated in thenorth-south section in Fig. 3.2. The axis of the fold has a NW-SE azimuth. Folding on a similar scale is responsible for the Baldaoive Synform, which according to Henley, (1968) has a N-S axis. Henley terms these two folds F4, the Baldaoive synform being F4a, the Langvann antiform F4b.

In the Ny Sulitjelma area there are several shear zones in which the rock is severely fractured. In places the rock is sufficiently fractured as to be a breccia, though there is only little relative movement between fragments. In the zones the schistosity is slightly folded, but most of the deformation is by fracture, so it is assumed that the deformation is a late phase.

Jointing is well developed over the whole area, but has not been studied in this investigation. Holmquist made many observations in 1895 which were written up by Sjögren in 1896 and discussed with further observations by Vögt in 1927. According to Vogt's synthesis the joints are vertical, falling into two groups which strike 027° and 300°, with some subsidiary ones striking 330°.

Mine company maps of the mine workings at Ny Sulitjelma show a fault which is the eastern termination of the Ny Sulitjelma ore body. The fault is marked on Map 5 of the Ny Sulitjelma area, and its effects on the ore body shown on Fig.3.4 .The fault was not visible on the surface, although conditions are not generally favourable for its detection since it lies at the eastern end of the body of banded amphibolites and quartzites which lie within the Furulund Schist at Ny Sulitjelma , as described in Chapter 3.4. Fig.3.4 shows that the azimuth of the fault is 140° and the throw varies between 50m. in the south-east and 200m. in the north-west. The azimuth is the same as that of faults further north which cut the Sulitjelma Schist Sequence and the Sulitjelma amphibolites and which are marked on Maps 1 and 4 . These Waterfall zone faults have similar throws, though it is impossible to determine the throw as accurately. Several of the faults appear to die out in quite short distances, though the longest, along which the gorge below the main waterfalls is cut, extends several kilometres, and can be identified by a marked feature on the aerial photographs and by a fault breccia zone some 2 to 3m. wide.

CHAPTER 5

EARLY FOLDS OF THE FURULUND SCHIST

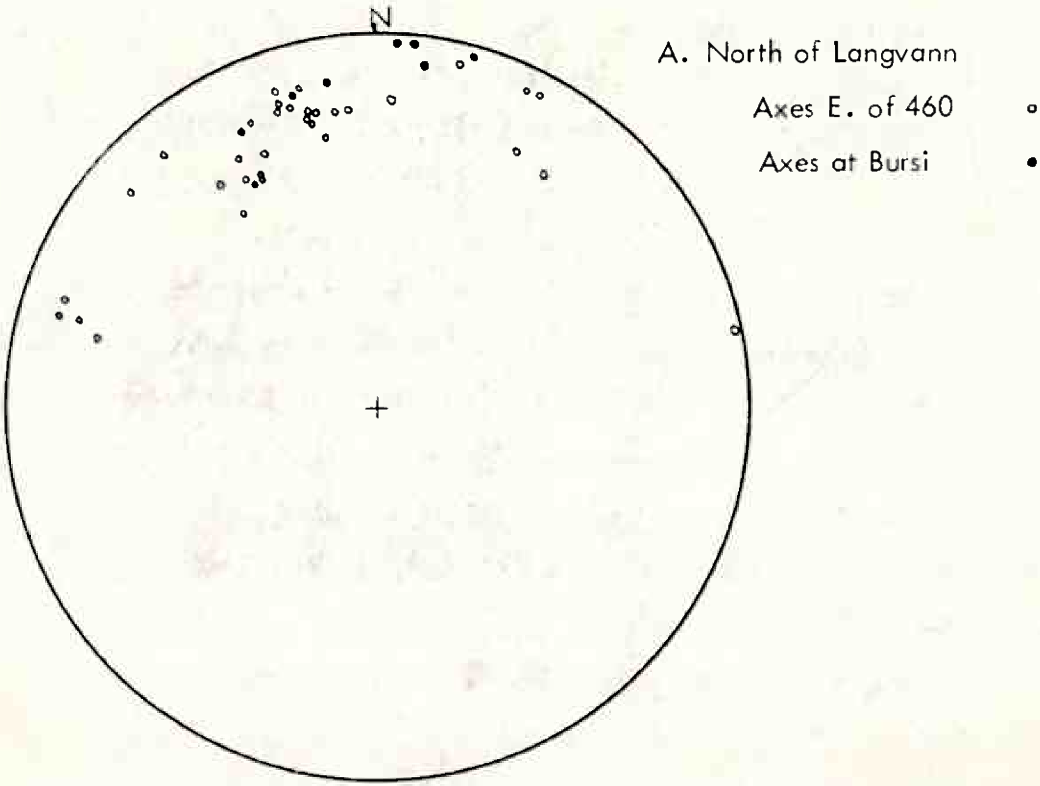
5.1 Introduction.

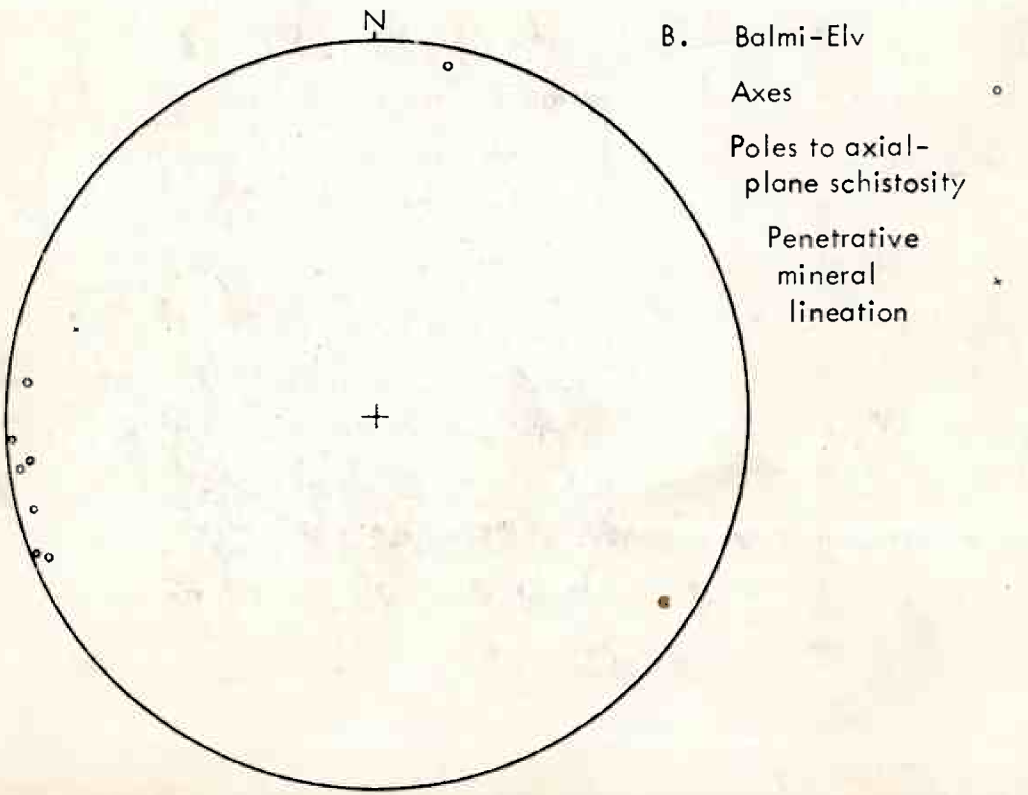
Early folds are here distinguished as those in which the regional penetrative schistosity lies parallel to the axial plane of the fold. No large scale early folds can be detected within the Furulund schist but the uniformity of lithology would make any repetition of succession difficult to see. Minor early folds are seen in several parts of the thesis area. Their distribution, density of occurrence and axial directions are shown in Map 2, and it is clear that their distribution is irregular; folds being relatively common in a band east of Giken and at Bursi, and rare elsewhere. The style of the folds varies considerably, but in general they are tight or isoclinal.

5.2 Previous descriptions.

Henley (1968) has described early folds in the large area of Furulund schist south of Langvann, dividing them into two groups, F1 and F2, which formed during two deformation episodes D1 and D2. The main regional schistosity-lineation fabric he refers to as S2, having formed during the D2 deformation. This D2 event was the major deformation of the Sulitjelma rocks in Henley's interpretation, having destroyed all traces of the D1 fabric (S1) except for the occasional relics in garnet porphyroblasts. Henley's D1-D2 interpretation is here questioned. The F1 folds of Henley, (isoclinal or tight mainly found in Balmi Elv, south of Langvann) have axial directions oblique to the penetrative mineral lineation, while F2 folds (also isoclinal) have axial directions parallel to the mineral lineation. Henley gives the following trends for the two groups:- F1 axes - 240° to 250°, F2 axes - 275° to 285°.

FIG. 5.1 AXES OF EARLY FOLDS FURULUND SCHIST





plot of early fold axes measured by the writer in the Balmi Elv stream section south of Langvann, from where Henley has described most of his Fl folds. The majority of these fold axes plot between 250° and 280°, falling neatly into the gap between the directions of Henley's Fl and F2 fold groups. A certain scatter of axes is always inevitable. The directions of the axes of the early folds of the Furulund schists do not indicate that the folds are of two generations.

Henley states that there is fabric evidence for an early phase of deformation prior to the generation of the main biotite fabric. This evidence is that fine-grained schistose fabrics are occasionally preserved as trails within some garnets. As discussed in Chapter 7.6, all garnets seen north of Langvann grew after the establishment of a good schistosity, during a slight deformation. Occasional garnets (eg. in specimen 401 from Ny Sulitjelma) have much finer inclusions than do other garnets, but in these cases the external fabric is also finer than usual, and continuity is preserved between the external schistosity and the internal trails. All that Henley's garnets indicate is that some garnets either grew in an unusually fine-grained matrix or grew earlier than other garnets.

In addition to the above arguments there are other objections to the hypothesis of two phases of folding. If the second phase of folding generated new folds of bedding then the early schistosity would have to be folded on a large scale. The new schistosity developing would be a non-penetrative crenulation cleavage. In the pelitic Furulund schist metamorphic differentiation would occur and the biotite and quartz would become banded. Further deformation could make the schistosity penetrative, but the banding of the quartz and biotite would remain. There is no trace of such in the Furulund schist. If the first-formed schistosity remained planar existing folds could be modified and surfaces crossing schistosity could be folded, but no new folds of bedding could be generated. As described in Chapter 5.10 it is suggested that limited deformation of this type has occured.

Fig. 5.4 Early (syn-schistosity) fold of calcareous band in the Furulund schist which has been refolded by later post-schistosity folds which are overturned to the [illegible]. The photograph also shows the typical joints developed in the Furulund Schist.

See section 5.5 on page 40.

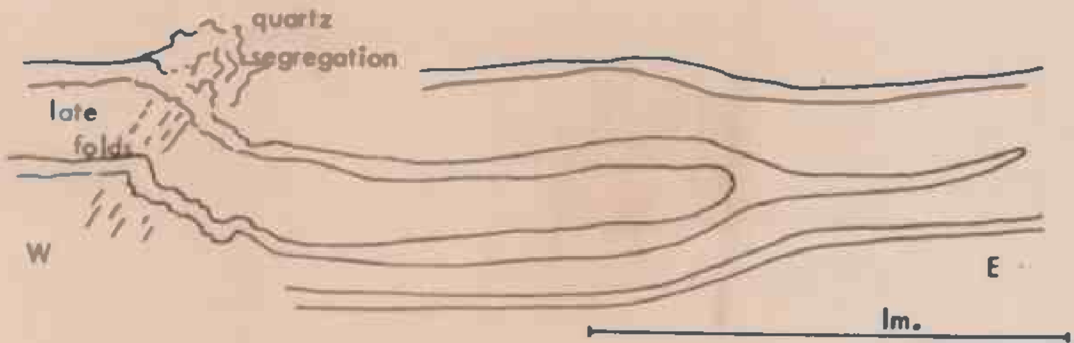
The only difference between the two groups is the geometrical one of their axial directions. Henley makes an assumption that if a fold is generated at the same time as a schistosity-lineation fabric then the axis of that fold will be parallel to the penetrative mineral lineation. Since half the folds he observes have axes oblique to the mineral lineation, he suggests that there was an earlier deformation in which the F1 folds were generated, their axes being parallel to a lineation L1 now destroyed by recrystallisation. The initial assumption must be questioned. The relation of a schistosity-lineation fabric to the finite strain ellipsoid of the deformation which generated that fabric has been discussed by Flinn (1965a). Flinn associates an L-tectonite with a prolate deformation ellipsoid, the lineation being parallel to the direction of maximum extension, the schistosity parallel to the plane containing the minimum and intermediate strain axes. Thus Flinn states "All deformed conglomerates in metamorphic rocks showing L-S tectonite type fabrics have the pebbles elongated parallel to the lineation. " (1965a, pg 41). The relationship of fold axes to the deformation ellipsoid is not so simple. The work of Flinn (1962) has shown that the attitude of a fold axis within its axial plane is governed solely by the original attitude of the layer that is being folded and therefore fold axes bear no special relation to the axes of the finite strain ellipsoid, except that they lie within the plane containing the maximum and intermediate axes.

Since Henley's initial assumption is incorrect, part of his argument in favour of two generations of early folds is invalid and the rest of the argument must be re-assessed. On the basis of axial directions, Henley divides the early folds into two groups with axial trends 240° to 250° and 275° to 285°. Fig. 5.1a is a plot of all the early fold axes measured by the writer north of Langvann. The majority of these fall between 310° and 030°. The variation in any small area north of the lake is comparable with the variation between 240° and 285° (range of 40°), Henley's entire range of azimuth readings. Fig. 5.1b is a

Fig. 5.2 Isoclinal early fold in the Furulund Schist. Base of the cliff feature east of Giken. Typical of the finely banded rocks with isoclinal folds as described in section 5.4 on page 40.

Fig. 5.3 as above.

FIG. 5.4 Early (syn-schistosity) fold of calcareous band refolded by post-schistosity folds which are overturned to the east. Note the quartz-segregations associated with the post-schistosity folds. Note the typical joints in the schist.



Traced from sketch in field note book (14.11).

Henley's division of the early folds into two groups and his description of the regional schistosity as S2 is therefore held to be unjustified and is not followed in this account.

5.3 General description of the early folds.

All the early folds found north of Langvann are folds of bedding and appear to be syn-schistosity. They are therefore termed F1 and the schistosity S1. Most of the folds described from Balmi Elv are assumed to be of the same generation, since they bear the same relationship to the schistosity. There are, however, some folds in Balmi Elv which are later than schistosity yet do not fold schistosity. Two examples were seen, one of an F1 fold bedding-schistosity intersection lineation which is folded in the plane of schistosity and the other, of calcite bodies which cross schistosity and are folded. These are termed F2 folds, and the deformation which caused them is tentatively correlated with the deformation which occurred during garnet growth north of Langvann.

F1 folds east of grid easting 460 are divided into four groups on the basis of location and style. The style is evidently related to the lithology, which explains the connection between style and location. The few early folds that were found in the thorough examination of the Bursi area in the west were of widely different styles though axial directions were similar.

Fig.5.1a is a plot of F1 fold axes, those from the east of the region being open circles, those from Bursi being filled circles.

Sense of overturn could rarely be determined. It was impossible to tell which limb was the short limb due to the small size of outcrops. Two folds in the east were overturned to the west and two in the west overturned to the east.

The reason for the distribution of the folds is not clear. The range of density of occurrence of folds shown in Map 2 is only slightly exaggerated; examination of map 1 indicates that some areas were mapped more thoroughly than

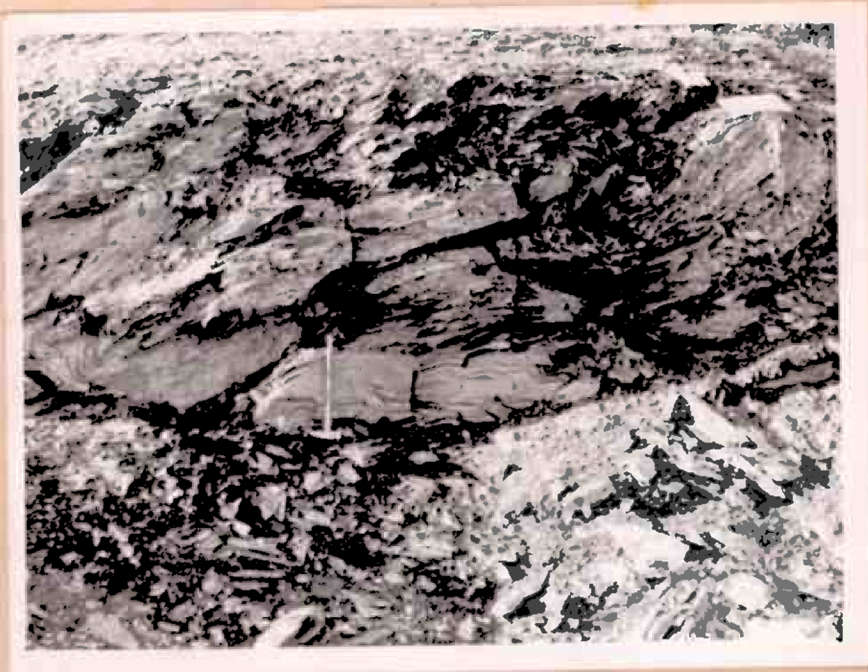


Fig. 5.5 Isoclinal pre-schistosity fold of calcareous band in the Furulund schist refolded by post-schistosity folds. The later folds are best developed in the more pelitic parts in the left of the photograph. See section 5.5 opposite.

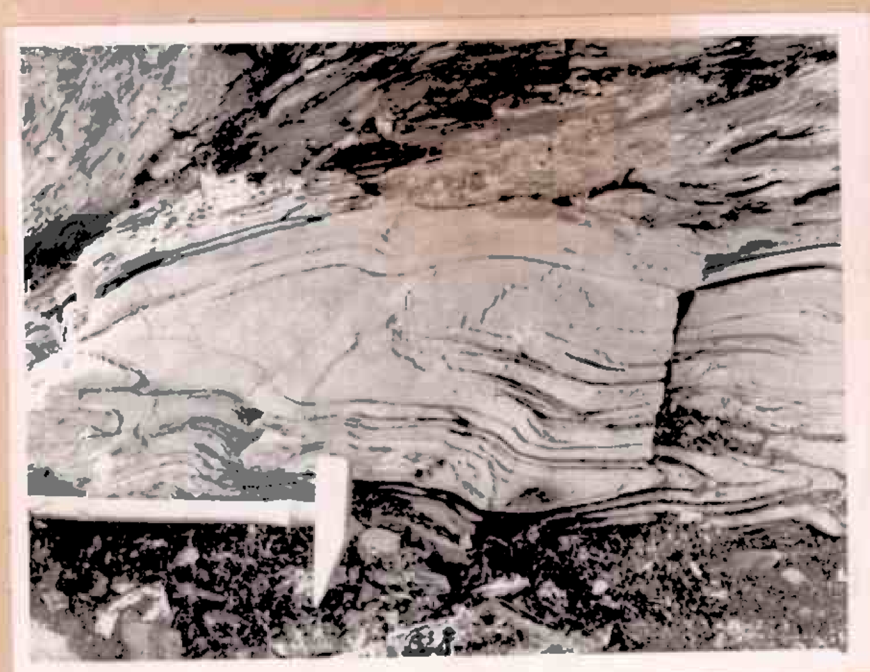
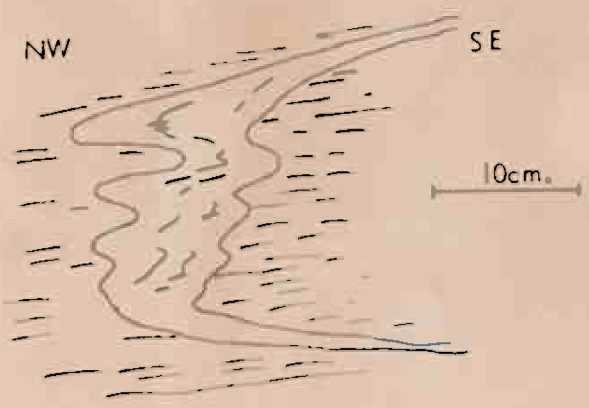


Fig. 5.6 Close-up of the above photograph. Note the intense folding.

FIG. 5.7 Syn-schistosity fold of calcareous band in the Furulund schist. Photograph is taken almost along the fold axis. Location- about 1km. east of Giken.



Traced from sketch in field note book (13.23)

others. It is certain, however, that some areas are relatively deficient in early folds. It is possible that the zone rich in minor folds represents the two hinge areas of a "Z" type major fold, a fold with two very large "long" limbs, and a very small "short" limb. As stated in Chapter 4.4, there is no evidence from the succession for a major early fold involving repetition, so it is assumed that the zone does not represent the hinge zone of an"M" type major fold (see Elliot 1968 pg. 172 for definition of 'M' and 'Z' type folds.)

5.4 Isoclinal folds in the cliff north-east of Giken.

Above the track which rises from Giken towards Ny Sulitjelma is a steep cliff caused by the resistance to erosion of a band of garnet-rich schist which overlies soft rusty phyllitic schist, (see succession on page 31.) At the base of the cliff immediately overlying the rusty phyllite is a rock with very thin bands of highly calcareous schist. Bands can be seen to terminate in folds or be folded as a whole. Since the folds usually occur on massive faces it was impossible to tell what attitude the axes had. The style of these folds is shown in Figures 5.2 and 5.3.

5.5 Folds of calcareous bands east of Giken.

As noted in the sections on lithologies and stratigraphy, bands of highly calcareous schist up to lm. thick can occur in the Furulund schist. Occasionally these can be seen to terminate or bifurcate in isoclinal folds. In the far east of the thesis area two examples were seen where the isoclinal folds were themselves refolded by post-schistosity folds. These are illustrated in Figures 5.4, 5.5 and 5.6. Some of the folds of calcareous bands are not so tight, as is illustrated in Fig. 5.7. Axes of these folds were usually readily determined by measuring the intersection of bedding on schistosity.

5.6 Folds south of path linking Giken to Ny Sulitjelma.

South of the Giken-Ny Sulitjelma path are found a considerable number of folds with a very distinctive style. As can be seen from figures 5.8, 5.9, 5.10 and 5.12, the folds are made up of two orders of folding, a large first-order fold with small second-order folds superimposed. The second order folds are tight (definition of Fleuty, 1964a) with angular hinges and may be described as zig-zag or chevron folds. The second order median surfaces (definition of Ramsay, 1967) from folds which vary in tightness of closure between tight and open, yet have a smoothly curved shape. The intersection of bedding on schistosity gives a lineation which is readily measured. Although folds with zig-zag second order folds are the most common, they are associated with folds of a variety of styles as at locality 10.46. Here it is plain that the folds are all of the same generation and that different lithologies have caused the development of different styles of folding. Folds of the distinctive style described above occur alongside more normal folds of calcareous bands as described in Chapter 6.5 above. Figs. 5.11a,b,c and d illustrate the different styles of folds that have developed at locality 10.46.

5.7 Early folds between Giken and the church.

These folds lie at a higher stratigraphic level within the schist than those described in the section above, being in the highly garnetiferous zone near the top of the succession. Large glacially smoothed outcrops show tight folding. Thin sections of these rocks show clearly that the axial planes of these folds are parallel to the schistosity, and that the porphyroblasts of garnet and hornblende here have grown later than any of the folding. Fig. 5.13 illustrates the appearance of specimen 506 in thin section. Figures 5.14 and 5.15 show the styles of the folds developed.

Fig. 5.8 Synschistosity fold of Furulund schist east of Giken. Second order median surface of the fold has a gentle S shape. The photograph is taken looking along the axis of the fold. See section 5.6 on p[illegible]

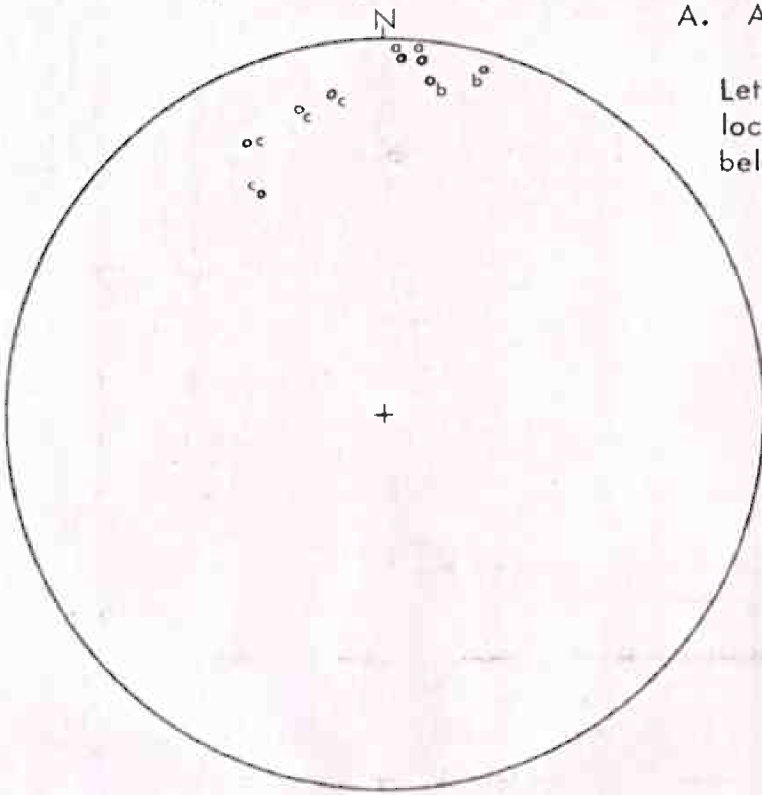
Fig. 5.9 Same type of fold as in Fig. 5.8 above. The second order median surface is tighter here.

Fig. 5.11c Isoclinal fold of calcareous layer.

Fig. 5.11d Same locality as the other photographs, but quite a different style. Probably of the same generation, but different lithology.

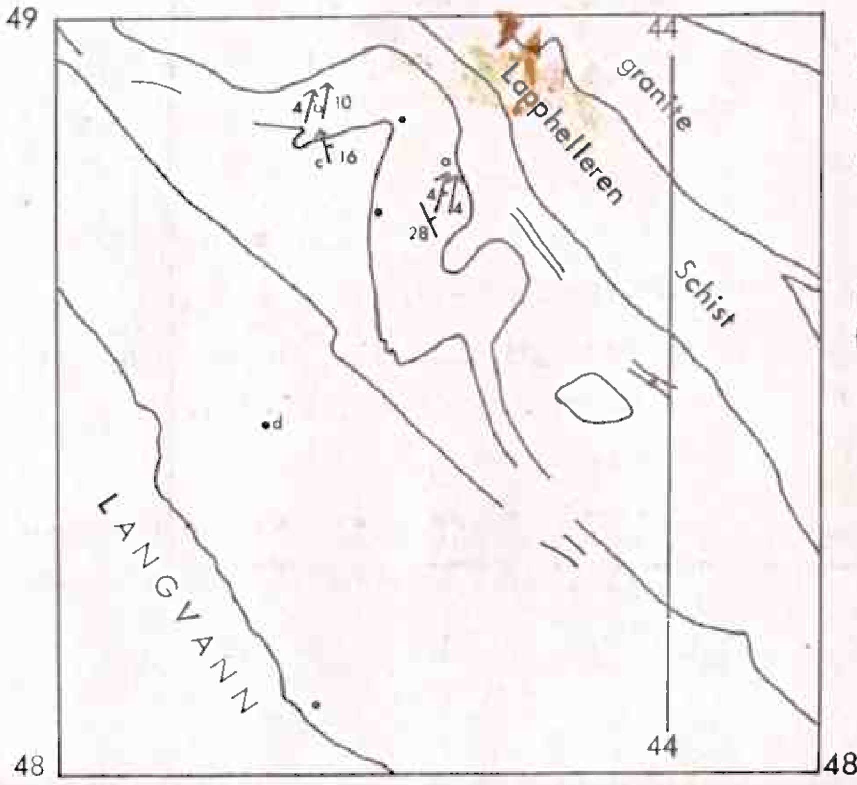
FIG. 5.16 EARLY FOLDS AT BURSI

A. Attitude



Letters refer to localities on map below

B. Distribution



Fold axis indicating sense of overturn

Axial plane

Locality with fold - no data

Scale:- 1:10,000

FIG. 5.10 Styles of early folds in Furulund schist south of path between Giken and Ny Sulitjelma.

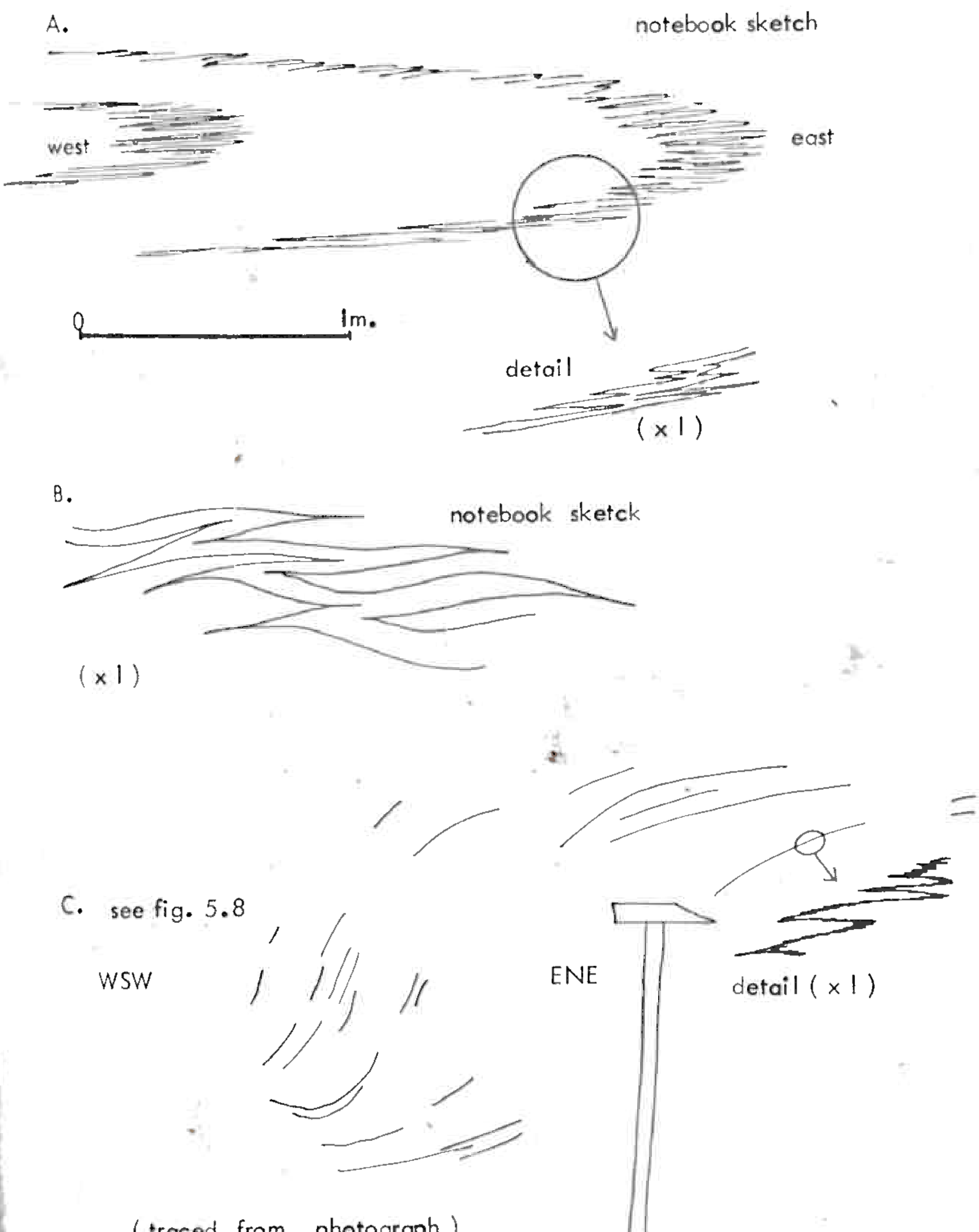


Fig. 5.11a Locality in the Furulund Schist about 1km. east of Giken. Described in section 5.6 on page 41. Several styles of syn-schistosity folds are developed adjacent to one another. The locations of the close-up photographs are indicated.

Fig. 5.11b A rounded fold of a calcareous band. Clearly the same fold closure as is shown in Fig. 5.11c.

5.8 Early folds at Bursi.

The small number of folds observed here vary considerably in style but axes from three localities plotted separately in Fig. 5.16A all have a northerly trend. Figures 5.17, 5.18, 5.19 and 5.20 illustrate the variation in style, and in scale. Two of the folds could be seen to be overturned to the west. Fig. 5.18 illustrates a fold (at locality 'b' on Fig. 5.16B) which has a line of quartz segregations parallel to the axial plane, near the hinge. The quartz vein was clearly emplaced and boudined after the fold.

5.9 F1 folds in Balmi Elv.

Early folds are very common and are well displayed in this stream section. The majority are tight to isoclinal with a very well-marked bedding-schistosity intersection. Fig. 5.21 illustrates this lineation, which can be seen to be not perfectly straight. Typical appearances of folds are as in Fig. 5.22.

In the south part of the stream section these isoclinal folds are orientated with their axes trending north , for example, 012 trend, 04 plunge, but further north early folds trend between 250 and 280, as is shown in Fig.5.1B.

5.10 F2 folds in Balmi Elv.

Figures 5.23 and 5.24 illustrate folding of calcite bodies which cross the schistosity at a low angle. The schistosity itself has not been folded. Only some of the lithological layers appear to have been affected. The style of the folding seems 'similar'. It is suggested that these folds have been generated by inhomogeneous simple shear, the shear plane being parallel to the schistosity. The amount of shear clearly varies within the individual layers, and from layer to layer. At a nearby locality on a planar schistosity surface, an originally straight bedding-schistosity intersection lineation has been folded into a moderately tight fold,a situation similar to that illustrated in Ramsay 1967, page 473, Fig. 8.11.

Fig. 5.13 Photomicrograph of specimen 506 to illustrate the parallelism of axial planes and schistosity , x60, Plane polarised light .

Fig. 5.12 About 10cm. above the hammer head is an early fold. The second order folds are isoclinal. The second order median surface is tightly folded.

Fig. 5.19 Isoclinal early fold at Bursi. The light band immediately above the hammer contains a fold closure which opens to the right (south-east). The dark band slightly higher can be seen to contain a fold closure which opens to the left.

Fig. 5.21 Bedding - schistosity intersection lineation. This is caused by early folding in the Furulund schist south of ~~xxxxx~~ Langvann. ~~xxxxx~~ Note that the lineation is not perfectly straight.

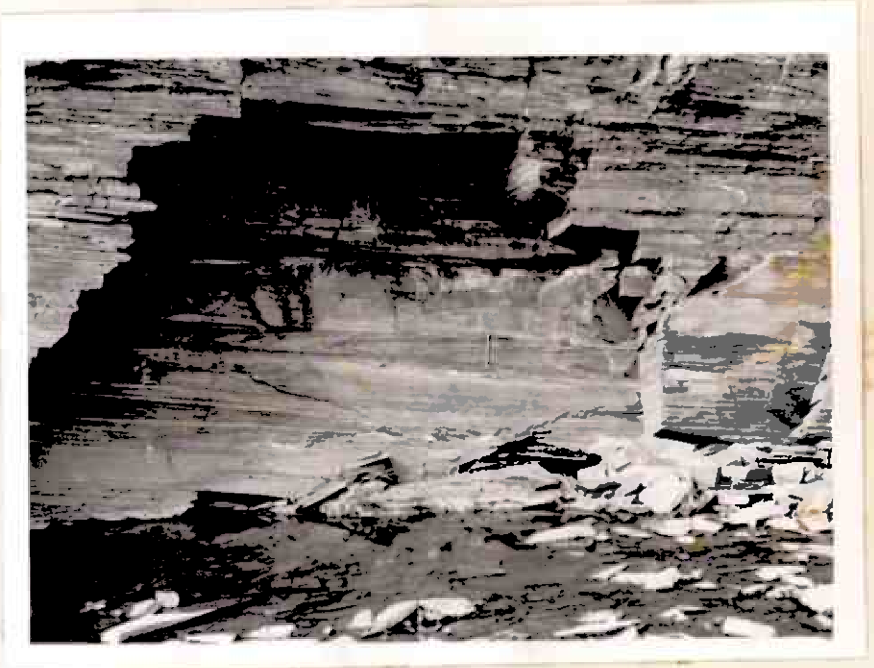


Fig. 5.22 Isoclinal fold in Balmi Elv. The closure crosses the centre of the photograph at the level of the hammer.
See section 5.9, pg 42.

Fig. 5.14 Synschistosity early folds about 500m. west of Giken, as described in section 5.7, page 41

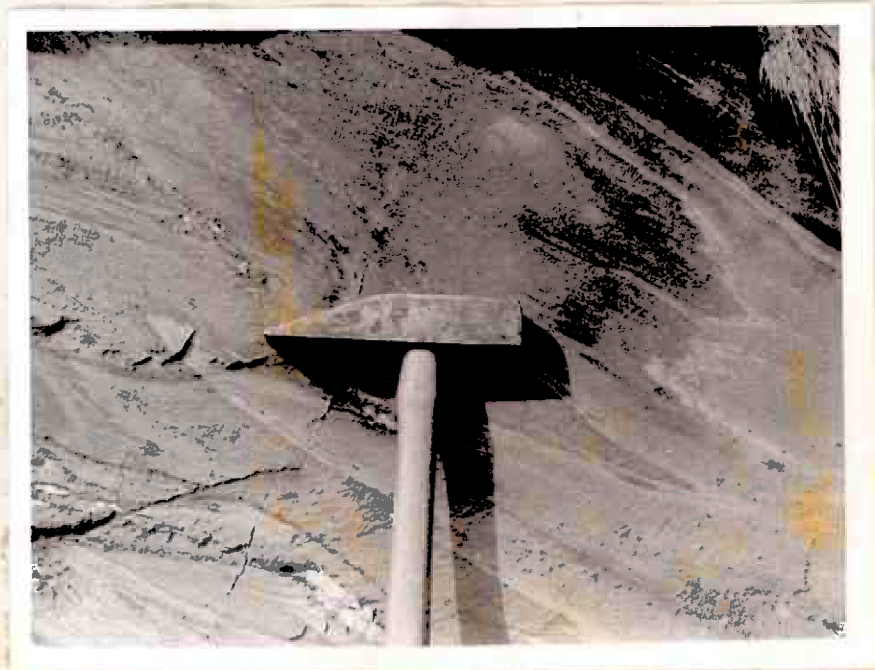


Fig. 5.15 As above.

Fig. 5.17 Early fold at Bursi, locality "a" in Fig.5.16b. See section 5.8, page 42.

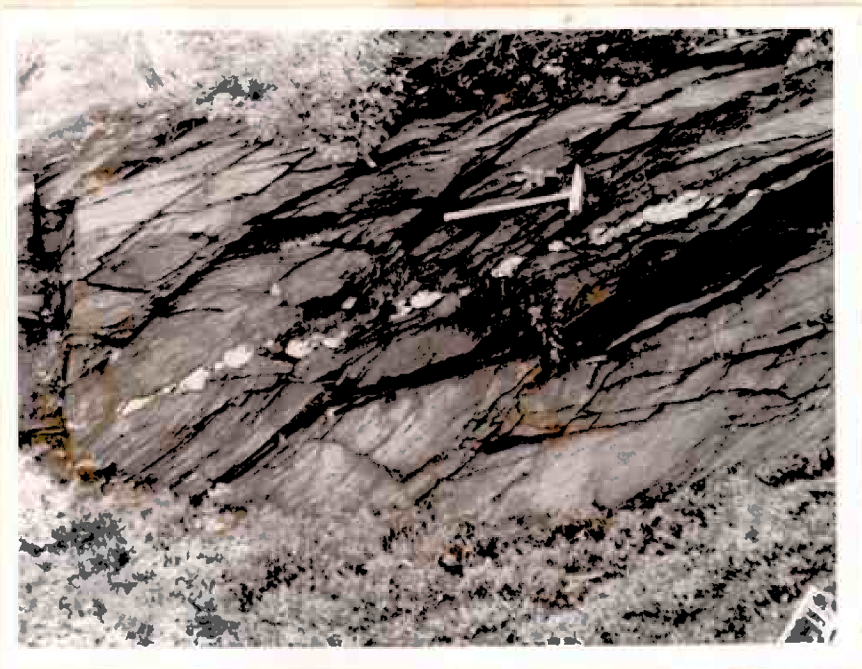
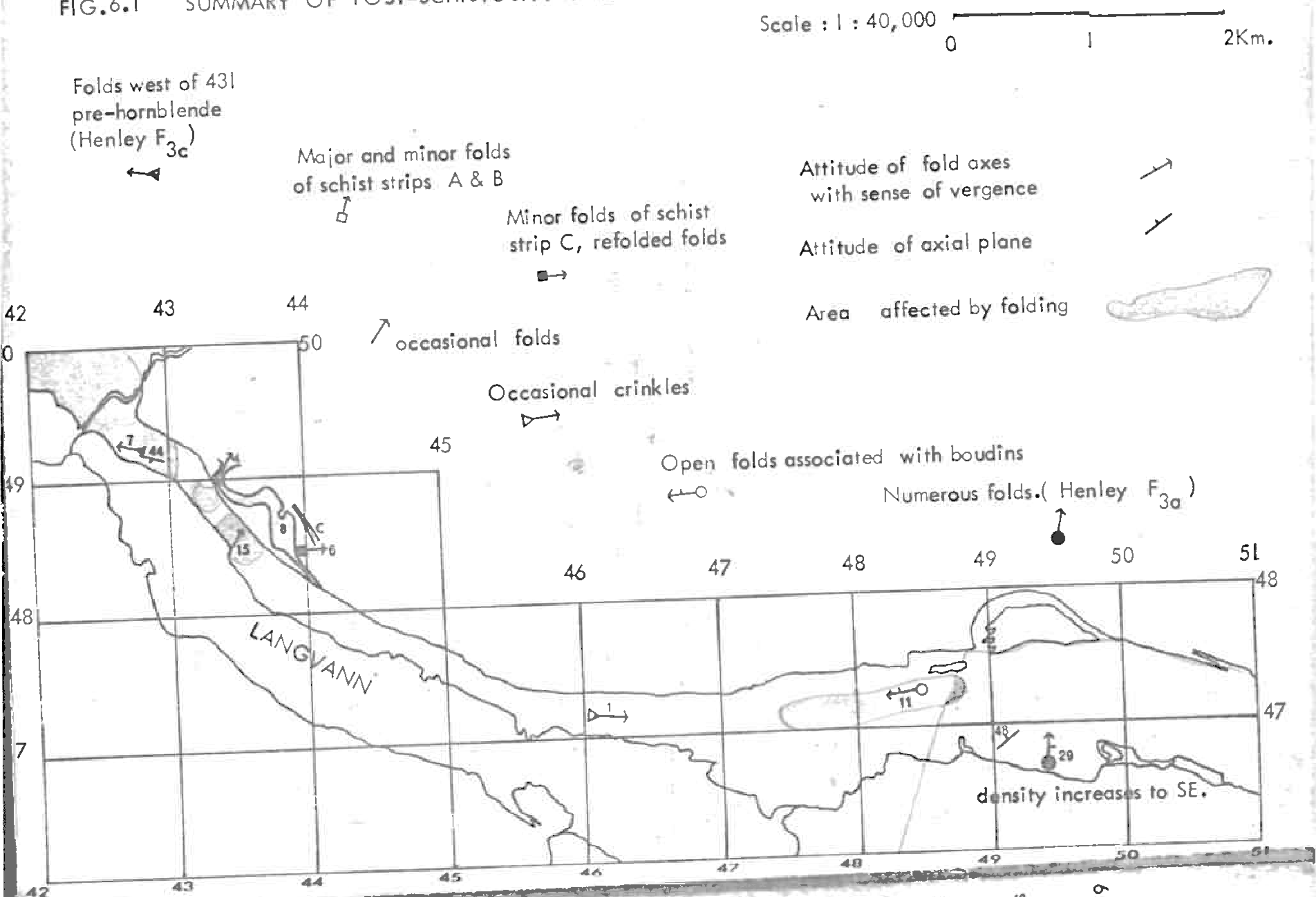


Fig. 5.18 Early fold at Bursi, locality "b" on Fig. 5.16b. This is on the largest syn-schistosity folds seen in the Furulund schist of the thesis area. The fold opens to the west. It is viewed from the south, and the photograph is taken looking along the axis of the fold. A set of quartz segregations lie parallel to the axial plane. See section 5.8 on page 42.

Fig. 5.23   Early folded in Balmi Elv. Bedding and schistosity are nearly parallel. Early calcite bodies have been strongly deformed by flattening , taking up the fold shapes seen here.

Fig. 5.24   Close up of above.

FIG.6.1 SUMMARY OF POST-SCHISTOSITY FOLDING OF FURULUND SCHIST



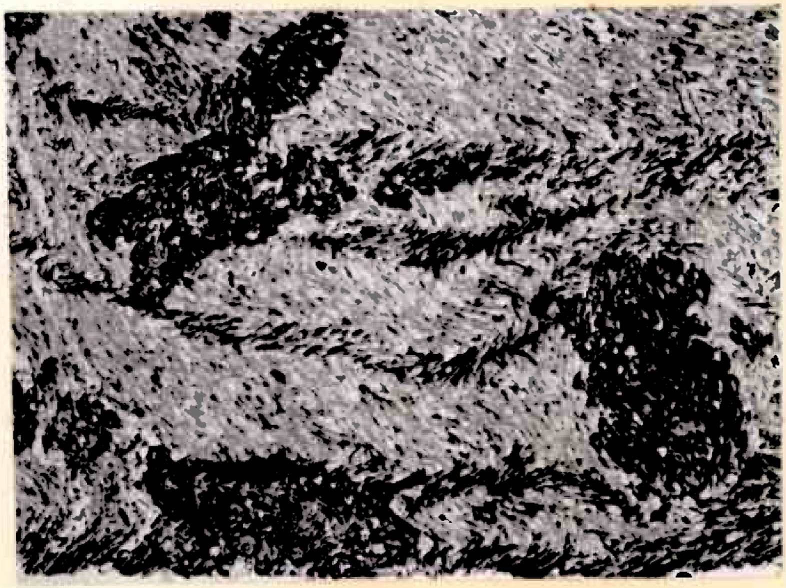
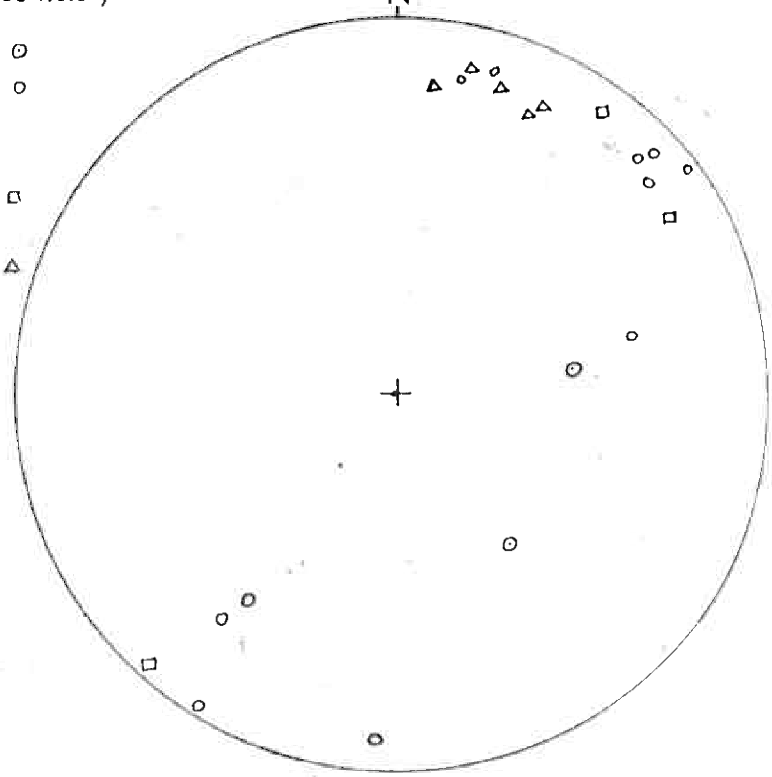


Fig. 6.24 Photomicrograph of specimen 717. x15.
Plane polarised light, crossed polars.
The specimen is taken from a fold closure west of grid section 431, Burni. The thin section is cut normal to the fold axis. The rock has a strong crenulation cleavage which is parallel to the axial plane of the fold.
Hornblende (marked Hb) has grown after the folding.
Garnet (marked Ga) has grown before the folding since the crenulations are deflected around the crystal and the pattern of inclusions is not related to the folded mica outside as it is in the case of the hornblende.
The garnet shows a ( ) pattern of inclusions indicating that the axis of rotation of the garnet is parallel to the thin section and therefore normal to the fold axis.

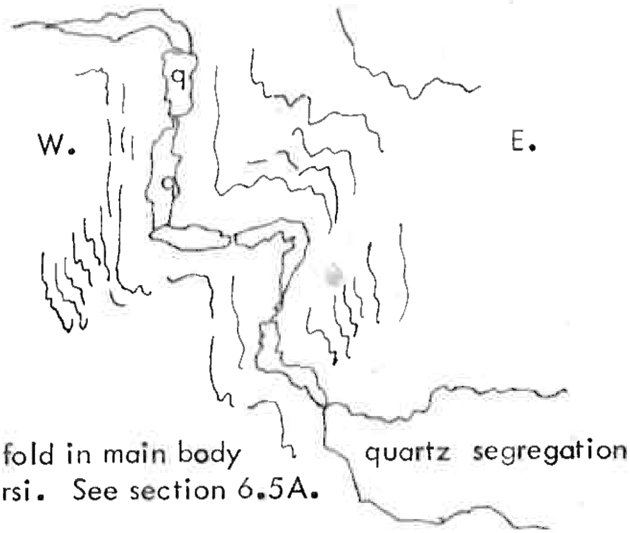
FIG. 6.25 Minor folds in the Furulund schist between the church and Bursi.

(main body of Furulund schists)

Poles to axial planes :- ⊙
Axes measured direct :- o
(at Bursi)
Constructed axes around
Bursi (π diagram) :- □
Constructed axes near
mine office :- △



Lambert equal area projection



(x ½)

FIG. 6.26

Style of minor fold in main body of schist at Bursi. See section 6.5A.

FIG. 6.27

Open fold in main body of schist at Bursi. See section 6.5B.

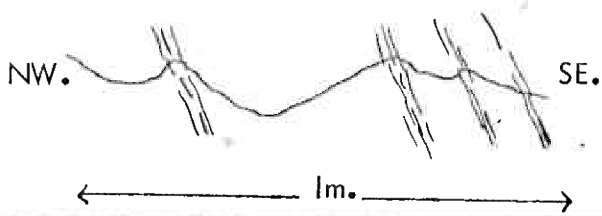


Fig. 6.18 Detail from the same exposure as Fig. 6.17

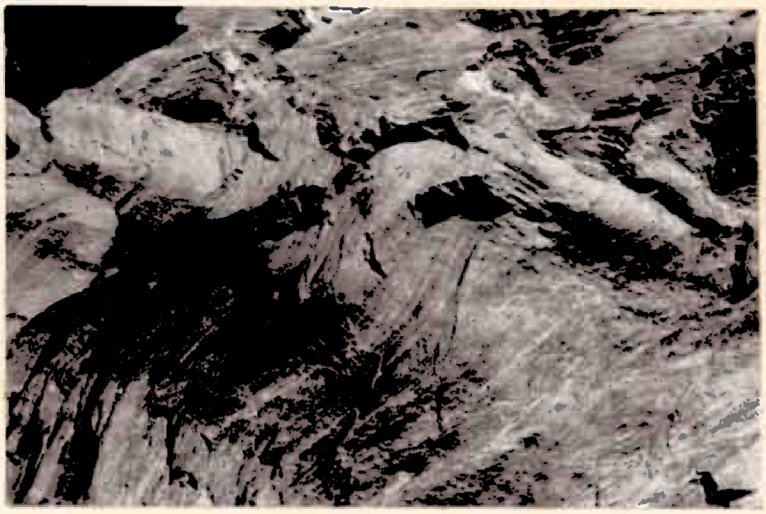


Fig. 6.19 Open folds immediately east of Giken Elv, near the top of the Furulund Schist.
See section 6.3 on page 46.

Fig. 6.20 Open folds in cliff N.E. of Giken. The folding here appears to be related to the location of quartz segregations.

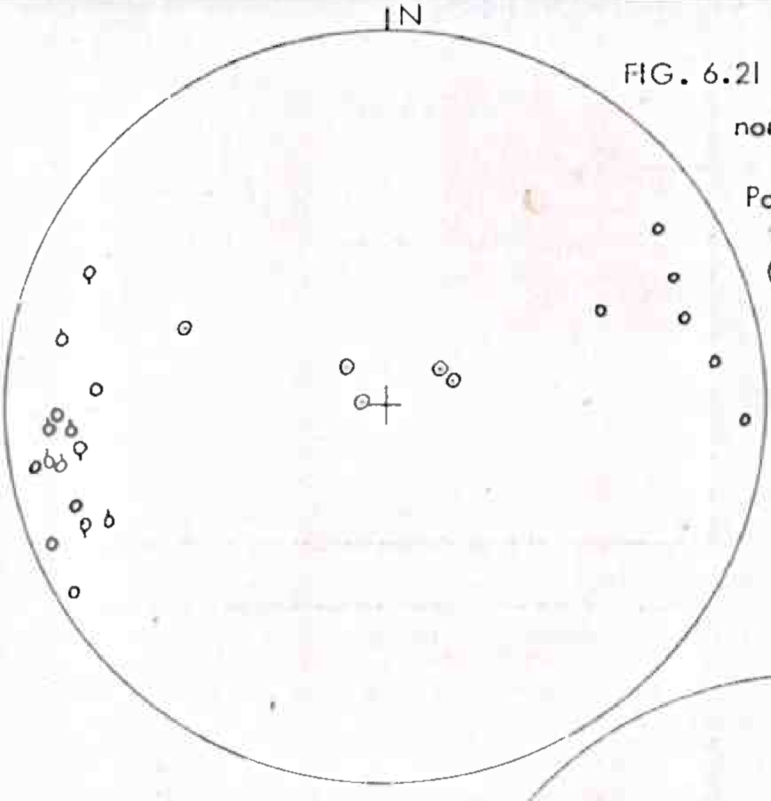


FIG. 6.21 Open folds in cliff feature north-east of Giken.

Pole to axial plane :- ⊙
Fold axis :- o
(overturned to N.:- ♂
(overturned to S. :- ♀

both stereograms are Lambert equal area projection.

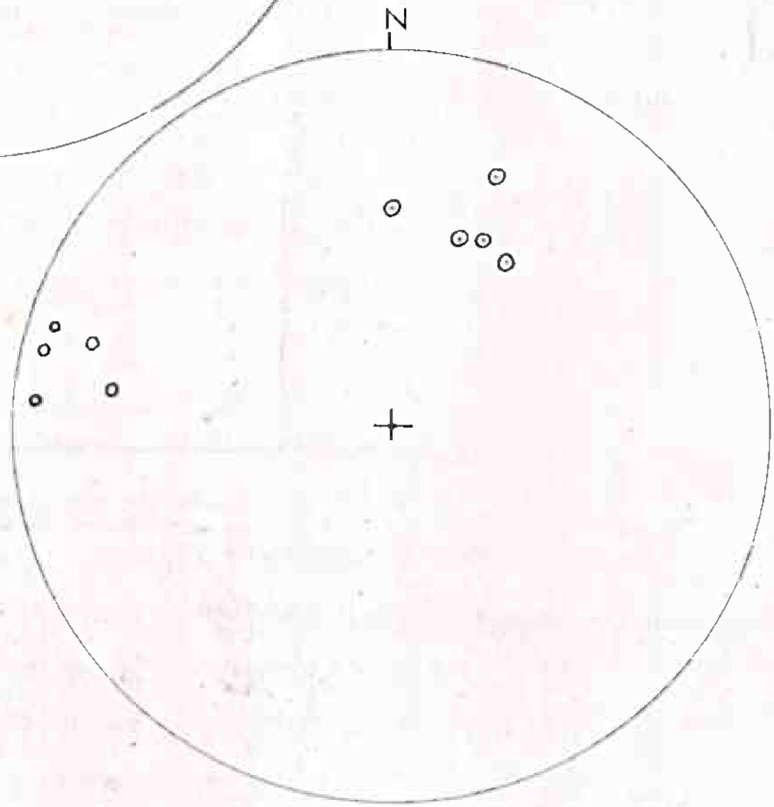


FIG. 6.22 Folds west of grid easting 431.

Pole to axial plane :- ⊙
Fold axis :- o

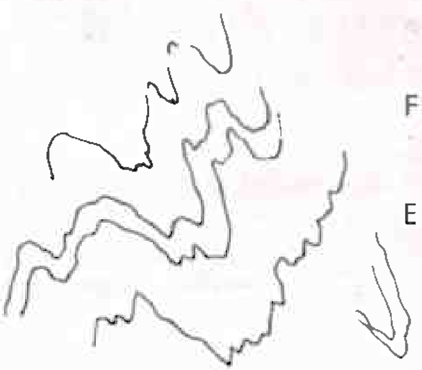


FIG. 6.23 Folding west of grid easting 431. notebook sketch.

(× ½)

Furulund schist as seen in Fig. 6.19.

Fig. 6.21, opposite, is a plot of 20 axes measured, divided into those which are overturned to the north, the south and those not overturned in any particular direction as far as could be seen.

6.4 Folds west of grid easting 431.

Along the road between Glastunes and Grönli west of 431 there occur a large number of post-schistosity minor folds with east-west axes. According to Henley (1968) who designated them F3c, they occur as far west as Hellarmo, 4km. west of Grönli. Only the eastern margin of this fold domain was therefore visited.

Fig. 6.22 is a plot of axes and poles to axial planes. The east-west axes and the south-west dipping axial planes have very different attitudes from those of the folds at Bursi described below in sections 6.5 to 6.9. Fig. 6.23 illustrates that at this locality all limbs appear to be about the same length and therefore the fold appears to be hinging.

The relative age of these folds is determined from specimen 717, shown in Fig. 6.24. Hornblende and muscovite overgrows the tightest of the crumples, but the garnet is earlier than the folding. The garnet has rotated during growth about an axis normal to the fold axis, so there is no connection between the events unless there has been considerable change in the direction of the folding axes during triaxial progressive deformation. In Fig. 6.24, a photomicrograph of a section perpendicular to the fold axes, the garnet in the top right shows a ( ) section indicating that the axis of garnet rotation lies in the plane of the section.

Henley states that these F3c folds are post-garnet and post-hornblende.

stratigraphic level, where the metamorphic grade is lower. He describes in detail their development as kink zones with north-west dipping axial planes and axes plunging east of north.

The folds are extremely variable in style, scale and attitude as is illustrated in Figures 6.2 to 6.11. Folds occur singly or in groups, groups being more common in the south-east. The appearance of such folds piled on top of oneanother as in Fig. 6.3 has led to the term "stacked folds" being applied to them in the field. Small areas with abundant folds are separated by relatively large long-limb areas in which no closures can be seen. Some of these areas are marked on Map 3.

Folds are usually close (definition as in Fleuty 1964a) though some are open, some tight. They vary in shape across the units involved, and along the axes, folds sometimes dying out. Fig. 6.5 illustrates how the angularity of the hinge zones can change across a fold. Some folds have very smooth shapes while some are virtually kink zones - compare Fig. 6.6 with Fig. 6.7 . Depending on the lithology, axial plane structures can be developed ; in some rocks there is a good crenulation cleavage , as in Fig. 6.12, of specimen 309.

The stereogram, Fig. 6.13 is a plot of axes and poles to axial planes and it can be seen that the 153 axes measured are spread between 290° and 040° with pitch varying from 00° to 56°, though pitch is usually between 10° and 40°. In any one outcrop the variation in trend is about half the total range. There does not seem to be any systematic change of direction over the area; domains with different axial directions cannot be detected. Two examples of these folds deforming syn-schistosity folds of calcareous bands were seen, and are illustrated in Figures 5.4 and 5.5 .

In order to determine the age of folding relative to the growth of porphyroblasts, a careful search was made for garnets within the folded area, but only two garnetiferous specimens were found (309 and 313) both in the garnet rich zone near the top of the succession. In both rocks the garnets,

Fig. 6.7 Post-schistosity fold, overturned to the east. Note the smoothly rounded shape which dies out downwards.

Fig. 6.8 Post-schistosity fold, overturned to the east. White calcareous bands are strongly folded. Such folds are found in the cliff feature east of Gihen.

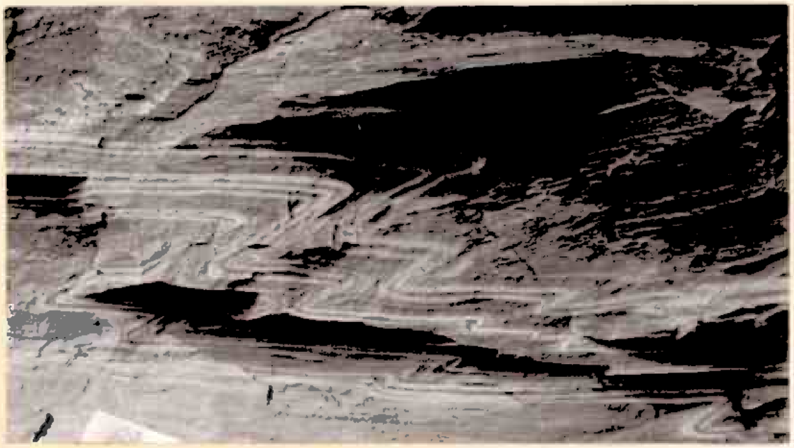


Fig. 6.9 As above.

(and in 309, the hornblendes) are clearly older than the tight microcrumpling of the schistosity as is illustrated in the camera lucida sketch of specimen 309, Fig. 6.12. In both cases, however, the porphyroblasts contain S shaped inclusions indicating that relative rotation had taken place between garnet and matrix during growth. In both cases the axis of garnet rotation lies near the axis of folding, and the sense of rotation is the same. In the stereogram Fig. 6.14 (opposite previous page) the rotation axes for garnets in the two rocks (determined by the method outlined in Chapter 7.10 and 7.11) are plotted alongside the axes of folds measured within a few centimetres of the specimen. These results strongly suggest that garnet and hornblende growth took place during the early stages of this fold deformation, although an alternative explanation is that this is a further example of the parallelism of orientation of successive deformations which is common in Sulitjelma.

6.3 Open folds north-east of Giken.

These folds mainly occur in the cliff which runs from Giken towards Ny Sulitjelma. They have axes plunging gently east or west, and axial planes sub-horizontal, very variable in azimuth of strike. The direction of overturn is usually to the north, but they are such open folds that it is usually difficult to determine which is the short limb. Figures 6.15 to 6.20 illustrate their typical style. They are frequently developed next to boudins and to the low angle discontinuities that are common in this cliff, and are described in Chapter 8.2, and illustrated in Figures 6.15 and 6.16 . It is possible that the folds represent some kind of scar folding (Rast 1956). They are commonly associated with small crinkles seen near quartz segregations and boudins. In addition to the open folds of Fig. 6.18 much tighter folds are also seen, some being virtually kinks. It is possible that there are several different generations of folds here. Open folds similar to these are occasionally seen elswhere in the

Fig. 6.15 Open folding in the cliff NE of Giken. A large number of discontinuiti in bedding can be seen.

See section 6.3 on page 45

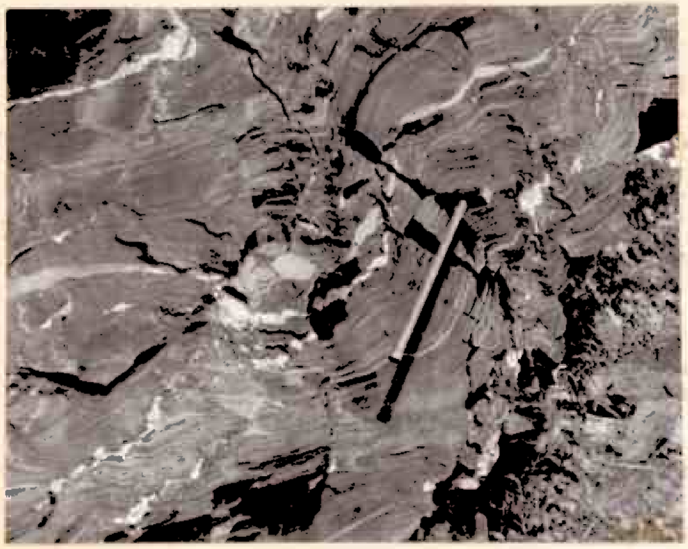


Fig. 6.16 Detail of above photograph.

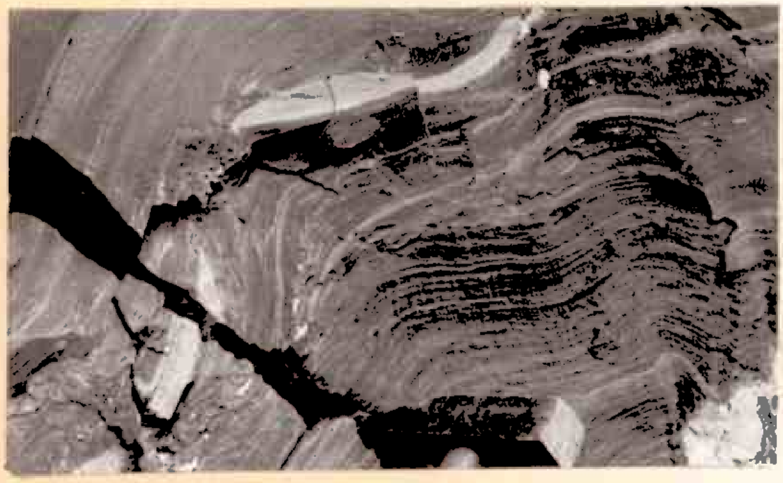


Fig. 6.17 Open folds in cliff N.E. of Giken.

See section 6.3

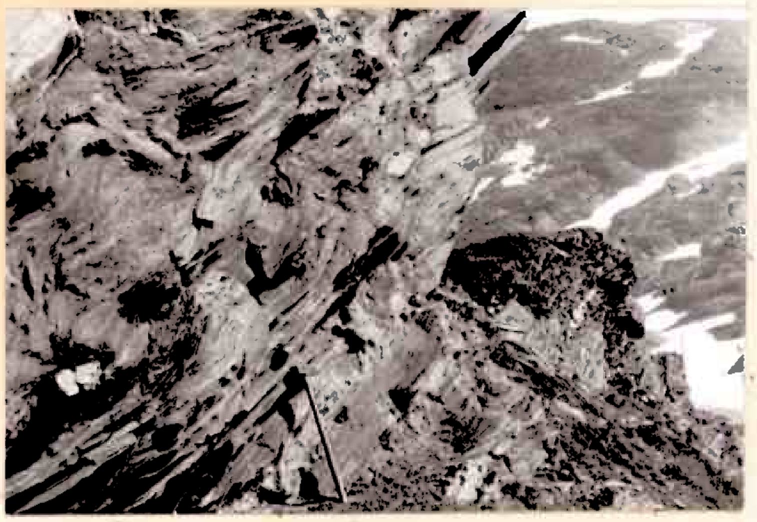


Fig. 6.4 Post-schistosity fold, overturned to the east, with moderate development of axial plane structure. Note the change in style across the bedding.

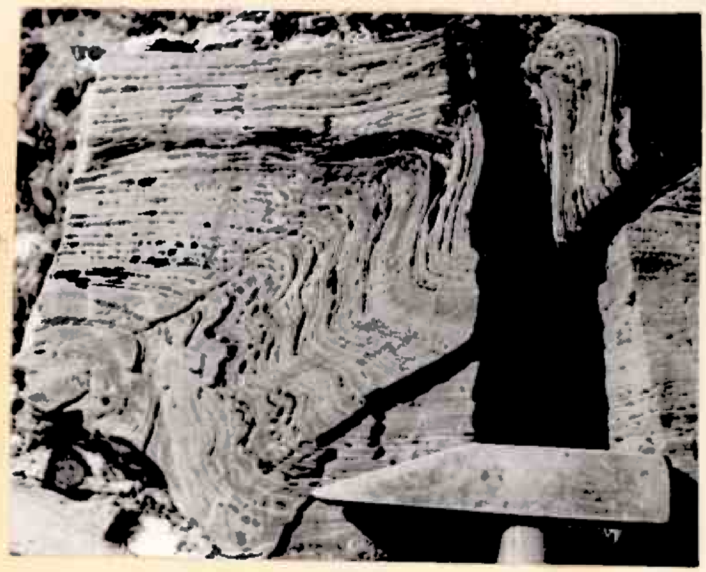


Fig. 6.5 Post-schistosity fold, overturned to the east, The fold dies out downwards.

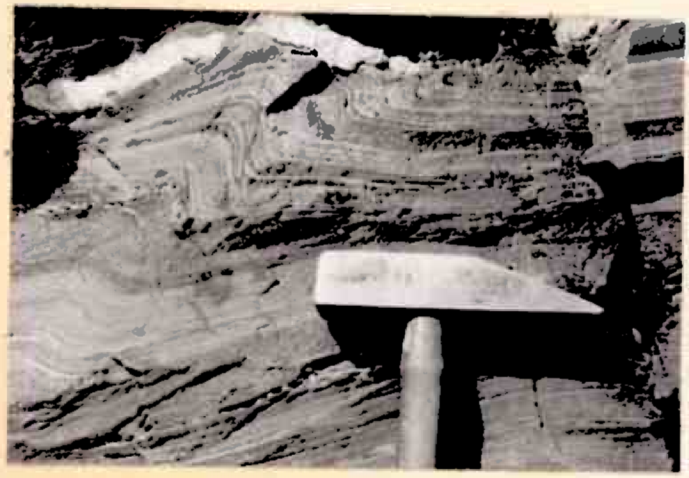


Fig. 6.6 Post-schistosity fold, overturned to the east. The degree of angularity of the hinge varies across the bedding.

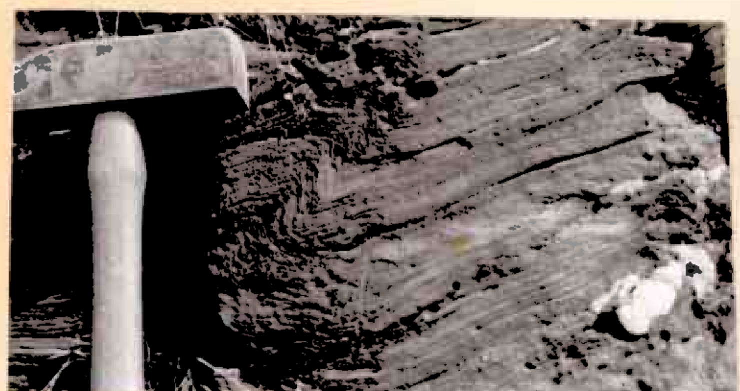


FIG. 6.13 Post-schistosity folds in the east of the thesis area, overturned to east.
(Furulund schist)

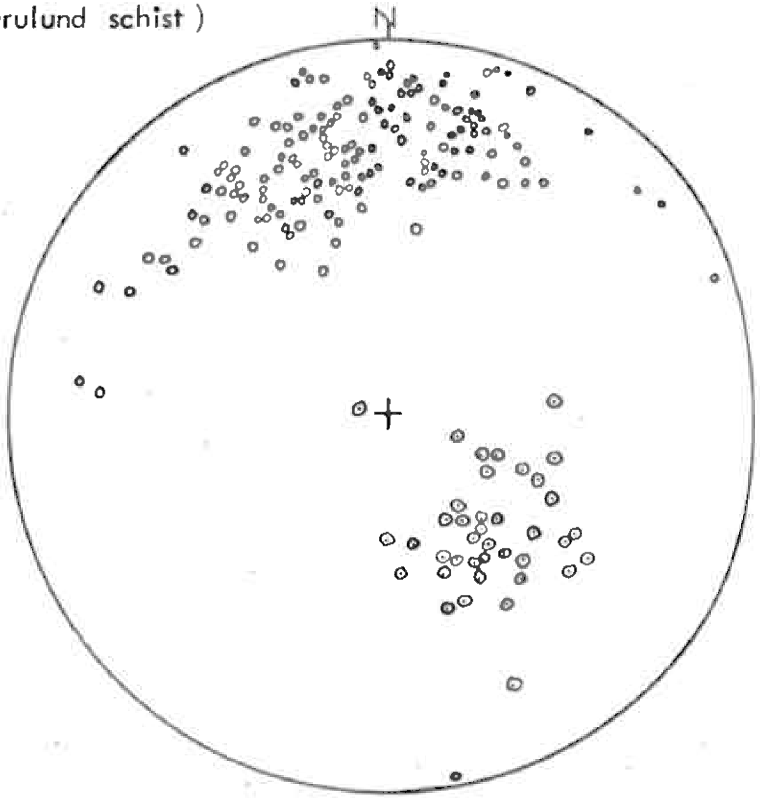
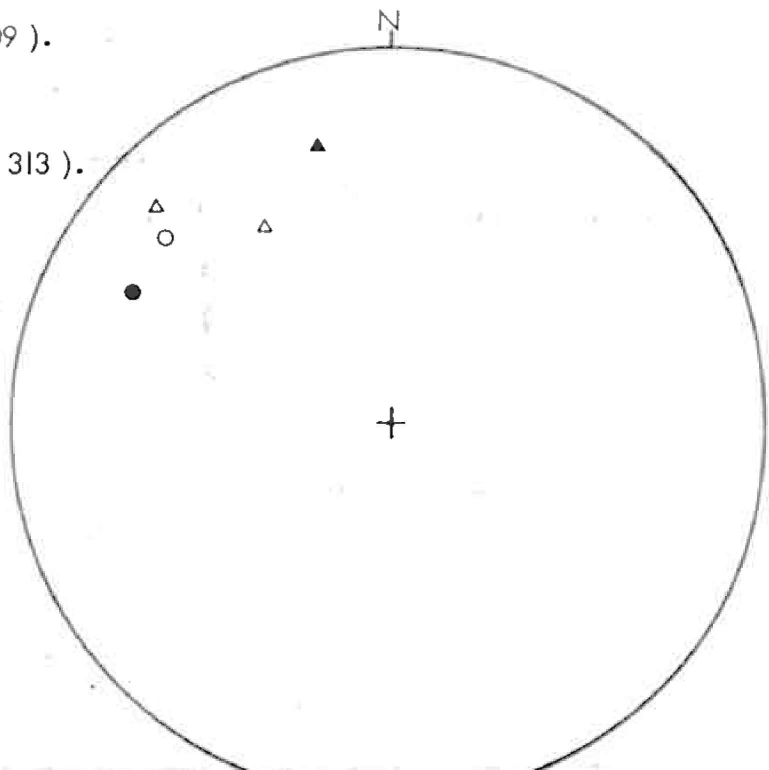


FIG. 6.14 Post-schistosity folding and garnet rotation. (Furulund schist).

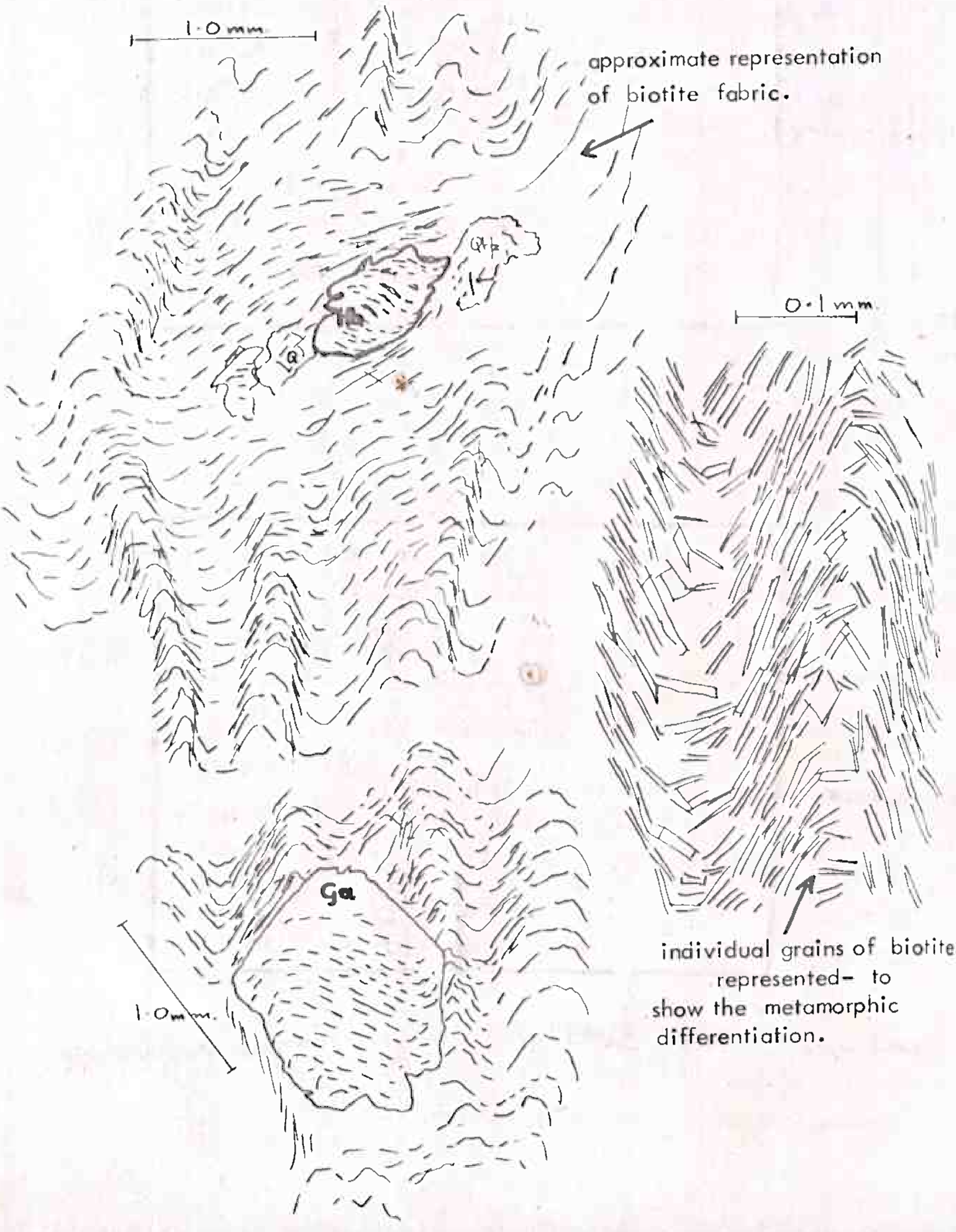


Lambert equal area projections.

Fig. 6.10 Post-schistosity fold, overturned to the east. Typical of the large examples of this category found in the far east of the thesis area,.

Fig. 6.11 Post-schistosity fold, overturned to the east. Strong axial plane structure. There is very little change in style across bedding.

FIG. 6.12 Camera lucida sketch of specimen 309 to illustrate folding later than porphyroblast growth, and crenulation cleavage.



CHAPTER 6

POST - SCHISTOSITY FOLDS OF THE FURULUND SCHIST

6.1 Introduction.

Folds described here are those which clearly fold the regional schistosity. Minor folds of this type occur commonly and can be categorised into several groups of which only one is related to major folding. Minor fold axes are plotted on Map 3. Fig. 6.1 summarises the minor folding by showing where the main areas of folding occur and by indicating typical attitudes of fold axes and axial planes. It can be seen that folds occur in two main areas, west of grid easting 440 and east of 460. Between these areas folds are rare though crinkles are evenly distributed and in addition there are occasional gentle folds with large wavelength and small amplitude. These are seen mostly near the lake and west of 455. It may be noted that the central area contains many boudins as described in Chapter 8.2, although boudinage and folding do overlap.

In addition to the major folds of the schist strips at Bursi, described below, there are also open regional warps of schistosity, as was mentioned in Chapter 4.5 . The thesis area lies on the north limb of the Langvann antiform, the rocks dipping north or north-west.

6.2 Minor folds in the far east of the region.

These folds are characteristically overturned to the east. Their axes plunge in a northerly direction and their axial planes dip to the north-west. Although they are found everywhere within the region shaded on Fig. 6.1, and very occasionally further west, they become much more common to the south-east, as indicated on Map 3. Henley has described these folds over a wide area south-east of the thesis area and he classes them as F3a. Nicholson (1967) mentions that they continue some eight kilometres to the east, at the same

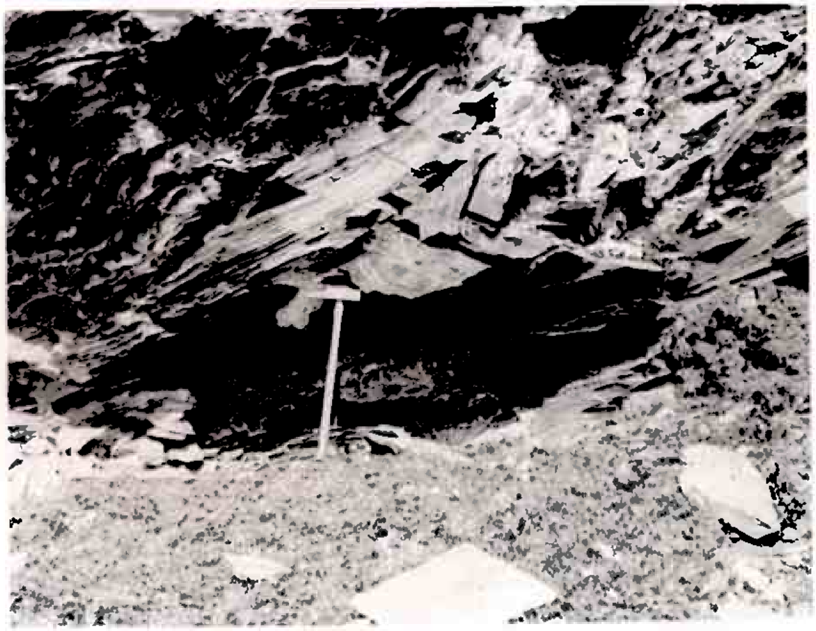


Fig. 6.2 Post-schistosity fold in the east of the thesis area. Overturned to the east. The fold has a strong axial plane structure. Specimen 609 taken from this locality. Note the change in intensity of the folding. Photograph taken along the fold axis.
See section 6.2, page 43.

Fig. 6.3 Same group of folds as in Fig. 6.2, but here developed as "stacked folds". Viewed from the south along the fold axis.

6.5 Minor folds between Bursi and the Church (in the main body of schist).

There are just a few isolated examples of minor post-schistosity folds in the main part of the Furulund schist between the Church (Map 1) and Bursi. Fig. 6.25 is a plot of axes and poles to axial planes of folds in this area. There are only a few folds but they all plunge gently to the NNE or SSW. On the basis of style they can be divided into three of four distinctly different groups.

A. Two folds, seen at Bursi, whose style is shown in the sketch Fig. 6.26. The axial surfaces dip about 40° to the west and the axes plunge gently to the south. They are overturned to the east.

B. Gentle to open folds with slight axial planar structure developed occasionally. They are illustrated in Fig. 6.27, opposite.

C. Folds generated by the large boudin at Bursi (see Chapter 8.2, and Map 6). The folds vary in style from rounded open folds of the schist dragged into the boudin scar to chevron folds. These are illustrated in Figures 8.17 and 6.28. The axis of the folding is constructed by a π diagram from schistosityreadings taken around the entrance to Bursi mine, the diagram beingreproduced as Fig. 6.30.

D. Very gentle flexures present in the Furulund schist at Lake level west from the Church. Such folds were not seen east of the Church. The folds have relatively small hinge zones, some 10m. across, separated by straight limbs some 50m. to 100m. long. On Fig. 6.25 the constructed axes of some of these are shown, those around Bursi as o , and those from further east as △ □. The best example of these folds , from just east of the mine office (Map 1), is shown in Fig. 6.29. Fig. 6.31 is a plot of all schistosity measurements made between the Church and Glastunes. The poles fall on a great circle indicating that folding was about an axis trending 025°, plunging 16°, a direction similar to that of the scar folding at the Bursi boudin. The unusual feature of isolated hinge zones could be explained if the folds were generated by flowage of the rock into the boudin scars. The example of the Bursi boudin, and the common occurrence of small boudins give weight to the argument.

Fig. 6.28 Chevron folds at Bursi associated with the large boudin in Fig. 8.17

Fig. 6.29 Gentle fold immediately east of the Mine Office. The photograph is taken looking along the axis of folding. It is probable that this fold was generated by the schist being pulled into the gap formed during the generation of a large boudin.

FIG. 6.30 Schistosity attitudes at the Bursi mine entrance.

This illustrates the deflection of schistosity into the scar of the large boudin at Bursi.

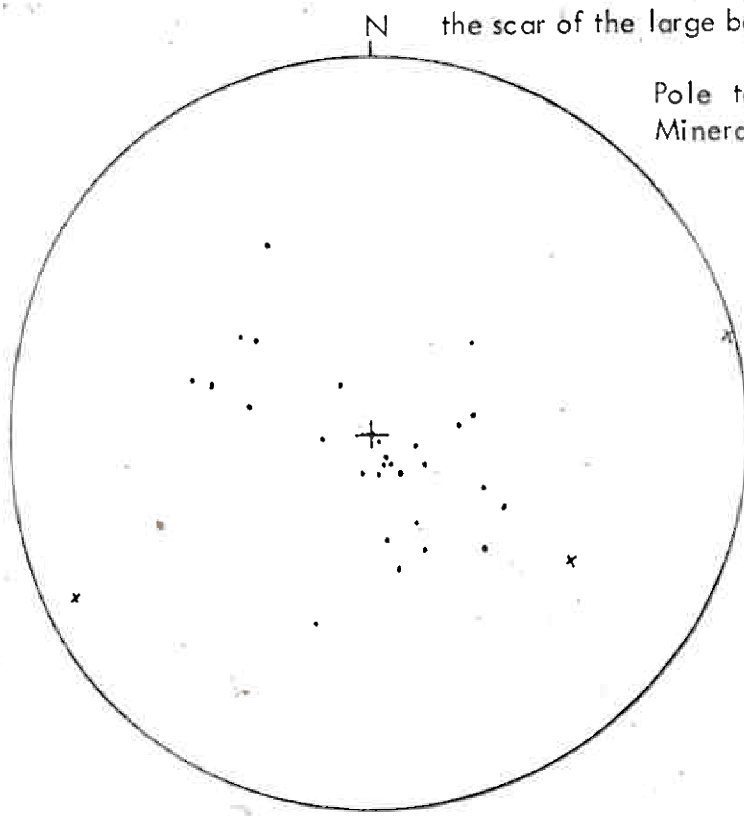
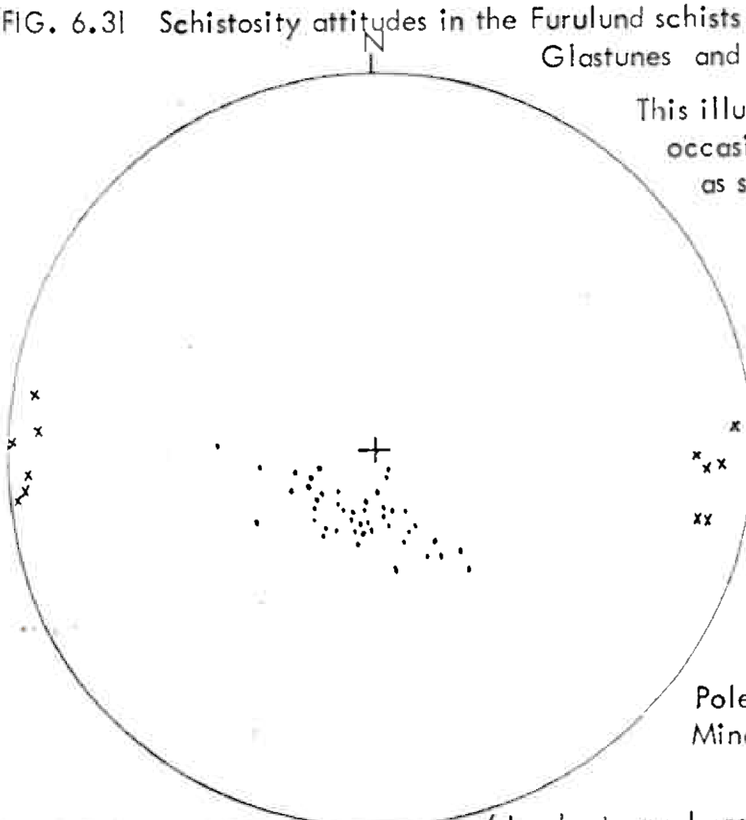


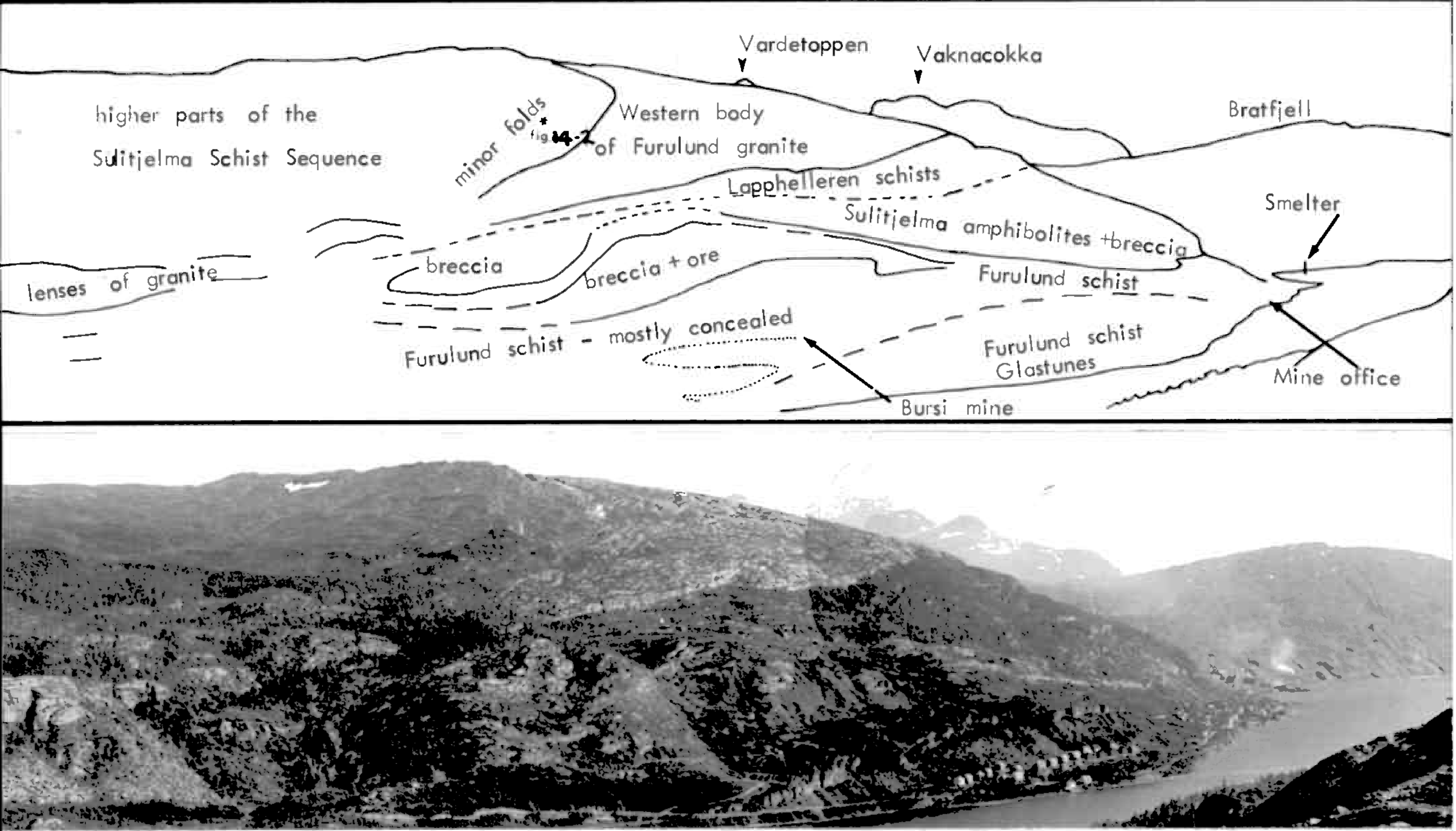
FIG. 6.31 Schistosity attitudes in the Furulund schists (main part) between Glastunes and the church.

This illustrates the effects of the occasional gentle folds such as seen in Fig. 6.29.



(Lambert equal area projections)

FIG. 6.33. BURSI FROM THE WEST - TO ILLUSTRATE POST-SCHISTOSITY MAJOR FOLDING



6.6 Major folds at Bursi.

As is described in Chapter 3.4 there are at Bursi three strips of schist lying within the Tectonic breccias associated with the amphibolites of Sulitjelma. These strips are strongly folded on both major and minor scales. Strip B is folded into a large antiform, the north-west limb of which is recumbently folded back to the south-east. This is shown in Fig. 6.32, a sketch section across the Bursi area, the panorama Fig. 6.33, Fig. 1.3 and the map, Map 6. Since neither the Furulund schist below, nor the Sulitjelma Schist Sequence above show anything like such folding, it is described as disharmonic. The body of copper ore which lies beneath the strip of schist may have acted as an incompetent horizon, allowing the small scale sliding which would be necessary to allow the disharmonic folding.

The axis of the major disharmonic folding may be determined directly from a plot of the poles to schistosity in the folded zone. Fig.6.34 is such a plot with the crosses being measurements taken near the hinge of the fold. The pattern approximates to a great circle indicating folding around an axis trending 035°, plunging 0°, though it would also fit a small circle distribution around a point with much the same trend but a plunge of 10-20°. This might indicate that the schistosity was not planar before the phase of folding began. Since the original attitude of the schist strip is not known, this is a possibility.

It is convenient here to mention the folding of the Lapphelleren schist and the Furulund granite above these rocks at Bursi. NW of Bursi the granite has thinned to a sill some 10-20m. thick and it is here gently folded into a monocline overturned to the west. This is clearly shown on Map 1 and on Map 6. The schistosity of the granite and Lapphelleren schists has been plotted as poles on Fig. 6.35 and indicates folding around an axis trending 034° and plunging 20°, though there is a fair scatter. This axis is similar to that derived in Fig. 6.30 for the folding of the schist below the zone of disharmonic folds. This suggests

FIG. 6.32 Sketch section at Bursi to illustrate the disharmonic folding and the structural situation of the strips of Furulund schist within the tectonic breccias.

Horizontal and vertical scale - 1:5,000. Section is normal to the post-schistosity fold axes.

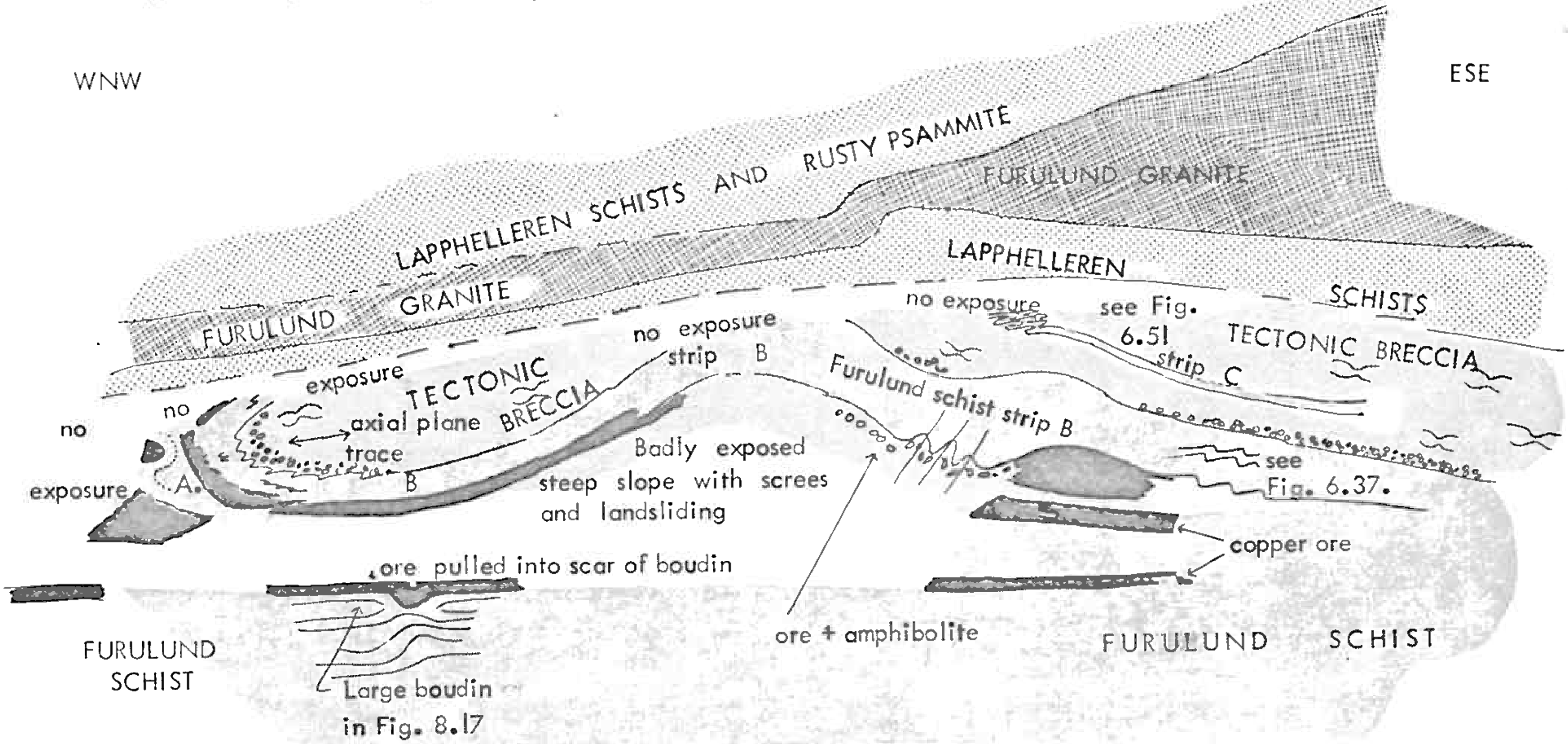
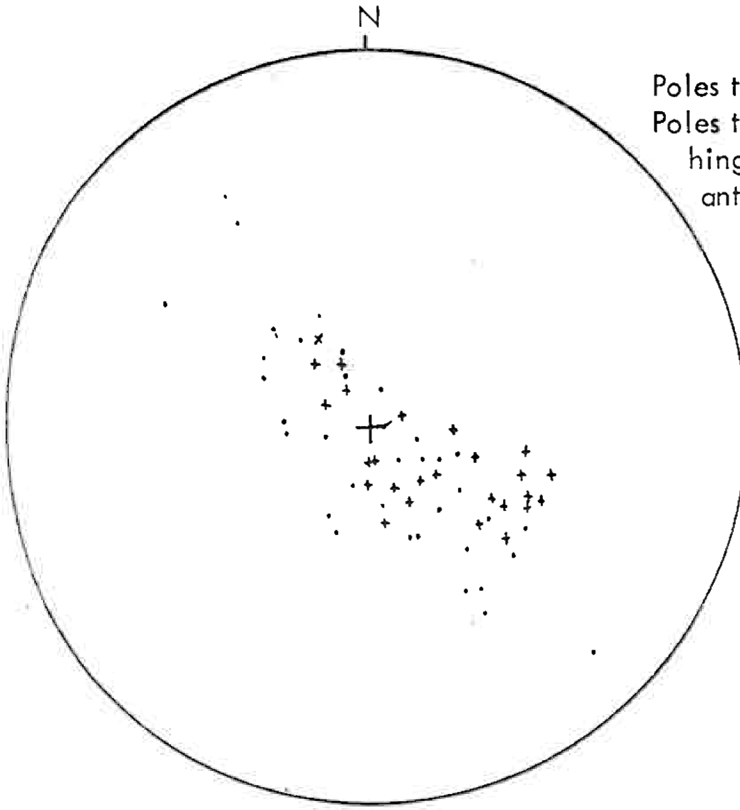
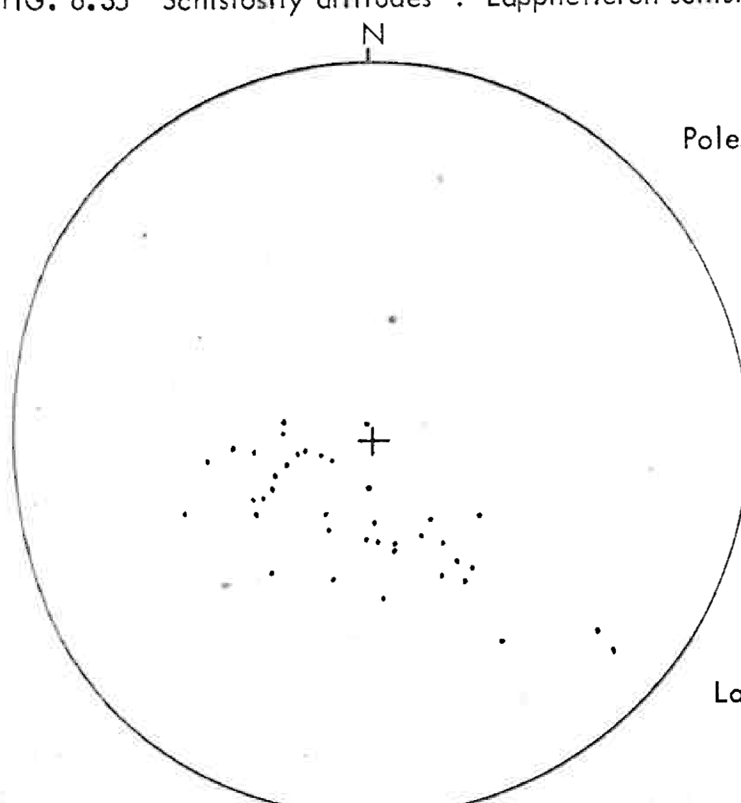


FIG. 6.34 Schistosity attitudes : Furulund schist strip B, Bursi.



Poles to schistosity :- •
Poles to schistosity in hinge zone of antiform :- +

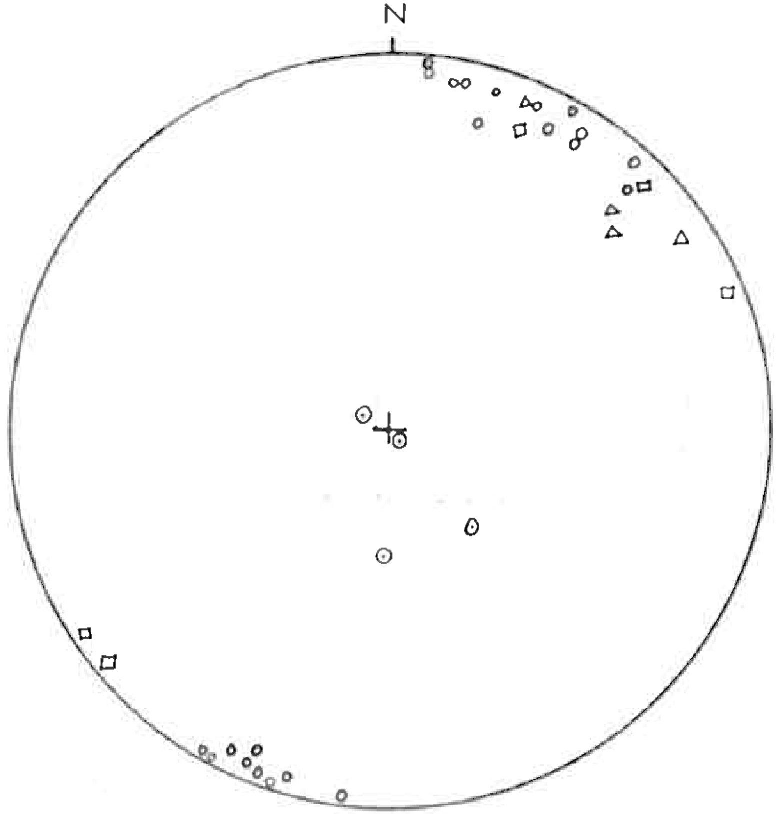
FIG. 6.35 Schistosity attitudes : Lapphelleren schist and Furulund granite above Bursi.



Poles to schistosity :- •

Lambert equal area projections.

FIG. 6.36 Furulund schist, strip B, Bursi. Fold axes from nose of recumbent fold



Fold axes -

Lower limb :- △
Upper limb :- □
Hinge :- ○

Poles to axial plane :- ⊙

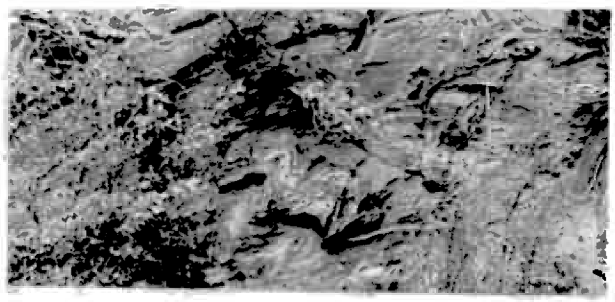


Fig. 6.37
Post-schistosity folds of Furulund schist in strip B within the tectonic breccias at Bursi. East of the disharmonic antiform in strip B.

that the orientation of strain axes does not differ markedly on each side of the zone of disharmonic folding.

6.7 Minor folds of schist strip B.

Most of the folds seen in this strip have axes trending NNE-SSW and a sense of overturn matching the recumbent fold, that is, overturned to the south-east on the lower limb of the fold and to the north-west on the upper limb. This is indicated on Map 6, and on the section Fig. 6.32. As can be seen, the upper limb has no great extent. Most of the folds are seen on the hinge of the major recumbent fold. Fig. 6.36 is a plot of axes from near the hinge, distinguishing those which are on the lower limb :- △, those which are on the upper limb:- □ and those which are on the hinge:- ○. The tectonic breccia forms the core of the recumbent fold, and the lowest rock in it appears to be a conglomerate. This rock is deformed, with the fragments flattened parallel to the axial plane of the fold, and the direction of maximum elongation apparently lying near the fold axis. Some of the flattening can be seen in Fig. 9.10 .

Although not many folds are seen away from the hinge zone, there is a good example just east of the eastern limb of the antiform, illustrated in Fig. 6.37.

Figures 6.37 to 6.40 illustrate the styles of the folds in strip B. Most of the folds are 'parallel' type folds, belonging probably to class lb of Ramsay(1967), being buckles of competent quartz-hornblende layers 2-4cm. thick. Specimen 634 is shown in Fig. 6.41, cut normal to the fold axis. An attempt was made to study the geometry of this fold in detail, but it was impossible to define the layers with sufficient accuracy. Fig. 6.42 is a photograph of specimen 599, taken parallel to the fold axis. Fig. 6.43 is traced from the specimen, and shows the relation of the crenulation cleavage which has developed in the pelitic layers to the folding of the relatively competent quartz-calcite layer. The position of thin sections from the rock are also marked. Section 599C is illustrated in Fig. 7.20 , and the coarse second cleavage can be seen clearly. Fig. 6.44

Fig. 6.38 Minor folds on the hinge of the recumbent fold of schist strip B. See section 6.7 (page 49)

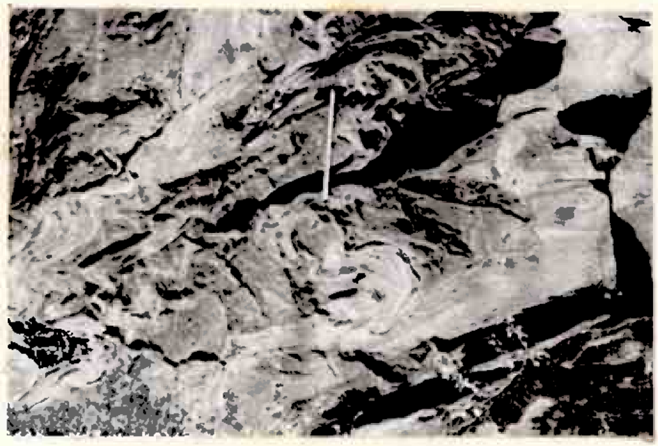


Fig. 6.39 Minor folds on the hinge of recumbent fold of schist strip B. Competent bands within the schist are conspicuous.

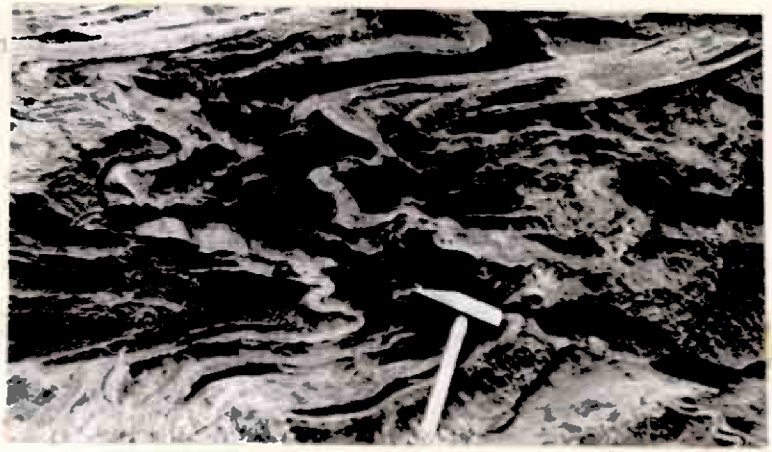
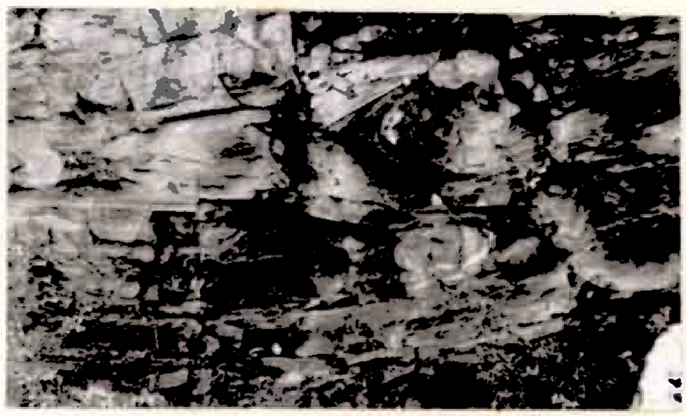


Fig. 6.40 Large isoclinal folds on the hinge of major recumbent fold of schist strip B. Specimen 632 is from the minor closure immediately below the hammer.



shows the dip isogons which are weakly convergent towards the inner arc of the fold. Fig. 6.45 is a graph based on measurements of the folded layer, 't' being the orthogonal thickness and 'T' being the thickness parallel to the axial surface, following the method of Ramsay (1967). The plot on this graph shows that the fold falls into Class Ic of Ramsay(1967) and it is suggested that the fold was generated by buckling and has since been modified by further strain.

The age of the folding can be determined from specimens 599, 634, 633 and 632. The folding is clearly later than garnet growth. From specimen 599 thin sections were cut normal to the fold axis. Sections through garnets showed the pattern characteristic of those sections which contain the garnet rotation axis. Such sections are seen in Fig. 7.20, a photomicrograph of section 599C. Since the axis of garnet rotation is therefore normal to the fold axis, and the axial plane crenulation cleavage (seen in Fig. 7.20) is compressed around the garnets, the folding and the garnet growth are taken to be quite separate events.

In specimen 632 there are many small garnets whose 'syn-kinematic' inclusion trails indicate rotation around an axis parallel to that of the folding of the rock. The rock, illustrated in Fig.7.18 , has a coarse penetrative second cleavage parallel to the axial plane of the fold. The position of specimen 632, on the hinge of a fold can be seen in Fig. 6.40. The specimen, numbered and replaced in its original position lies about 20cm. below the head of the hammer.

Specimen 634 is rich in apatite crystals, whose longest dimensions, parallel to the crystallographic 'z'axis lie parallel to the axis of folding. Inclusion trails within these grains are S shaped in sections cut normal to the folding axis, and straight in sections parallel to the folding axis. The apatites were therefore rotating about the same axis as the rock folding. It is therefore assumed that they grew during the folding.

Specimen 634 is also rich in hornblende. The grains contain planar inclusion trails (in three dimensions), and the schistosity is deformed around the grains, so it is assumed that the folding is later than the hornblende growth.

The folding is therefore contemporary with apatite growth, later than hornblende and in most places later than garnet growth.

In addition to the above folds, which fit the recumbent fold, there are two isolated folds which do not. These occur to the south-east of the fold, beyond the antiform, and involve the overlying fragmental rock. They are overturned to the north and have axes with east-west azimuths. They are illustrated in Figures 6.46 and 9.27 .

Near the crest of the antiform there is a small isolated fold overturned to the south with an axis trending 247, plunging 9°. Specimen 626 shows that the fold appears to be of a crenulation cleavage, the cleavage possibly correlating with the crenulation cleavage seen in the post-schistosity folds of this strip, and illustrated in Fig. 7.20.

6.8 Minor folds in schist strip A.

As mentioned in Chapter 3.4 the stratigraphic position of this strip is obscure. It lies below strip B, separated from the latter by about 1m. of ore and is itself strongly folded. Fig. 6.47 is a section across the strip looking northwards as seen from near the path which runs along the base of the outcrop. This evidence is used in the section Fig. 6.32 across Bursi. Fig. 6.48 is a sketch of the situation at the south-eastern end of the outcrop , at the small adit where the overlying ore was mined. The tippings from this adit have obscured exposure to the south. The schist does not appear to be perfectly conformable with the overlying ore. Fig. 6.49 is a stereogram of fold axes and poles to axial planes. An axis adjacent to the adit in the south-east is folded, and the various attitudes of this axis are marked. The attitude of the fold axes is similar to that of axes in the strip B, and Fig. 6.50 is a plot of all axes measured in strips A and B, (apart from the anomalous folds mentioned at the end of section 6.7). There is a good concordance between the axes of all these folds and the axes of the folds in the main part of the Furulund schist at Bursi, and the axes of the folds

FIG. 6.47 Folding of the Furulund schist strip A at Bursi. Situation half-way along strip, on path. (cross-section)

Section based on notebook sketch.

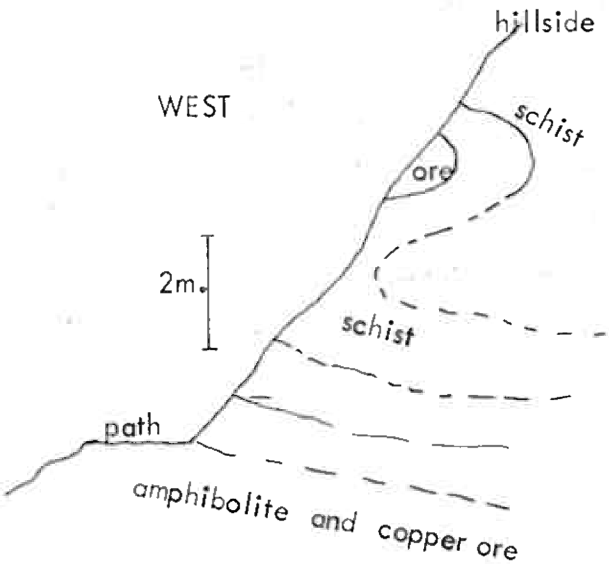


FIG. 6.48 Furulund schist strip A, Bursi. Situation at small adit at south end of the exposure.

Locality sketch based on field note-book.

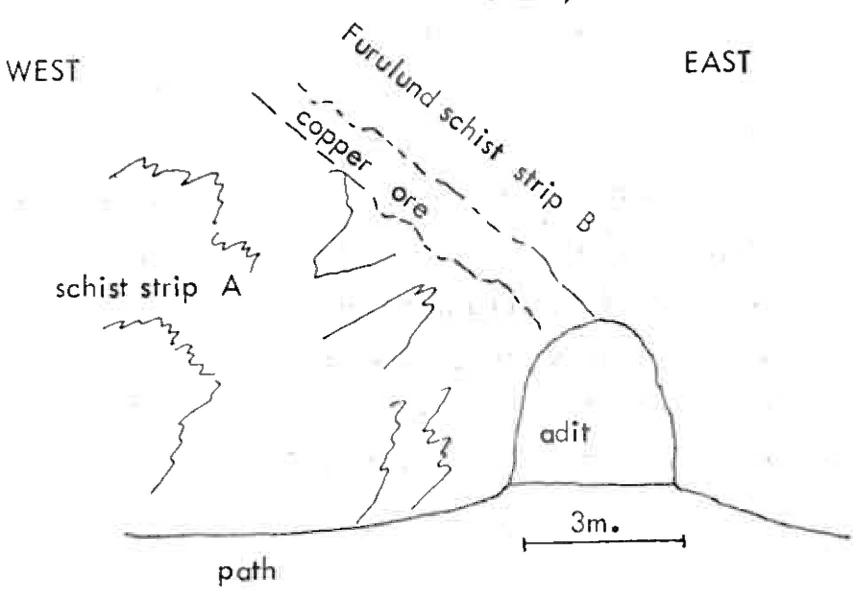


FIG. 6.44 Tracing of specimen 599 with dip isogons.

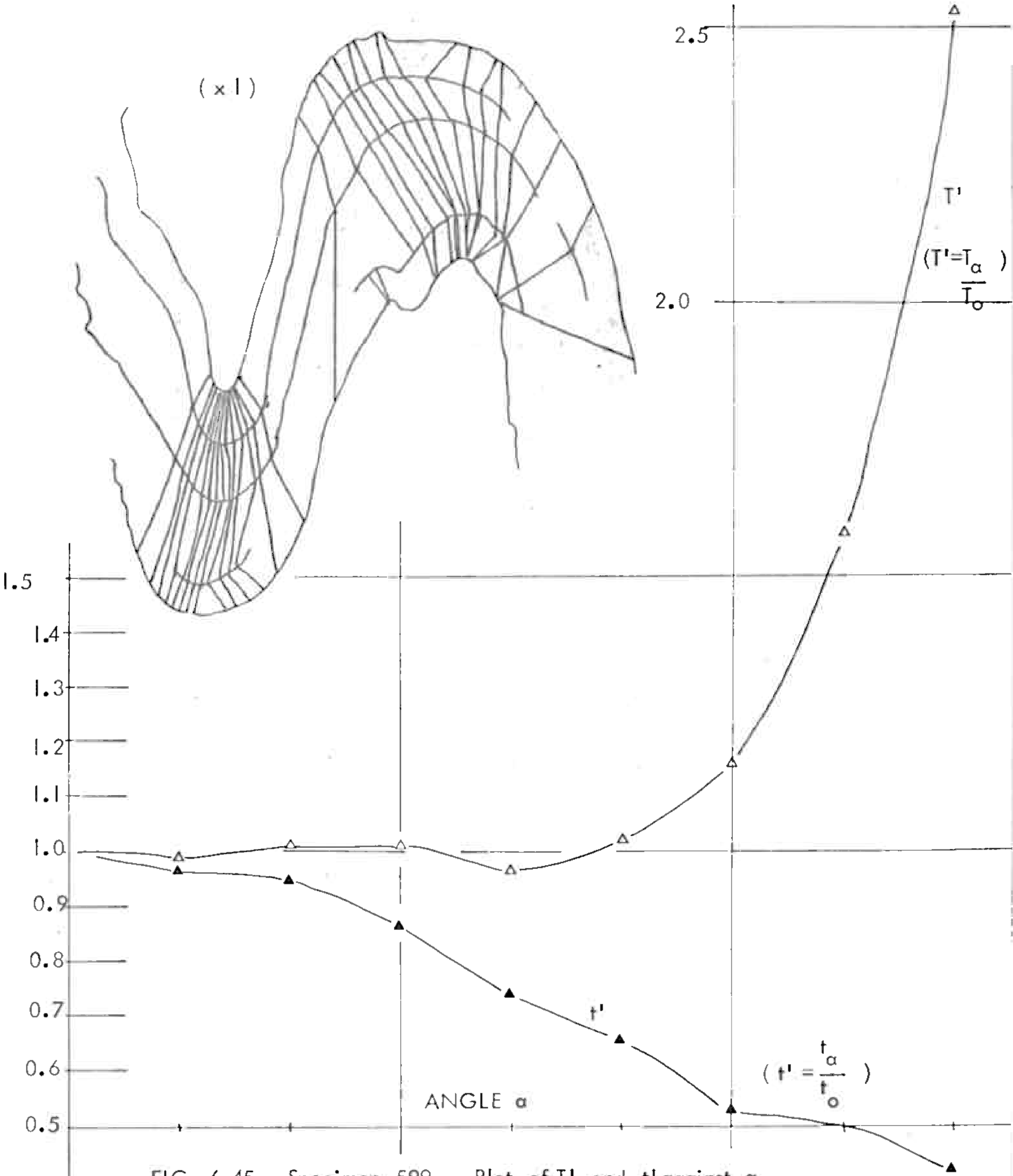


FIG. 6.45 Specimen 599 - Plot of T' and t' against α.
T', t' and α as in Ramsay (1967).

Fig. 6.46 Post-schistosity fold at the contact between Furulund schist and tectonic breccia above Glastunes. The fold is overturned to the north. This fact is unusual for folds of schist strip B.

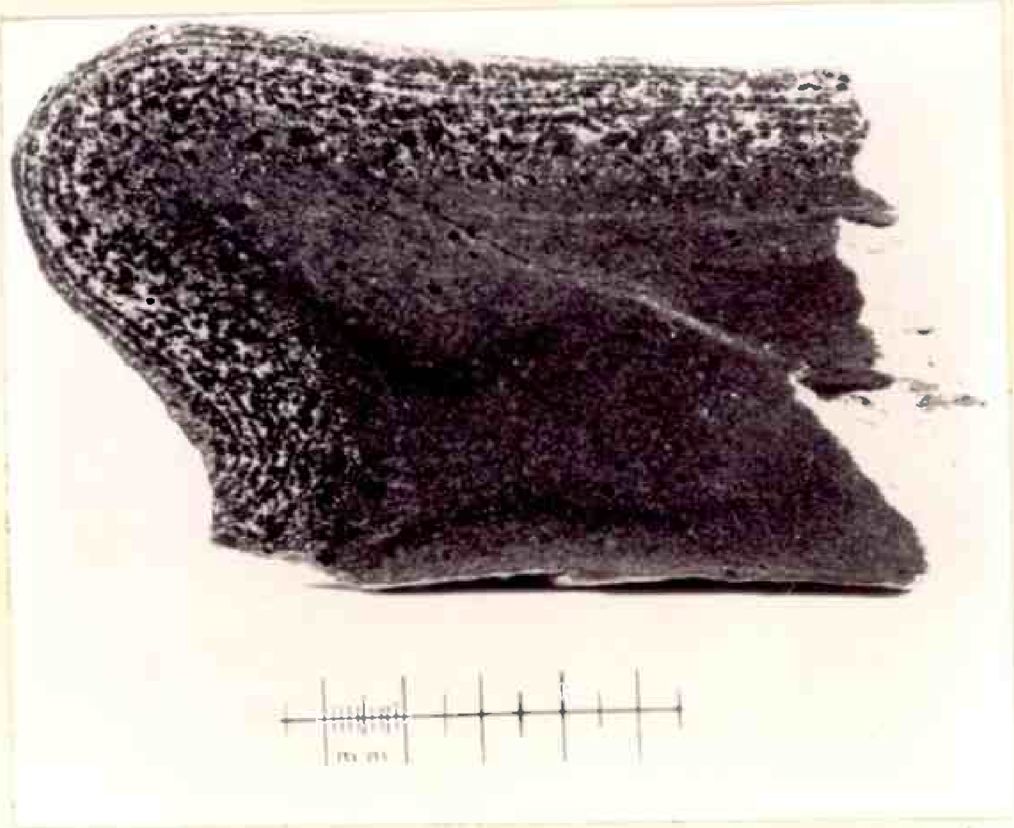


Fig. 6.41 Specimen 634 (approximately x 1) . A fold of a coarse-grained competent band.

Fig. 6.35 Specimen 599 ($x\frac{1}{2}$ approx.) Fold of a competent band. Note the crenulation cleavage parallel to the axial plane.

FIG. 6.43 Tracing from specimen 599 (xl), taken from a post-schistosity fold in Strip B, Bursi. (Furulund schist).

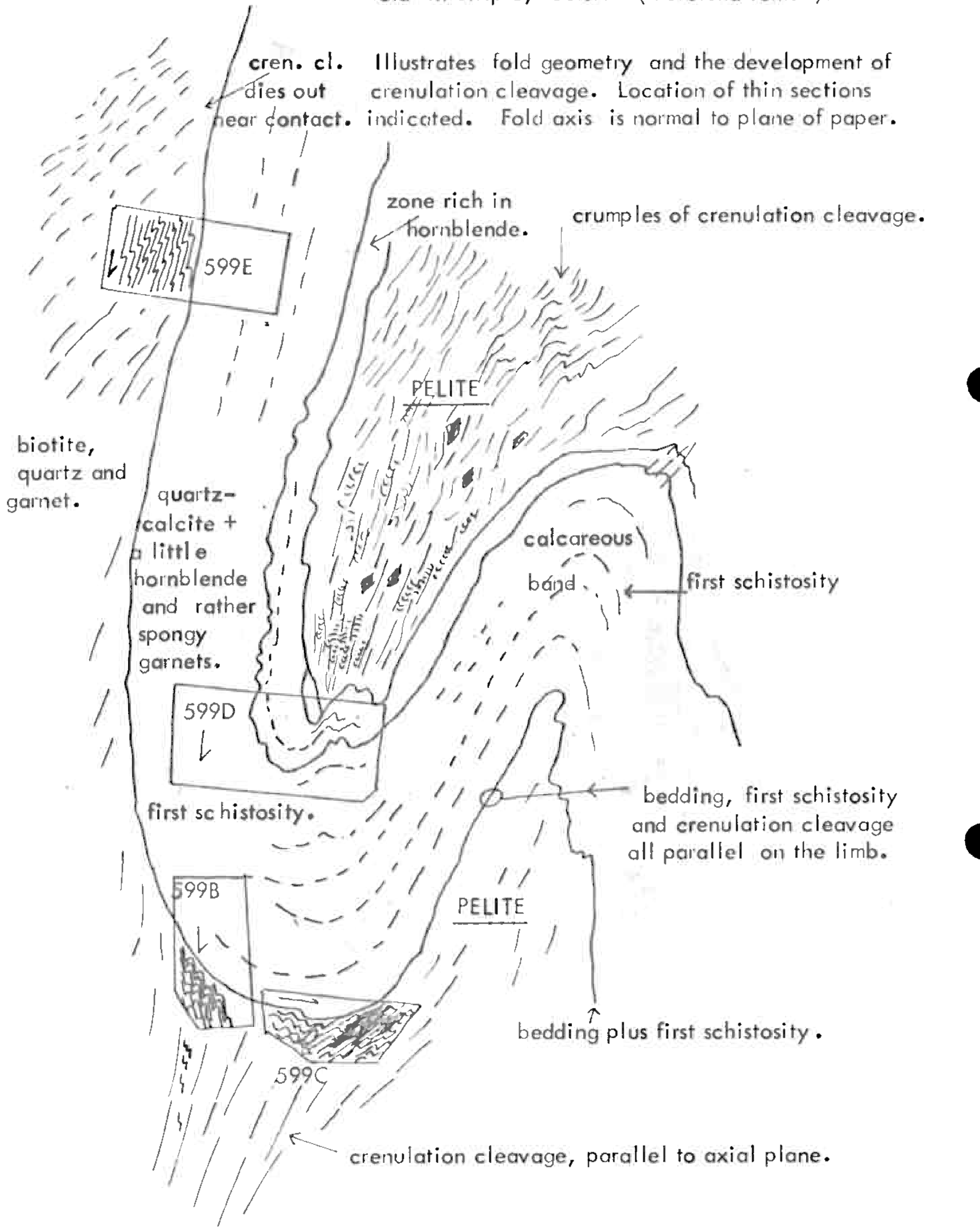


FIG. 6.49 Minor folds, Furulund schist strip A, Bursi.

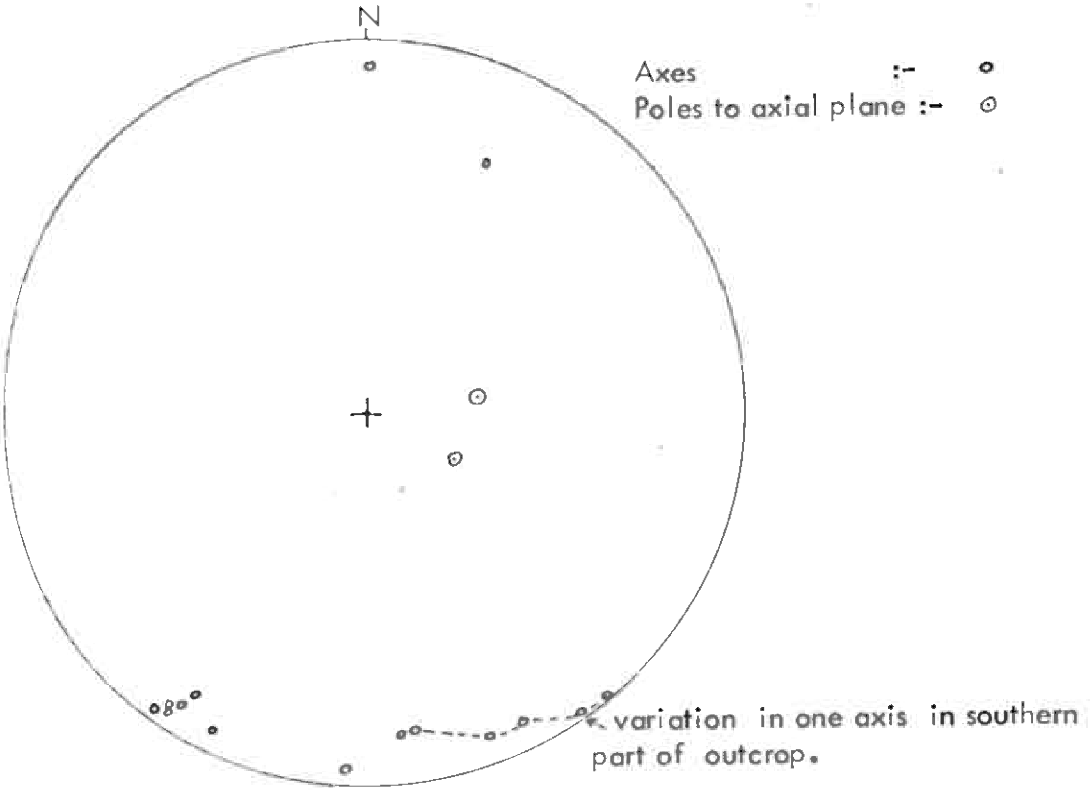
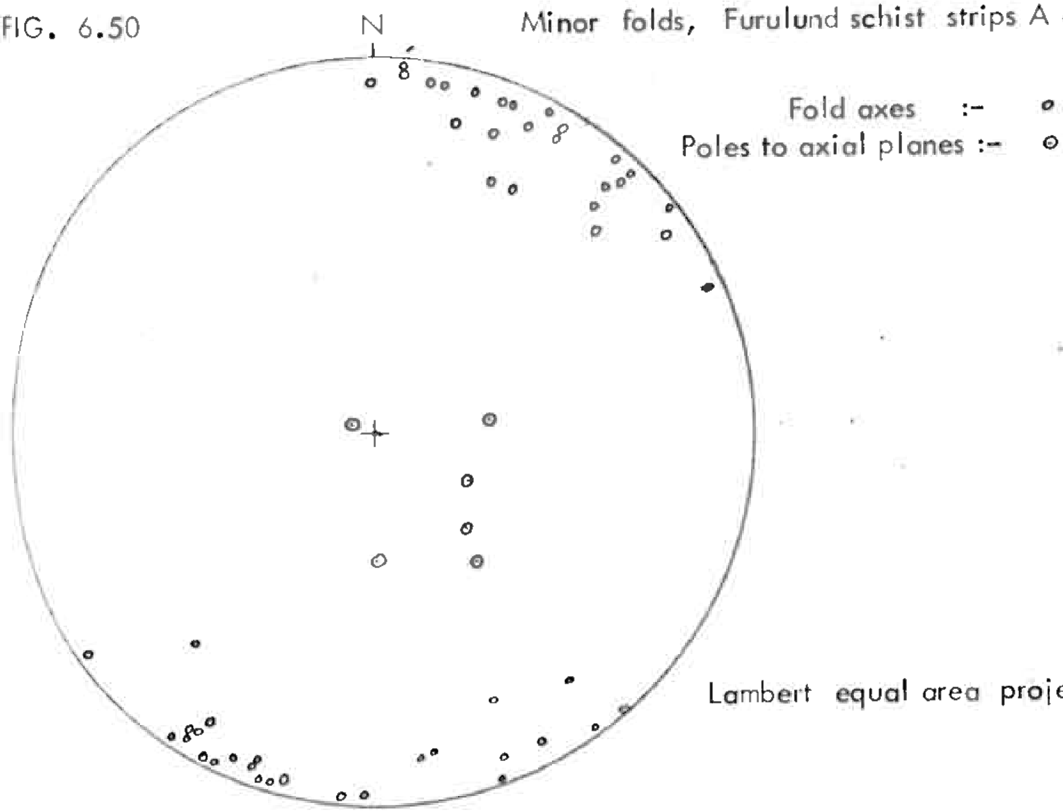


FIG. 6.50 Minor folds, Furulund schist strips A & B.



Lambert equal area projections

Fig. 6.51 and 6.52 Post-schistosity folds at the western end of the strip C of Furulund schist at Burei. In the upper photograph the bottom contact of the Furulund granite can be seen. Below the folds and the fallen blocks is an outcrop of amphibolite marked as such. This outcrop is shown in detail in Fig. 9.22. The arrows point to the outcrop of a refolded fold from which measurements in Fig. 6.50 were taken.

in the Sulitjelma Schist Sequence above.

The age of the folds in strip A appears to be the same as those in strip B; later than garnet growth. Garnets from strip A have planar inclusion trails, incontrast to the S shaped trails in the garnets of strip B, an indication that the lower strip did not share the same deformation during garnet growth.

6.9 Minor folds in strip C.

This strip of coarse-grained schist lies completely within the amphibolite breccia and is strongly folded on a minor scale. The strip is 2-3m. thick, except in the north-west where folding has caused repetition. The folds in the north-west are spectacular, with large amplitude and small wavelength, as is shown in Figures 6.51 and 6.52. The style is similar to those at the far north-west of strip B, illustrated in Fig. 6.40. Some of the post-schistosity folds are themselves refolded, as can be seen in the above figures and in Figures 6.53 and 6.54. Axes of the earlier folds are east-west, with near-horizontal plunge, axial surfaces being near-horizontal. Measurements from this outcrop are plotted on Fig. 6.55, those from the outlier of schist to the south-east (see Map 6) are plotted on Fig. 6.56. The folds from this outlier of schist are illustrated in Fig.6.57 and 6.58. Fig. 6.58 shows that after formation the folds have been modified by boudinage.

Refolding of post-schistosity folds.

Two examples were seen in place. In one case it was possible to measure the attitude of the earlier fold axis as it was folded around the later. These measurements are plotted on Fig. 6.59 after rotation so that the second fold axis lies on the Primative. There is a wide spread of points, but it appears that they lie closer to a great circle than to a small circle. Thus would indicate folding of the 'similar' type.

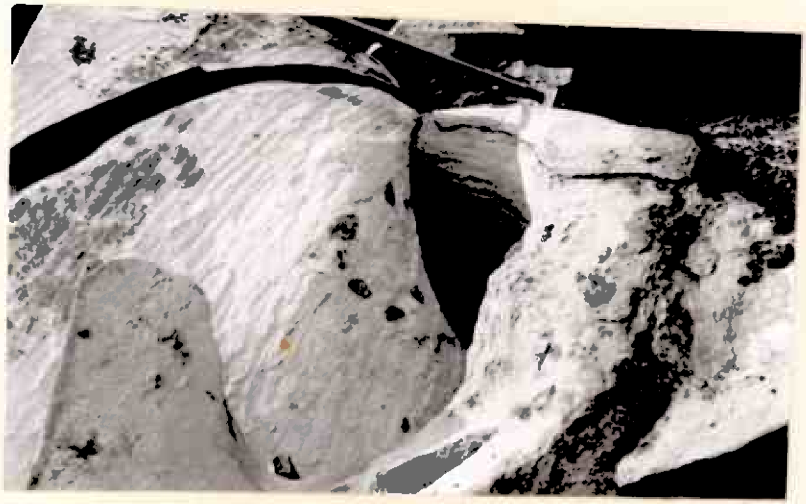


Fig. 6.53 Post-schistosity fold refolded by a later fold. There is a prominent lineation parallel to the axis of the earlier fold. The axis of the second fold is almost vertical, but is not straight. This is a fallen block.

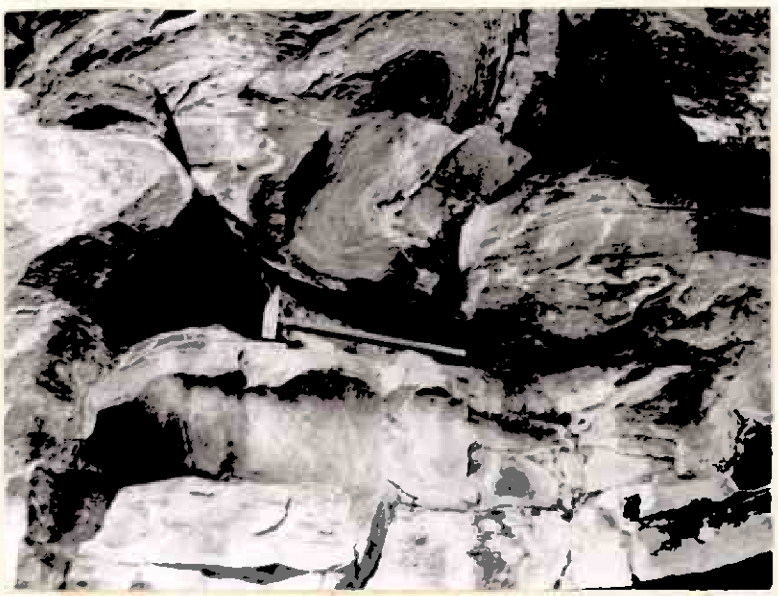


Fig. 6.[illegible] Another example of a refold, in place. The photograph is taken parallel to the axis of the earlier fold. The axis of the second fold is parallel to the hammer.

FIG. 6.55 Minor folds from west part of Furulund schist strip C, Bursi.

(from locality in Fig. 6.51)

Axes of early post-schistosity folds :- o
Axes of late post-schistosity folds :- ◎
Pole to axial plane of earlier folds :- ⊙

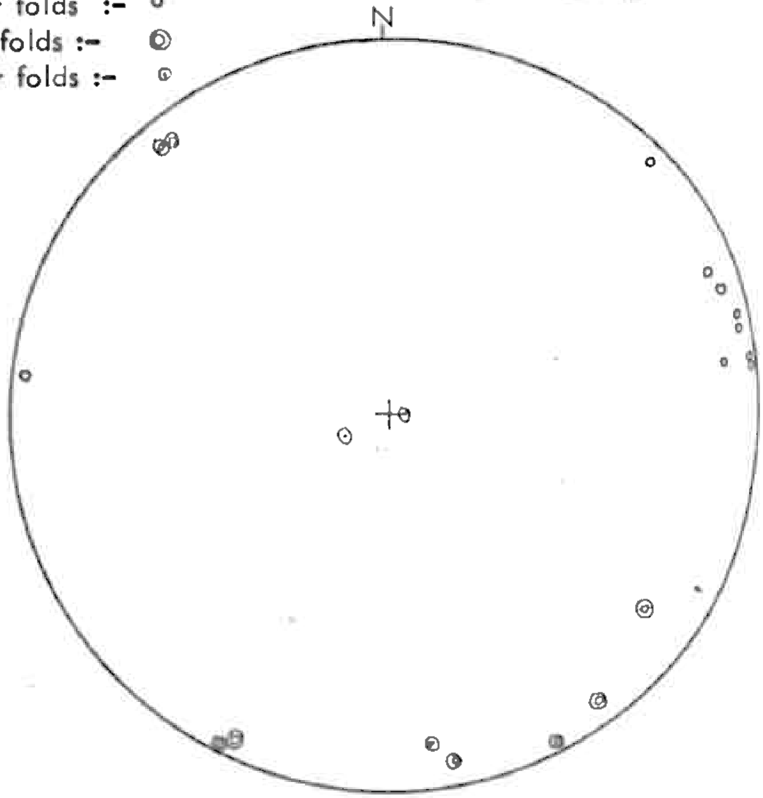
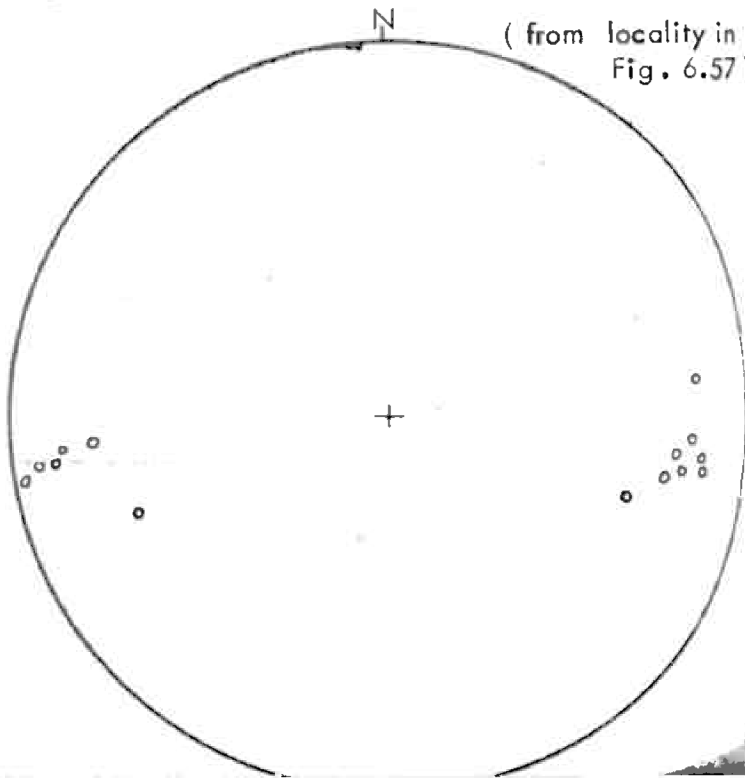


FIG. 6.56 Minor folds from outlier of Furulund schist- strip C., Bursi.

(from locality in Fig. 6.57)

Axes of folds :- o



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Style of the folds in strip C.

The large isoclinal folds as shown in Fig. 6.51 are very similar to those seen in the far north-east of strip B, shown in Fig. 6.40, while those in the outlier (Fig. 6.57) are more comparable with the majority of folds of strip B (Fig. 6.39), being buckles of thin relatively competent bands.

Strip C and the folds therein raise the following problems:-

A. The original attitude of the strip relative to the attitude of the main part of the Furulund schist is unknown.

B. Most of the folds have axes normal to the axes in the surrounding rocks ; compare Figures 6.55 and 6.56 from strip C with Fig. 6.50 from strip B.

C. The post-schistosity folds of strip C have been refolded or boudined, while such features are not seen elsewhere.

D. The relationship between strips C and B is unknown.

These problems are related to the further problem of the generation of the disharmonic folds of strip B at Bursi , and the 'box' folds at the same stratigraphic level at Furuhaugen (south of Langvann) as described by Henley (1968) and Nicholson and Rutland (in press). The intensity of the disharmonic folds and their restriction to the Bursi and Furuhaugen areas indicates a very unusual strain pattern in a narrow zone. The distribution and intensity of the minor folds and the pattern of the major folding suggests that the folds might be somehow connected with thrust movements of the Sulitjelma Schist Sequence rocks towards the east, the strain accompanying this movement not being restricted to one level, but extending downwards into the amphibolite breccia and the Furulund schist. It is possible that during such folding part of strip B became detached along a minor slide (Fleuty 1964b) and was carried a small distance to the east to form strip C. During the movement the orientation of the detached strip would become altered and further folding would be generated. The successive stages in the development of this structure are shown in Fig. 6.60.

FIG 6.57 Folds in the outlier of schist strip C at Byrd. The fold shape is controlled by the thin competent bands.

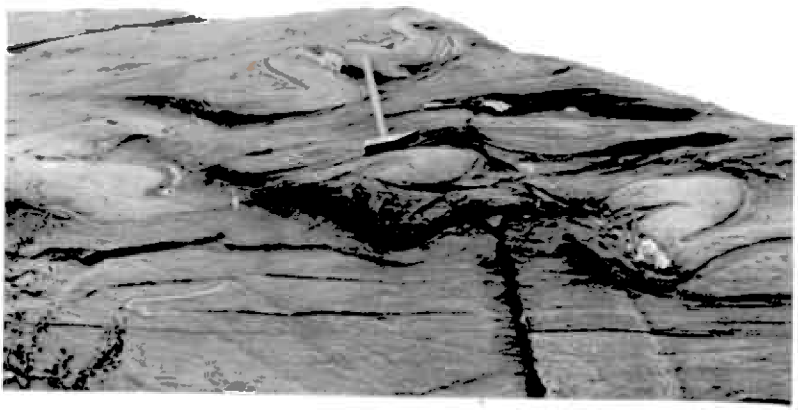
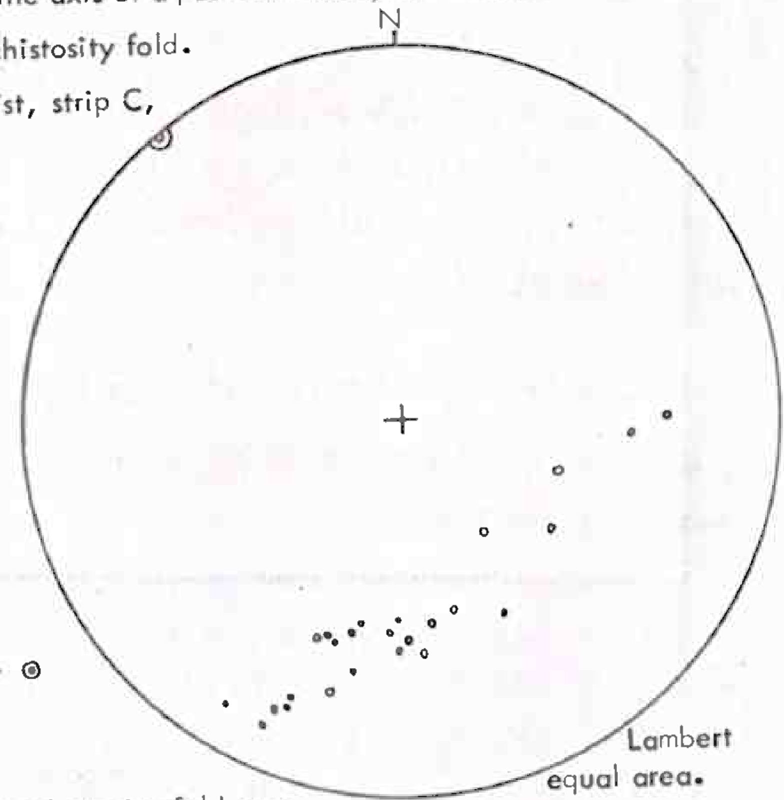


Fig. 6.58 As above. The folds have been boudined after formation. Quartz has segregated in the boudin necks.

FIG. 6.59 Folding of the axis of a post-schistosity fold round the nose of a later post-schistosity fold. Furulund schist, strip C, Bursi.

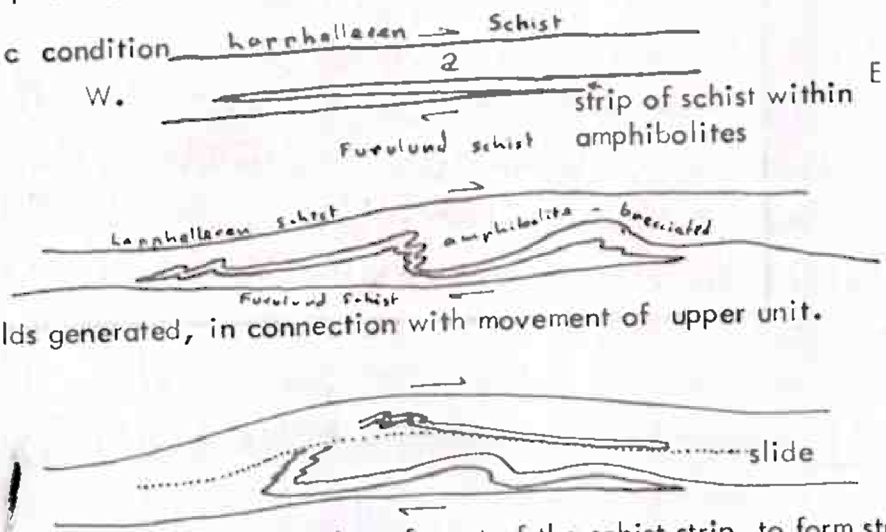


Axis of the later fold :- ⊙ (transposed onto the primative circle)

Axis of the earlier post-schistosity fold :- •

FIG. 6.60 A possible origin for the Bursi structures.

A. Pre-tectonic condition



B. Disharmonic folds generated, in connection with movement of upper unit.

C. Local slide developed with separation of part of the schist strip to form strip C.

An alternative explanation of the situation is that the two strips B and C have always been separate, being at different levels in the amphibolite breccia. While strip B was approximately parallel to the schistosity above and below the breccia and so was folded along the same axes, strip C lay at an angle to the schistosity outside and consequently was folded about different axes. This explanation, while not necessitating the (perhaps) extravagant association between the disharmonic folding and the minor thrust movements, does not explain the refolding or the boudinage of strip C.

6.10 Crinkles.

Small crinkles, of wavelength 3-4mm., and amplitude 1-2mm., are found in most parts of the thesis area and are distinguised on Map 3, their axes being marked ←• . They die out within short distances along the axes. Crinkles generally occur in two types of position; adjacent to boudinaged quartz segregations, and as tails on each side of garnets. They are also associated with the open folds north-east of Giken described in Chapter 6.3.

Crinkles developed on each side of rotated garnets during garnet growth should lie with the crinkle axis parallel to the garnet rotation axis. This was so for several of the specimens collected, but over the region the two kinds of axis show different attitudes. Fig. 6.61 shows that most of the garnet rotation axes trend between west and north, while Fig. 6.62 shows that most of the crinkle axes plot with trends WSW. Fig. 6.62 does not distinuish between the types of crinkle discussed above, since this information was only collected towards the end of the field-work. At one locality crinkles adjacent to quartz segregations were found within a metre of crinkles formed as tails to syn-kinematic garnets, and in this case the two axes were almost parallel, suggesting that lack of differentiation between the different types elsewhere may not be important.

FIG. 6.61 The axes of rotation of garnets in the Furulund schist.

Axis of rotation of garnets :- o
(derived by method described in chapter 7, based on Powell and Treagus 1967).

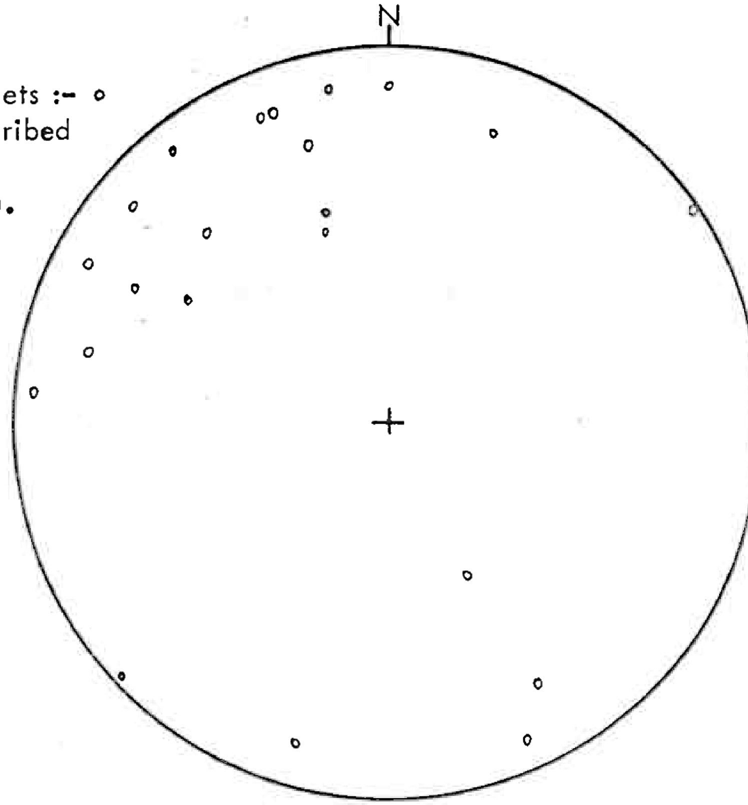
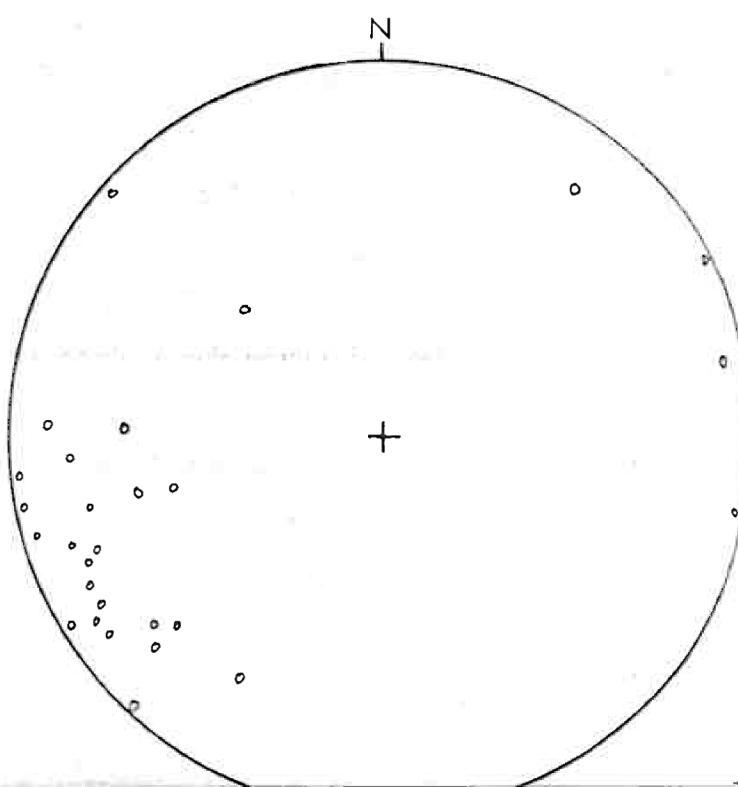


FIG. 6.62 Minor crinkles in the Furulund schist.

Axes of crinkles :- o



The association of crinkles with boudins and quartz segregations may be explained in the following manner. In Chapter 8.1 it is suggested that quartz segregations have originated through the boudinage of quartz veins. During this boudinage the schistosity would be dragged into the gap between the boudins. A slight compression following the boudinage would strain all the rocks, causing folds or crinkles to develop where the original attitude of the schistosity had been disturbed, but not folding the schistosity elsewhere, except where there were such inhomogeneities as garnets. The axis of such crinkling, being dependant on the attitude of schistosity in the scar fold, would be dependent on the original axis of boudinage. It was only possible to determine the axis of boudinage in nine cases and these are plotted on Fig. 6.63. They all lie close to each other, trending NE-SW. If the axial plane of the crinkling was known, and an assumption was made that the crinkling was a buckling phenomenon, or was generated by shear, it would be possible to predict the axes of crinkling. It can be postulated that if the axial plane were oblique to the boudin axis then the crinkle axes would be dispersed. Since Fig. 6.63 shows that the crinkle axes are sub-parallel to the boudin axes, it can be assumed that a special case has arisen, in that the axial plane of the crinkles contains the axis of boudinage. The orientations of the strain ellipsoid axes for both deformations would seem to be parallel.

The open folds north-east of Giken are frequently composed of a mass of crinkles, as in Fig. 6.18 . Either the crinkles are of the same age, or they are later , the later deformation having a special orientation relative to the earlier one.

6.11 Kink zones.

The folds described in section 6.2 are occasionally developed as kink zones, but this section describes other kink zones found in the thesis area. These are extremely sporadic. On Map 3 they are marked 'k'. In Fig. 6.64

FIG. 6.63 Boudinage in the Furulund schist – a plot of boudin 'axes'.

'axes' of boudins :- o

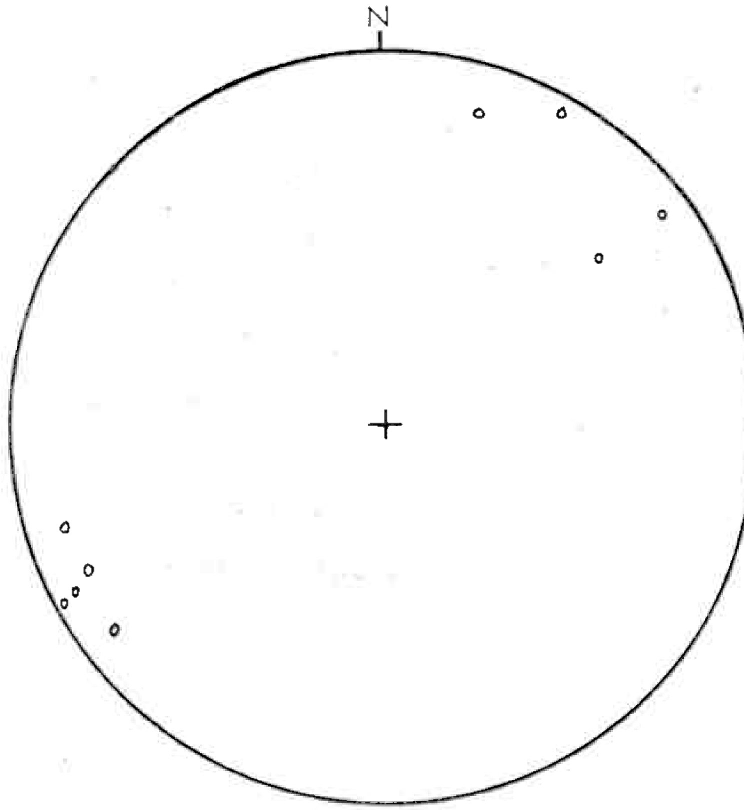
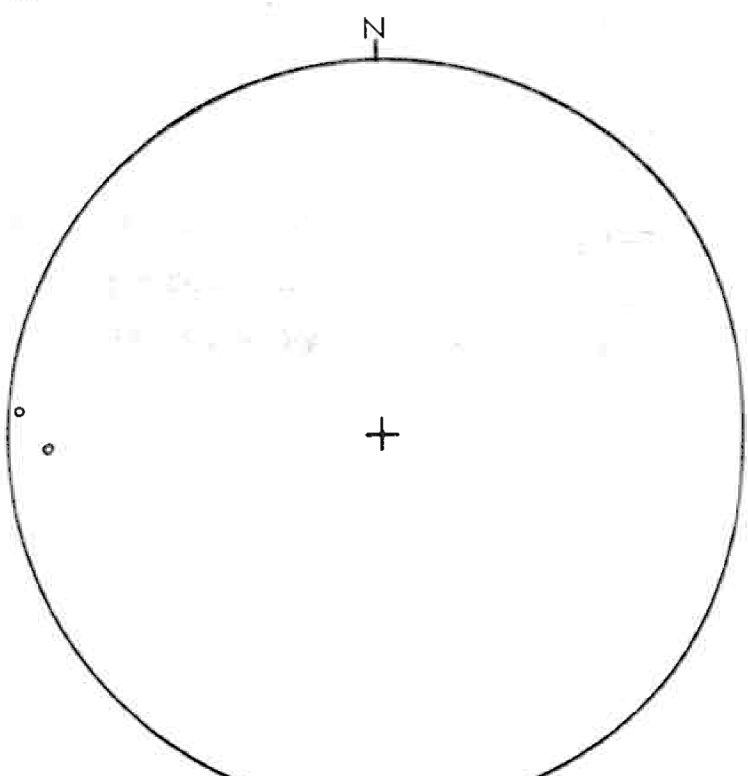


FIG. 6.64 Axes of kink folds in the Furulund schist.

Axis:- o



Lambert equal area projection.

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the axes and the poles to the axial planes are plotted, indicating the variation and the sparseness of the sample. The sense of overturn in four examples was to the N, N, NE, and E.

Specimen 418 of a kink was collected from the path between Giken and Ny Sulitjelma and shows that the kinking was later than the growth of random muscovite porphyroblasts.

6.12 Comparisons.

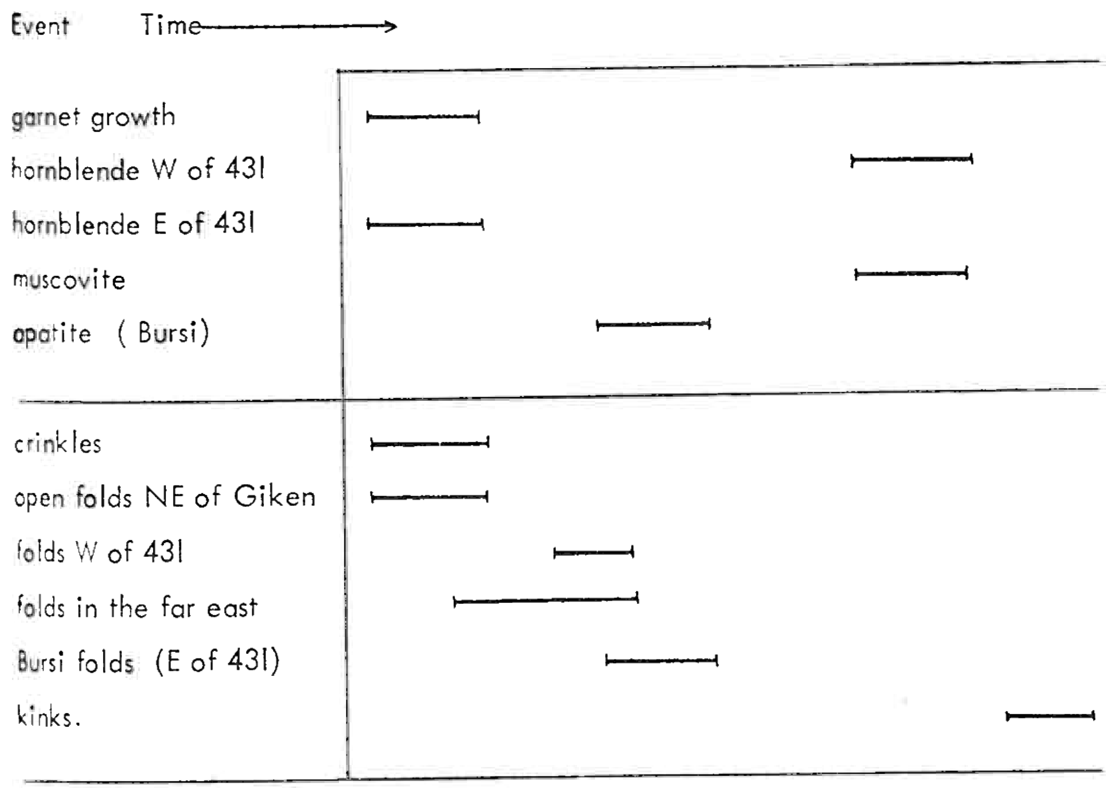
The relationship between all these fold groups is not simple to determine. The crinkles which are seen adjacent to the garnets are of the same age as garnet growth generally and therefore are the oldest post-schistosity folds. It is probable that the other crinkles are of the same age. The gentle folds north-east of Giken are probably of the same age, having a possible relationship to the boudinage.

The folds in the far east, overturned to the east are later than the crinkles, since they are mostly later than garnet growth. It is probable that they started forming at the same time as the garnets commenced growth, but continued to tighten after the garnet had stopped growing. This is based on the evidence in Chapter 6.2, that the axes of folding and of garnet rotation were similar in attitude and the sense of rotation was the same in each case. This could, however, be an example of the special orientation relationship that is common in Sulitjelma.

The folds in the far west (west of grid easting 431) are later than garnet growth, but earlier than hornblende growth. The evidence for the latter statement is in the one specimen 717, of which several sections have been cut, and is illustrated in Fig. 6.24. Henley(1968), however, regarded the folds as post-hornblende. It may be that specimen 717 is not typical of hornblende growth in these rocks. In view of the difference in orientation of the folds east and west of easting 431 it would be convenient for the two groups of folds to be of different ages. The Bursi folds are clearly later than garnet and hornblende growth and therefore are taken to be later than those west of 431.

The youngest folds are the post-muscovite kinks.

The sequence of events is therefore as follows:-



CHAPTER 7

MINERAL GROWTH AND ORIENTATION IN THE FURULUND SCHIST

7.1 Biotite.

The main fabric of the schists is the result of the preferred orientation of the biotite grains. Schistosity and lineation have generally been regarded as separate structures and although the strain significance of schistosity has long been understood, there has been considerable controversy concerning lineation. Flinn (1965a) points out that schistosity and mineral lineation refer to one structure which he relates to the finite strain ellipsoid. There is a range from perfect schistosity fabrics , 'S' tectonites, through 'L-S' tectonites to perfect lineation fabrics, 'L' tectonites. On the evidence of deformed conglomerates Flinn associates L tectonites with prolate deformation ellipsoids and S tectonites of oblate deformation ellipsoids. Variations of fabric within the L-S range are extremely common and can be related to variations in the type of flow during deformation. In particular Flinn (page 39) associates L tectonites with the special fabrics developed during thrust movements.

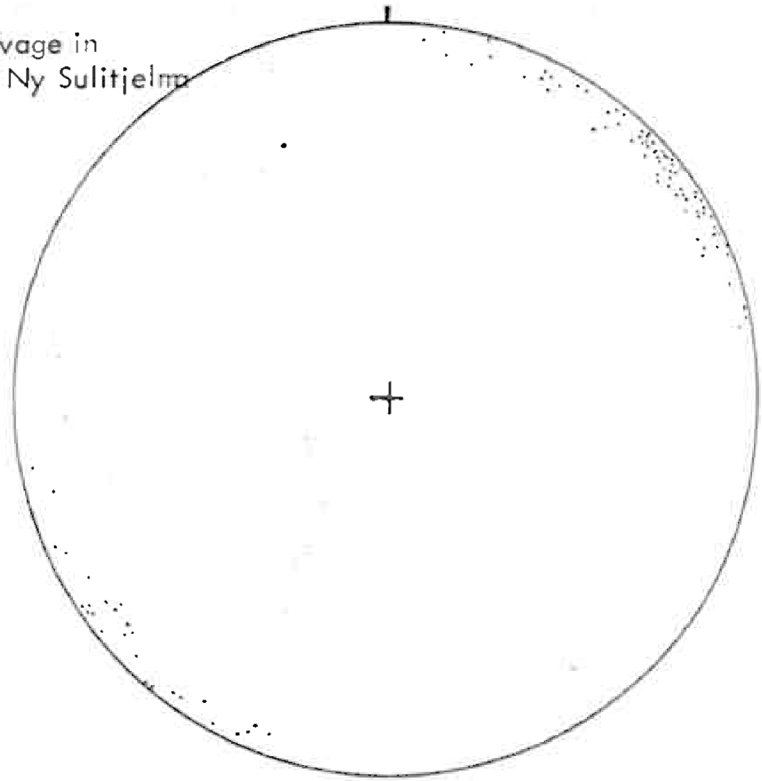
Mason (1967) suggests that the strong lineation in the rocks immediately south of the Sulitjelma gabbro was generated by thrust movements. As is discussed in the chapter on the mineral fabrics of the Sulitjelma Schist Sequence, on page 151, emphatic L tectonites are not restricted to the rocks on the south of the gabbro complex, but appear immediately adjacent to the gabbro on its western margin as well, the lineation becoming less conspicuous away from the complex. These tectonites are interpreted in this thesis as the result of unusually high strain in the vicinity of the relatively undeformed gabbro. Mason(pers. comm.) now agrees with this interpretation.

Variations within the L-S range in rocks away from the gabbro are considerable, but the large scale variation across the area appear to be no greater

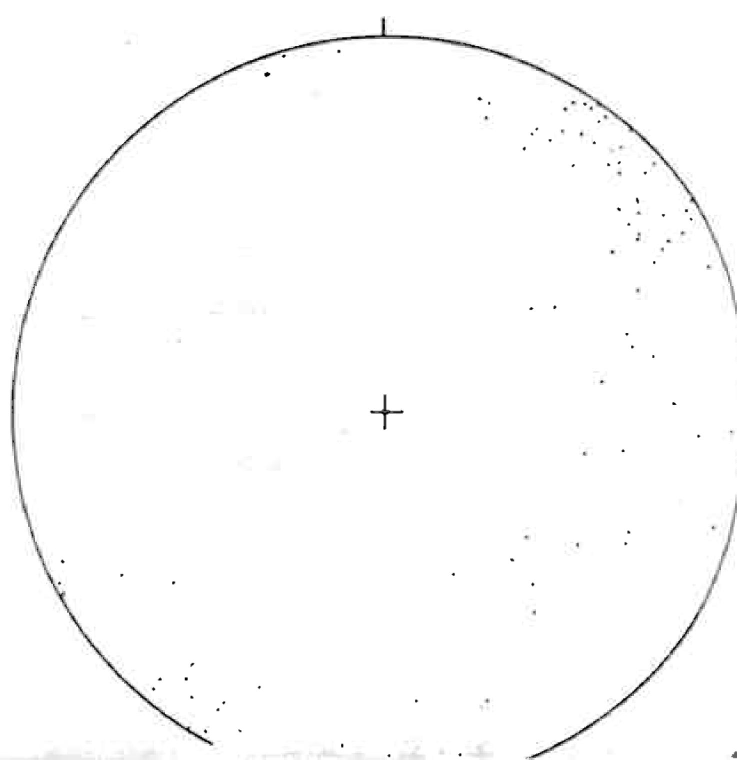
FIG. 7.1 Biotite fabrics in the Furulund schist north of Langvann.

100 poles to biotite cleavage in specimen 324, south of Ny Sulitjelma

section cut normal to lineation.



100 poles to biotite cleavage in specimen 314, east of Ny Sulitjelma.



than the variation within any one small area. No quantitative work has yet been done, but the uniformity of lithology within the Furulund schist would favour a systematic statistical study of the variation in fabrics using a computer to determine the position of any one fabric within the L-S tectonite range. Other factors such as grain size, and composition could be taken into account (Voll, 1960 pg, 506).

Fig. 7.1 contains plots of poles to biotite cleavages in the Furulund schist of the Ny Sulitjelma area, and illustrates the L-S tectonite fabric.

Biotites in the Balmi Elv stream section, south of Langvann, were much more variable in attitude than those north of Langvann. As in Fig. 7.2 , in thin section grains can be seen lying perpendicular to the schistosity, and at all angles in between. Other biotites are compressed around the markedly discordant ones. The strain causing this appears to have been irrotational, pure not simple shear, and orientated with the axis of maximum strain normal to the schistosity. All the biotites appear to be of the same generation, since there is no apparent difference in size between those biotites parallel to the schistosity and those normal. Fig. 7.3 is a plot of 100 poles to biotite cleavage in specimen 707 and in specimen 708 from Balmi Elv. Comparison with Figure 7.1 shows that the girdle is better developed, and the poles generally are more dispersed than they are for the Furulund schist north of Langvann.

Biotite porphyroblasts occur in one rock at Ny Sulitjelma (specimen 401). This is an unusually fine-grained rock found in the narrow strip of schist between the mass of banded amphibolite at Ny Sulitjelma and the main mass of amphibolite. The biotites have fine inclusions of quartz arranged in random or planar patterns (Fig. 7.4). The schistosity is strongly deflected around the porphyroblasts, and the biotites are strained, having deformed by kinking as in Fig. 7.4. . This particular rock has suffered late shearing, see Chapter 3.4 on page 21 .

FIG. 7.2 Biotite fabric, Furulund schist, Balmi Elv. Camera lucida sketches.

Specimen 707, cut parallel to lineation. Specimen 707, cut normal to lineation.

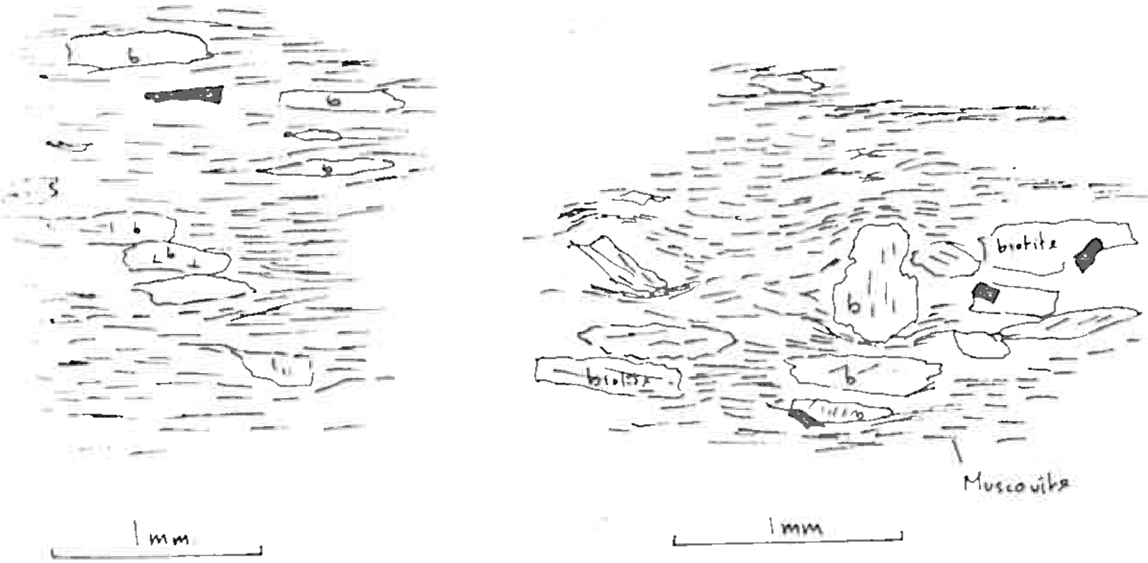
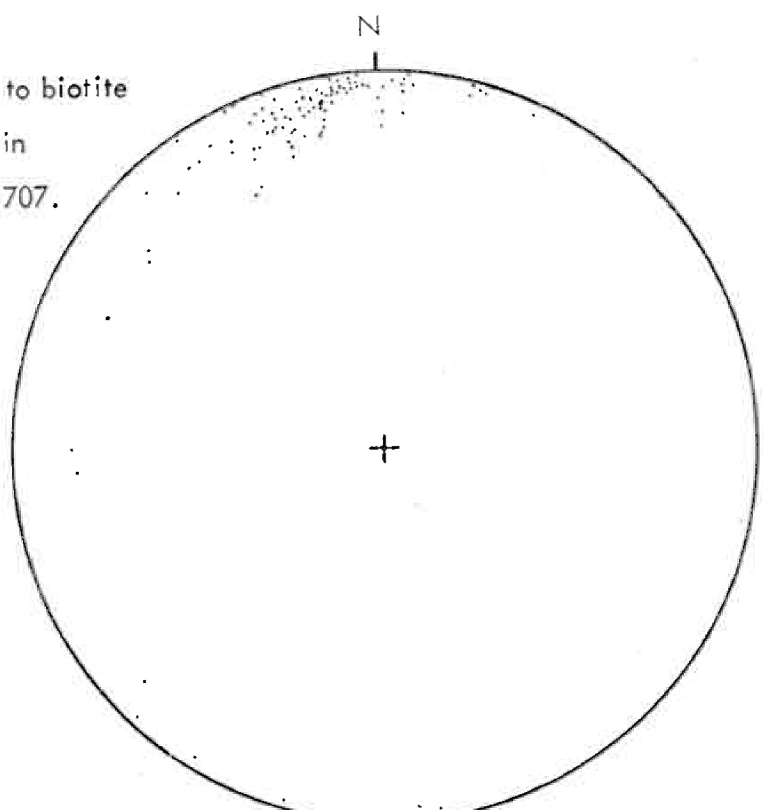


FIG. 7.3 Biotite fabric in Furulund schist, Balmi Elv, south of Langvann.

100 poles to biotite cleavage in specimen 707.



Lambert equal area

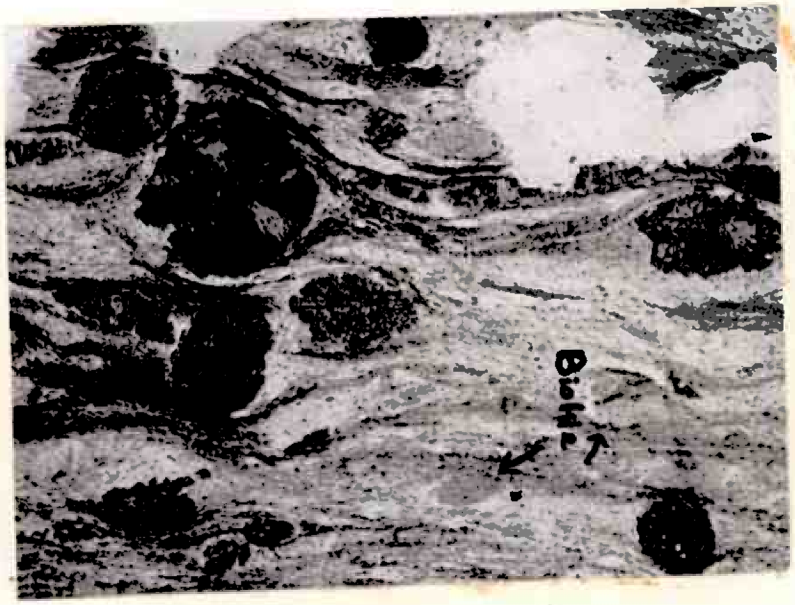
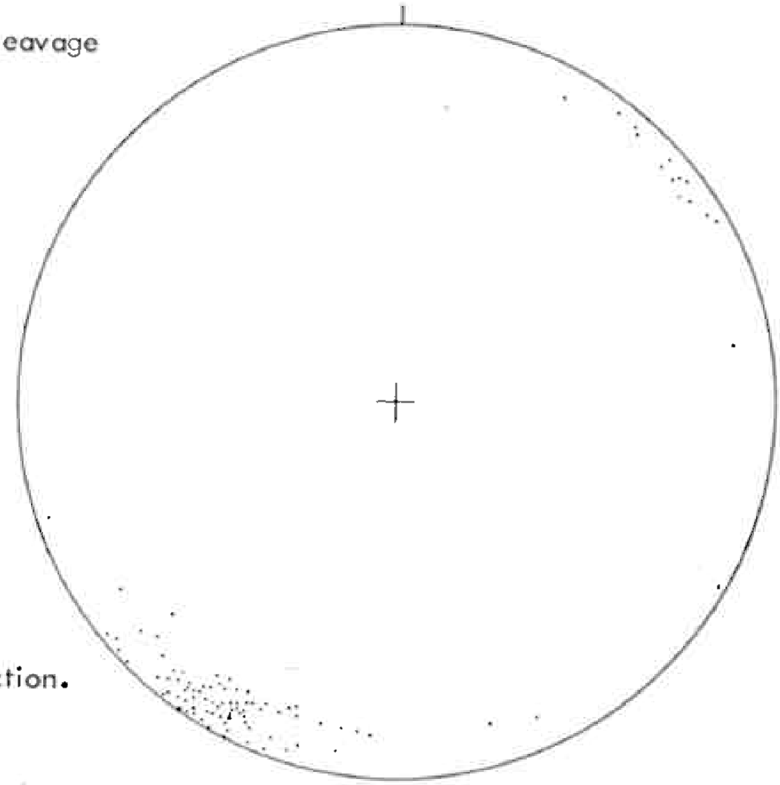


Fig. 7.4. Photomicrograph of specimen 401. x7. Plane polarised light. Note the biotite porphyroblasts, one being slightly kinked. The garnets have fine-grained inclusions. The rock has been strongly compressed after porphyroblast growth.

FIG. 7.5 Muscovite fabric in specimen 707, Balmi Elv. (Furulund schist).

100 poles to muscovite cleavage

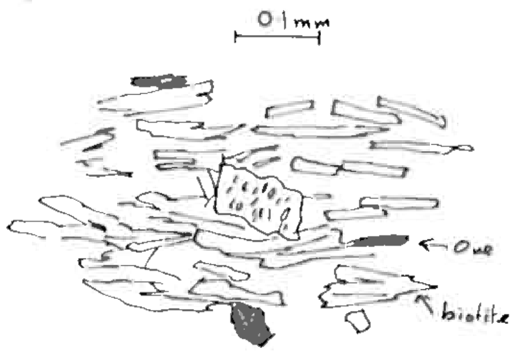


Lambert equal area projection.

FIG. 7.6 Camera lucida sketches of specimen 324 to show details of clinozoisites.

Fig. 7.6a Orientation of clinozoisite.

Fig. 7.6b Fine-grained inclusions.



Thin sections cut parallel to the schistosity show elongation of biotite grains parallel to the axis of the cleavage pole girdles. This suggests that the fabric developed during and not after the growth of biotites. There is further discussion of this in section 7.17.

7.2 Muscovite.

In some sections muscovite is seen as small flakes lying parallel to the schistosity of the biotites. The Balmi Elv rocks are especially rich in 'schistose' muscovite. Fig. 7.5 is a plot of poles to muscovite cleavage in specimens 707 and 708 from Balmi Elv, and can be compared with Fig. 7.3 of the biotites in the same rocks. The muscovites clearly have an L-S tectonite fabric, but the girdle is not so well developed as with the biotites.

Randomly orientated porphyroblasts of muscovite occur commonly throughout the Furulund Schist. With the exception of the development of kink folds as seen in specimen 418, the growth of muscovite is the last event that can be traced in the fabrics of the Furulund schist. The muscovites cut across all other folds, and are not themselves folded or other wise deformed. Schistosity is not deflected around them. In the case of specimen 418, a late kink fold has slightly deformed a muscovite porphyroblast.

7.3 Chlorite.

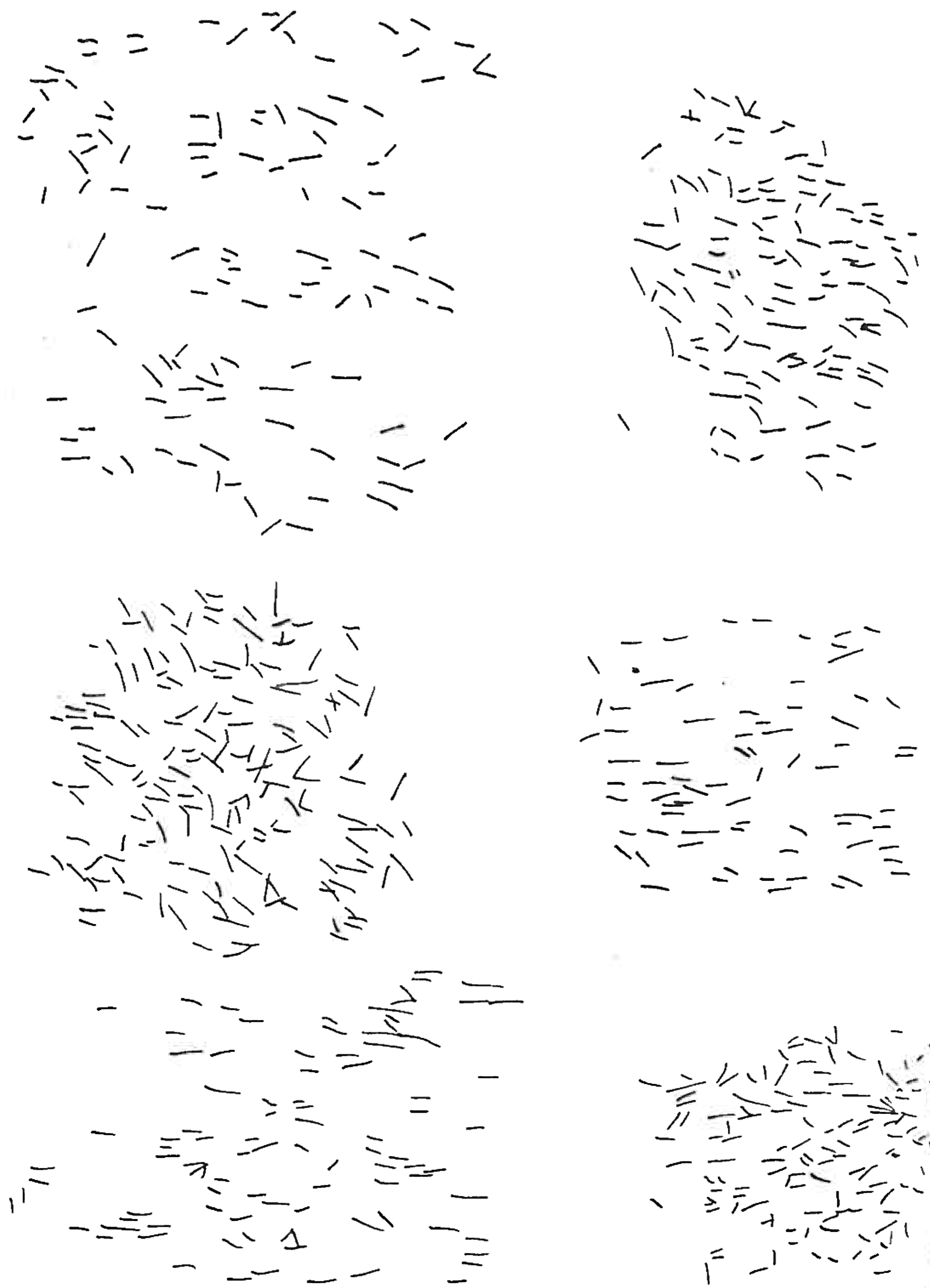
Chlorite is found in most specimens of Furulund schist. It occurs both in preferred orientation, parallel to the schistosity of the rocks and as random porphyroblasts. There are several examples of chlorite replacing biotite, but none seen of chlorite replacing muscovite. One specimen has a biotite crystal across which has grown a late muscovite, the rest of the biotite being partly replaced by chlorite.

The random porphyroblasts of chlorite are occasionally very slightly

FIG. 7.7 Hornblende fabrics in the Furulund schist.

Tracings from photographs of schistosity surfaces.

Original photographs taken within a hundred metres of each other, in the area between Giken and the smelter. Scale- approx (x $\frac{1}{3}$).



strained. They are either slightly earlier than the random muscovites (in which case they could not have grown by replacing them), or else they are more sensitive to slight stresses than are the muscovites.

7.4 Clinozoisite.

Clinozoisite occurs commonly as needles elongate parallel to the y crystallographic axis. They are invariably orientated parallel to the biotite lineation as in Fig. 7.6a. Occasionally the grains contain small inclusions of quartz, which as in Fig. 7.6b are generally orientated at an angle to the schistosity, and suggest that the clinozoisite grew at an early stage in the development of the biotite fabric. Clinozoisite is sometimes found as inclusions within garnets, and this also indicates a fairly early age for clinozoisite growth. No measurements have been made of clinozoisite orientation.

7.5 Hornblende.

Hornblende laths, up to 1mm. by 1mm. by 10mm., are common in many parts of the Furulund schist. Their elongation is parallel to the z crystallographic axis. They lie with their lengths within the schistosity plane and are to a varying degree orientated parallel to one another. The degree of parallelism varies considerably within quite small distances, for example, across the thickness of a hand specimen. Fig. 7.7 shows some typical hornblende fabrics, the diagrams being traced from photographs. Fig 7.8 of specimen 701 illustrates the tendancy of the hornblende to grow in sheaves. No petrofabric measurements have been made of hornblende orientation.

Fig. 7.9 is a photomicrograph showing the appearance of the hornblendes in thin section. They contain large quartz inclusions which indicate that the rock had a good schistosity fabric before the hornblendes grew. Sections cut normal to the z crystallographic axis show S shaped trails, while sections cut parallel to the z axis usually show straight or slightly curving trails. This indicates that the hornblendes have rotated slightly during growth and that the rotation axis lies near to the z crystallographic axis. In specimens containing both garnet and hornblende, such as specimen 619a (Fig. 7.9) the S shaped trails in both minerals are comparable and indicate that both minerals grew at about the same time.

In later sections of this chapter the rotation of garnet porphyroblasts during growth is discussed in detail. Many of the points raised are applicable to the study of syn-kinematic hornblendes, but there is an additional factor, the shape of the porphyroblast. Since the shape of garnets approximates to a sphere, it has no effect on the orientation of the rotation axis, which is dependent upon the type of strain, the attitude of the strain axes and the attitude of the schistosity. In considering lath-shaped hornblendes it must be realised that the shape has a strong effect on the orientation of the hornblende during deformation as has been discussed in recent studies by Bhattacharyya (1966) and by Gay (1966 and 1968). There is clearly a need to study the inclusion trails of syn-kinematic hornblendes in detail, but it was not possible in this present investigation.

One immediate result of a close study of the inclusion trails in hornblendes would be an indication of the means by which the hornblendes achieved their preferred orientation. In general two hypotheses have been advanced to account for the preferred orientation of minerals. One is that the minerals grew in a random orientation and were brought into preferred orientation by deformation, (see Flinn 1962, pg. 423, for a recent discussion) and the other is that minerals growing in a stress field grow with an initial preferred orientation of their lattices, (see recent discussion by Flinn, 1965). The S-shaped in the hornblendes in the Furulund schist indicate that the crystals were being orientated during growth.

The L-S tectonite fabric of the hornblendes is a product of the strain since hornblende growth commenced. It is evident that the strain was inhomogeneous since the intensity of the lineation varies over the area.

In the far west (west of grid easting 431, Map I) there is some hornblende which must be of a different generation from that found in most of the thesis area. Post-schistosity folds are here overgrown by hornblende grains, as is shown in Fig. 6 .24 of specimen 717, yet as the photograph shows, the folds are clearly later than the growth of garnet. As stated above, in the thesis area garnet and hornblende are generally approximately coeval.

7.6 Apatite.

Specimen 634 from Bursi contains abundant parallel-orientated prisms of apatite in grains some 3mm. by $\frac{1}{2}$mm. by $\frac{1}{2}$mm., elongated parallel to the z crystallographic axis. The diamond-shaped . basal sections show S shaped inclusion trails. Sections cut parallel to the length of the prisms show straight inclusion trails, indicating that there has been rotation during growth. The direction of the axis of rotation, parallel to the z crystallographic axis , is also parallel to the axis of the post-schistosity fold from the closure of which specimen 634 was taken. The folding of schist strip B at Bursi is therefore taken to be synchronous with apatite growth.

7.7 Garnet - introduction.

Certain parts of the thesis area are very rich in garnets, notably a zone crossing the area near the top of the succession, as described in Chapter 4.4, page31 . The growth of garnets has been investigated in detail. 73 specimens of garnet bearing schist were collected and from these some 165 thin sections cut.

Garnets in the Furulund schist in the thesis area are usually zoned,

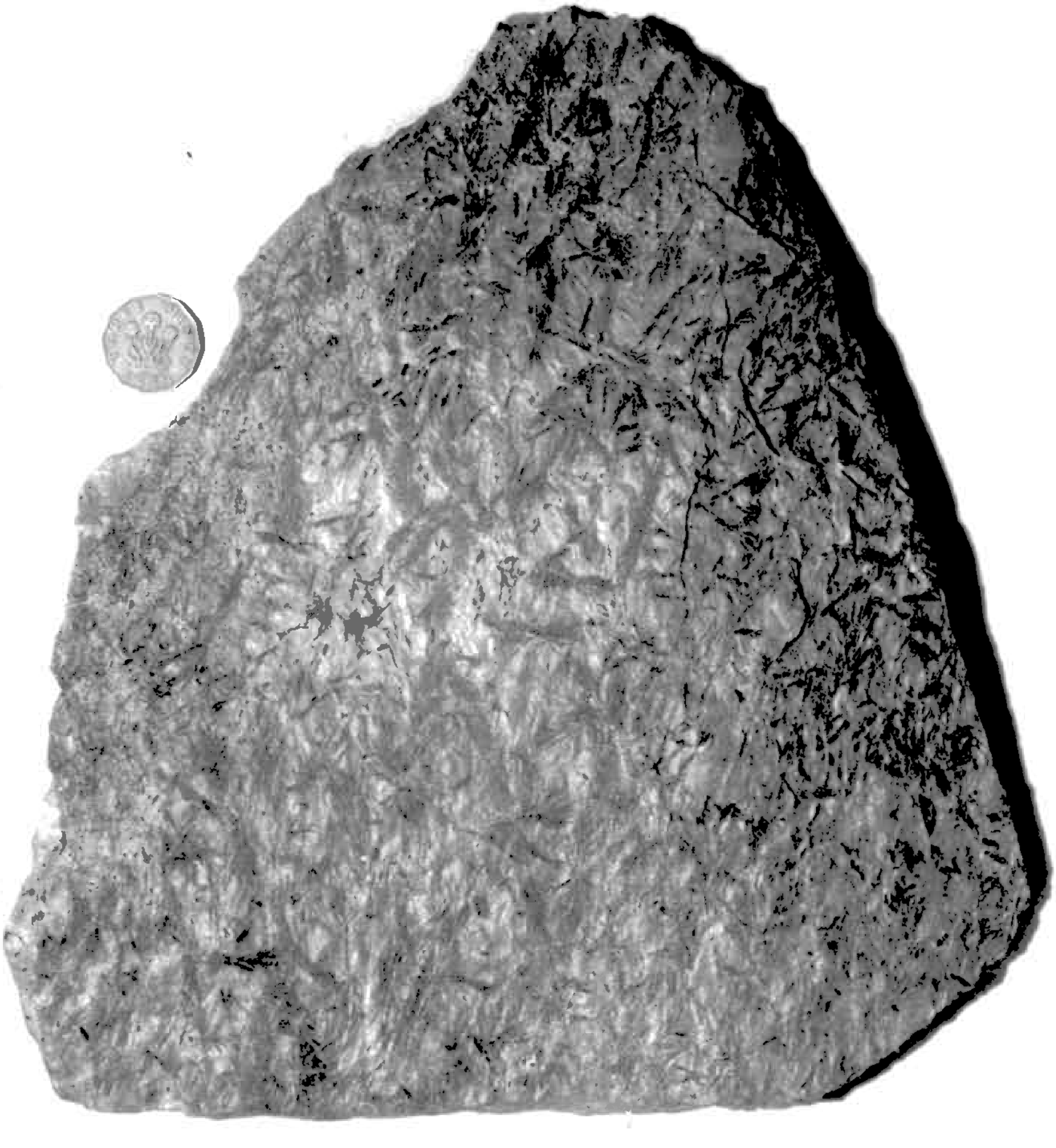


Fig. 7.8 Specimen 704 Hornblende rich [illegible] schist.
The hornblende is best developed in [illegible] ([illegible]).

Fig, 7.9 Photomicrograph of specimen 619 to show the similarity of inclusion fabric between garnets (G) and hornblendes (H). x7. Plane polarised light.

having a large inner zone with plentiful inclusions and a small outer zone with very few. In some garnets this outer zone is absent. Inclusions in the inner zone are tabular in shape, usually of quartz with the occasional grain of clinozoisite, though in calcite-rich schists calcite is represented. The shape of the inclusions indicates that the garnet grew after the development of a good schistosity in the rock. Fig. 7.10 indicates the criteria used to determine these facts. The geometry of the inclusion trails indicates that in some of the rocks the garnets grew during a deformation of the matrix which caused rotation of the garnet relative to host rock, in some rocks the garnets grew under static conditions, though the growth was followed by compression, and in one case the garnets grew during a non-rotational deformation. Garnets from Balmi Elv, south of Langvann have been studied from specimen N67 48 and contain small inclusions whose trails indicate slight deformation during growth. Schistosity has been compressed around these garnets, as it has around the garnets north of Langvann.

Henley, (Harte and Henley 1966,) has studied the zoning in the garnets of the Furulund schist, mainly from samples collected south of Langvann, and has used an electron probe microanalyser to demonstrate that there is compositional zoning in those parts of the garnets where there is no zoning visible through changes in the character of inclusion trails. Most of the garnets examined showed a gradual decrease of MnO and a gradual increase of FeO from the core to the margin of the garnets. The gradual changes occur in parts of garnets which show the same inclusion trail characteristics while sharp breaks in composition accompany discontinuities in the character of inclusion trails.

7.8 Outer zones of garnets.

Inclusions in the outer zones are usually very small, in section highly elongate. The patterns of trails within the outer zone, though frequently rather

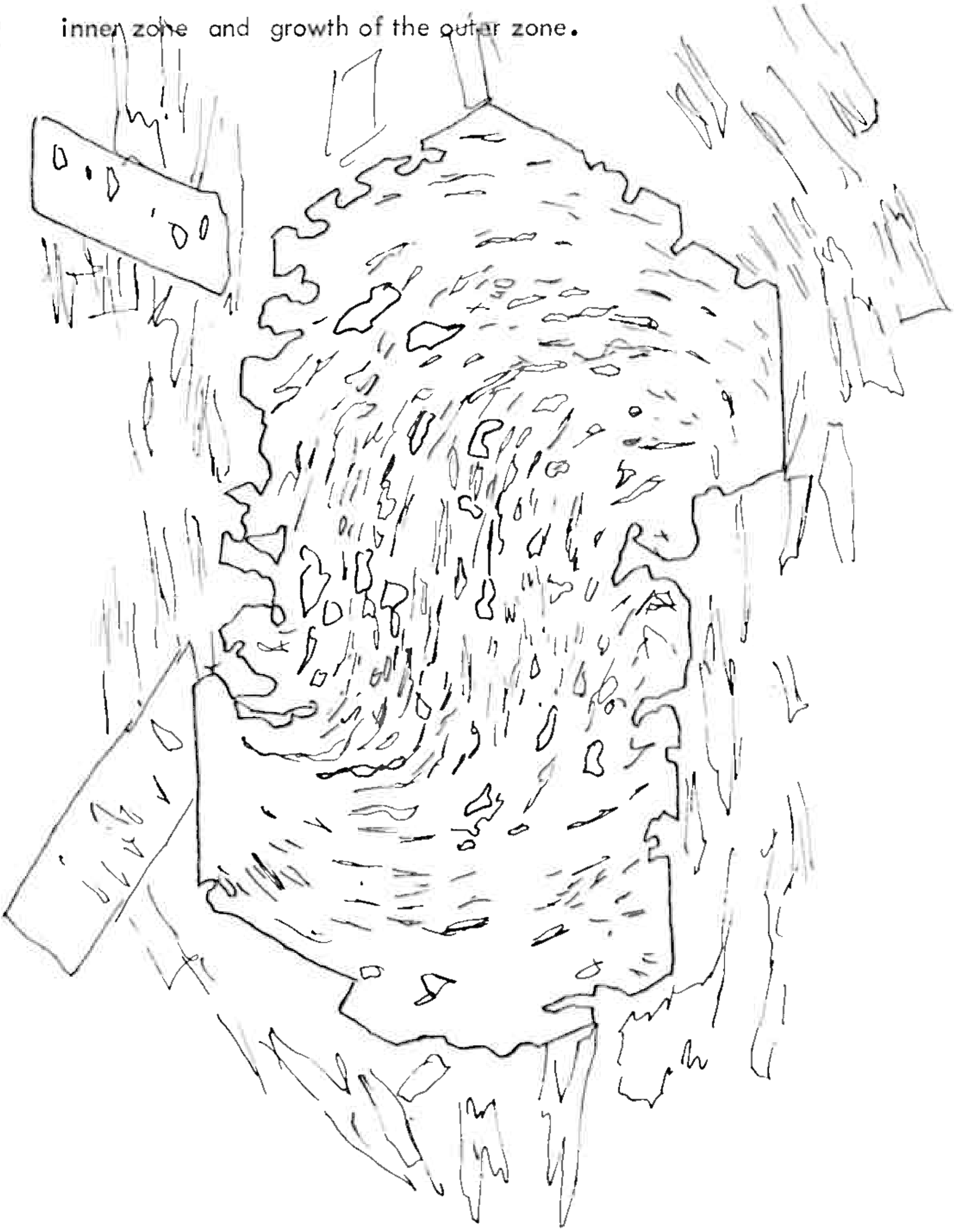
FIG. 7.10 Garnet growth in the Furulund schist- sketch of typical garnet, to show features of the inclusion fabric. Specimen 509.

Note that inclusions in the garnet are elongate- this character is seen in sections normal to this one, indicating that the inclusions are tabular. Note that their shape and size does not vary across the garnet.

Fabric of the outer zone is continuous with that of the inner zone, though the inclusions are very fine grained, and highly elongate. The outer zone is just continuous with the external fabric. Sometimes the outer zone is clearly later than the last compression of the biotite fabric.

FIG. 7.11 Example of the outer zone development of Furulund schist garnets. Specimen 518a.

The outer zone has very few inclusions. These inclusions are highly elongate, and their pattern indicates that there was no marked deformation between growth of the inner zone and growth of the outer zone.



While the outer zone is apparently continuous (in fabric character) with the external fabric, the latter is considerably coarser grained. The matrix fabric is only represented diagramtically on this sketch. See also Fig. 7.10.

indistinct, suggest that this outer zone grew during rotation, though in several cases the zone grows over schistosity which has been compressed strongly around the inner zone of the garnet. Fig. 7.11 shows the criteria used to determine this, and shows typical examples. The outer zone is most commonly developed as two patches on opposite sides of the garnet, where schistosity has been compressed most against the garnet. At these positions the schist contains very little quartz. It is assumed that the quartz has migrated to the "pressure shadow zones " at the sides of the garnet. Garnet growth in the biotite-rich area would need to reject very little material in the form of inclusions and consequently the outer zone is poor in inclusions. Trails of inclusions, when seen, are usually continuous from the inner to the outer zones of the garnets, the trails becoming slightly more curved as they pass between the zones. The trails in the outer zones are usually continuous with the fabric outside the garnet, as in Fig 7.11 ,but where there is no outer zone developed, then there is usually a discontinuity between the trails of the internal zone and the fabric outside. This discontinuity makes it difficult to determine the amount of rotation that has occured during garnet growth.

7.9 The inner zones of garnets.

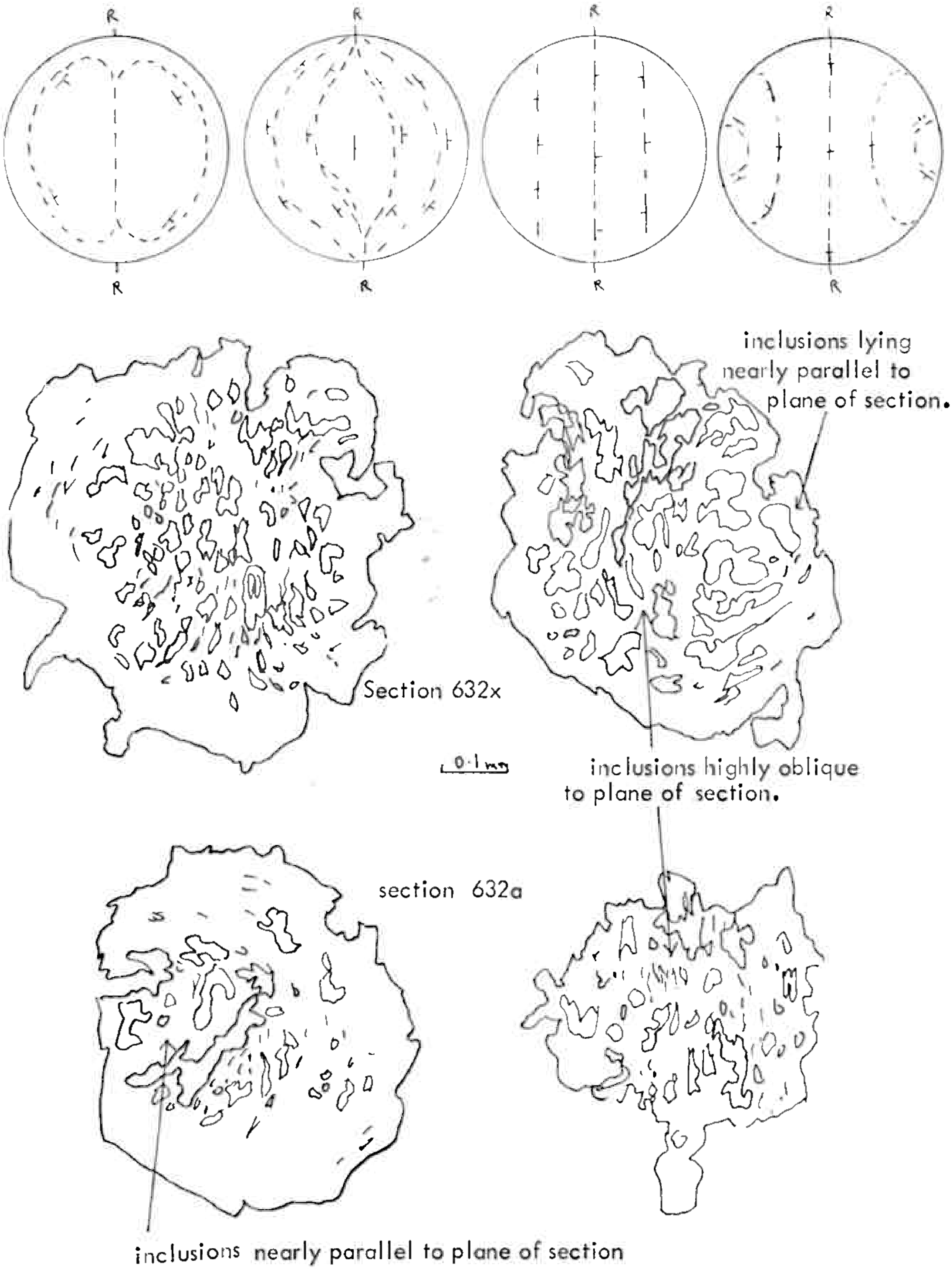
The 73 garnetiferous rocks examined may be divided into non-kinematic garnets, in which the inclusion trails in the inner zone are planar in three dimensions, indicating growth of the garnet during a static phase following the establishment of schistosity, syn-kinematic garnets, in which the inclusion trails are non-cylindroidal S shapes indicating rotation of the garnet relative to the matrix during growth, and those garnets whose trails of inclusions are so indistinct that it is impossible to determine anything of their growth history.

7.10 Theory of S shaped inclusion trails in garnets.

So called S shaped trails of inclusions in porphyroblasts are a common phenomenon ,(see Read, 1949) and it has long been known that they provide evidence of synchronous deformation and mineral growth. Despite the amount of work that has been done on garnets and their inclusion trails, as is summarised and extended in Spry (1963) ,it is only recently that the three dimensional geometry of these complex patterns has been investigated (Powell and Treagus, 1967). In this preliminary paper Powell and Treagus erect a model " based on the consideration of the growth of a near spherical body while it is rotating or while its matrix is rotating around it..... in an environment whereby originally rectilinear elements of the matrix are preserved as inclusions within the growing body. " Their study of this simple model shows that many sections cut through the model in different attitudes show S shaped trails, with variations in the degree of curvature. They demonstrate that Spry (1963) was incorrect in assuming that the trails of inclusions would be cylindroidal. Sections which contain the axis of rotation of the garnet show patterns which have a mirror plane symmetry, the rotation axis lying parallel to the mirror plane. Figure 7.12 shows three sections which according to Powell and Treagus contain the rotation axis, and also sections through garnets from the Furulund schist which show such patterns.

A starting point for the study of syn-kinematic garnets is a consideration of the deformation of their matrix. Spry supposed that the rotated garnets grew in a matrix being deformed by simple shear, parallel to the schistosity plane. There is, however, the problem of how simple shear on a large scale is generated in rocks. Ramsay (1962) pointed out that S shaped patterns of inclusions could result from pure shear deformation of the matrix if the axis of maximum strain were oblique to the schistosity, although there is a limit on the amount of curvature of the trails, since the garnet cannot rotate relative to the attitude of schistosity by more than 90°. Ramsay also suggested here that successive

FIG. 7.12 Syn-kinematic garnets – Patterns predicted by Powell and Tregus from sections cut parallel to the axis of rotation, and similar patterns from the garnets of the Furulund schist. See also Fig. 7.19.



flattenings about different axes, or simple shear, could account for the rotation of more than 90°.

For the purposes of discussion a general case for the deformation of the matrix may be taken as being progressive three dimensional deformation, the strain being either pure shear or simple shear or both, with the axes of the finite strain ellipsoid being oblique to schistosity.

A garnet growing during deformation will record in the pattern of inclusions the successive attitudes of the schistosity surfaces in the immediate vicinity of the garnet. For any infinitesimal step in the deformation the rotation axis is the intersection of the attitudes of the schistosity before and after deformation. Flinn (1962, pg. 394) discusses the rotation of planes during pure shear deformation. Flinn calls the path traced out by the poles of planes onto the projection net during deformation - "structural movement paths." If the structural movement path lies along a great circle of the projection then the plane is rotating around a fixed axis and the garnet too will appear to rotate around a fixed axis. Flinn demonstrates that only in certain special cases will the movement path lie along a great circle. Fig. 7.13 is taken from Flinn (1962) to illustrate the structural movement paths that develop. Flinn's special cases are firstly when the pole of the plane lies within a symmetry plane of the deformation ellipsoid - during deformation the pole will move within that plane only, and secondly when the deformation path (Flinn 1962) is $K=0$ or $K=\infty$, that is, when the deformation is biaxial. However, according to Flinn such special cases may possibly be quite common. Thus in the general case for pure shear, the garnet will not rotate about a fixed axis.

The situation is different for simple shear deformation. In the general case for the rotation of an oblique plane, structural movement paths fall on great circles of the projection and the growing garnet will rotate around a fixed axis.

FIG. 7.13 Structural movement paths. From Flinn, 1962 Fig. 2.

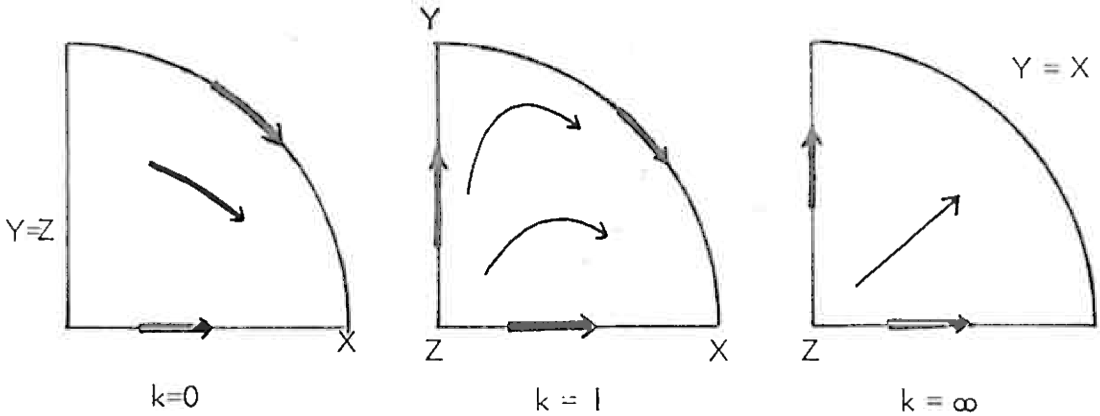
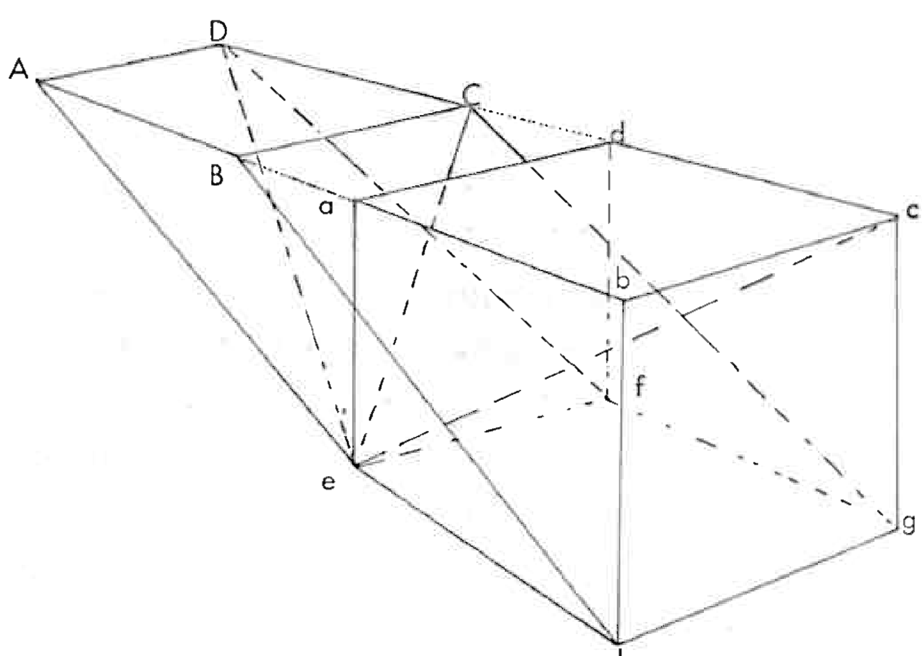


FIG. 7.14 The change in attitude of planes during simple shear deformation.

See text for explanation



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This is demonstrated as follows. The cube in Fig. 7.14 opposite is deformed by simple shear parallel to face (abcd) so that that face is translated to position (ABCD). (ec) represents the pole to an obliquely orientated plane before deformation. During simple shear point (c) will be displaced along a straight line (cdC) to point (C). At all times the line will lie within the plane (ecC). The plane to which this line is a pole will therefore rotate around a line normal to the plane (ecC). Thus in the general case for simple shear, a growing garnet will rotate about a fixed axis.

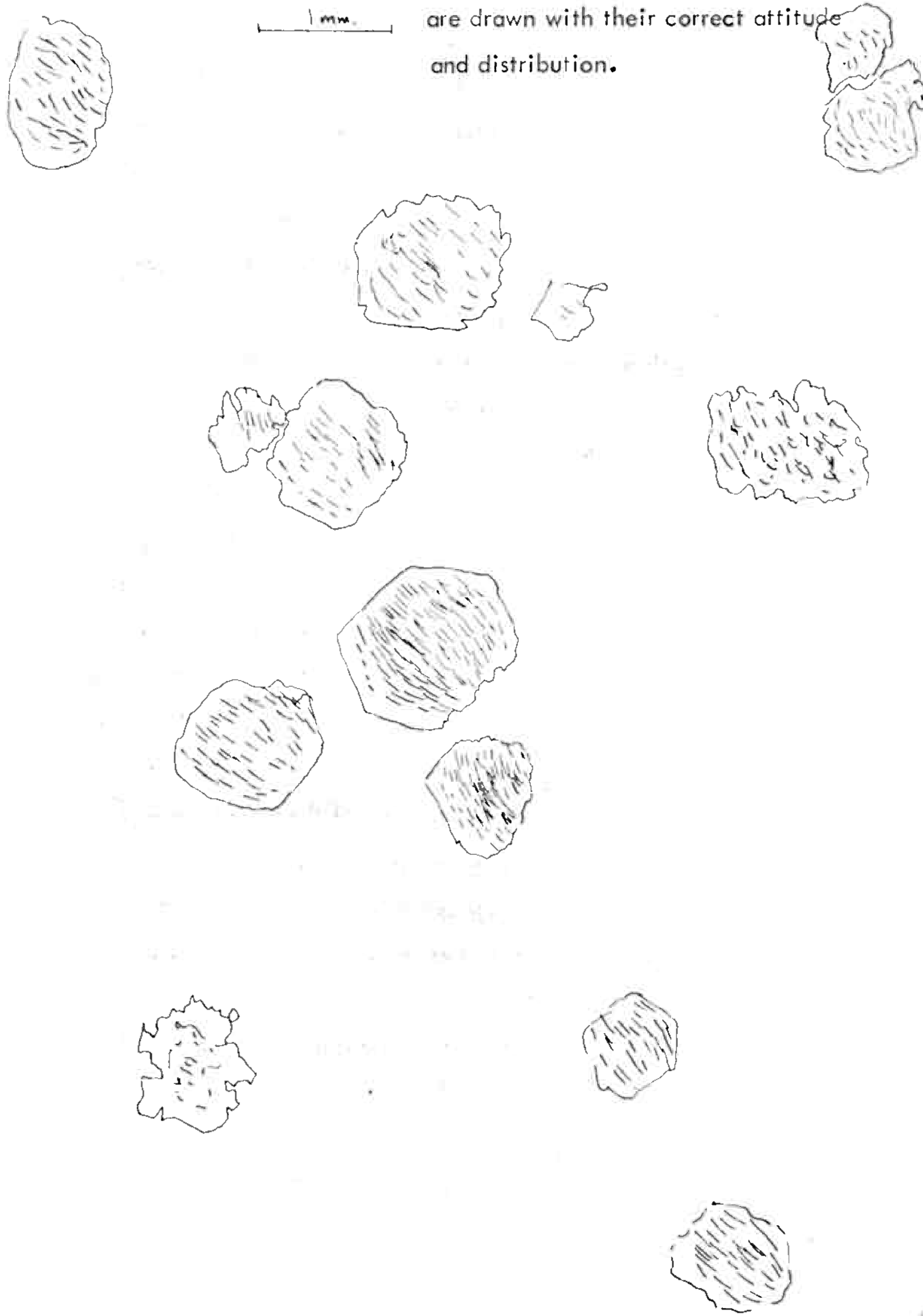
The model erected by Powell and Treagus applies therefore to simple shear deformation of the matrix and to pure shear deformation in the special cases outlined above. Obviously the next step would be to determine the three dimensional shape of inclusion trails for cases with variable rotation axis attitude.

A further complexity which must be mentioned is that the schistosity is deformed around the garnet and therefore the attitudesof the surfaces which are over-grown are determined both by the homogeneous deformation of the matrix and by the inhomogeneous deformation in the vicinity of the garnet.

7.11 Application of the theory to the Sulitjelma rocks.

Theoretically the best method of investigation is the serial sectioning technique described in Powell(1966) and Powell and Treagus (1967), but the garnets in the Furulund schist are rarely larger than 1mm. diameter so such methods are impossible with present cutting techniques. An initial assumption was made that the Furulund schist garnets had been rotated around axes which did not vary in attitude during garnet growth. Sections were cut which were estimated to contain the rotation axis; sections which contained the rotation axis being identified by using figure 2 of Powell and Treagus in the manner described on page 66, illustrated by Fig. 7.12.

FIG. 7.15 Camera lucida sketches of specimen 512 to show the variation in attitude of garnet rotation axes. External fabric ignored. The garnets are drawn with their correct attitude and distribution.



Two guides were employed to locate the most suitable section to cut. On schistosity surfaces small tails or crinkles could be seen on each side of each garnet. It can be deduced that the axis of this crinkling lies parallel to the axis of the garnet rotation, and sections were cut parallel to this crinkle (when it was seen,) usually with success. Secondly it may be deduced that in the very simple case where the axis of rotation remains constant throughout the deformation and the schistosity is not further modified after garnet growth, the axis lies parallel to the intersection of the schistosity before and after garnet growth, and therefore lies in the plane of schistosity in the rock at present.

In the Furulund schist north of Langvann there is often some continuity between the internal trails and the schistosity outside, though in some cases the outer zone also appears to have been rotated during growth. 37 thin sections were therefore cut parallel to the schistosity, 12 of which did not contain the rotation axis. In some of these cases the inclusion trails were not well enough defined to determine the attitude of the axis but in others the axis was definitely oblique to the schistosity. Some of these cases are accounted for by discontinuities between the trails and the external fabric, and some by apparent rotation of the garnet during growth of the outer zone.

In 24 rocks sections were seen which appeared to define the axis of rotation. As might be expected the attitudes of the axes in any one rock showed a degree of variation. The component of variation in the plane of the thin section is easily determined and is illustrated in Fig. 7.15, but the component normal to the section manifested itself in the appearance of S shaped patterns, as in Fig. 7.15.

By this hit and miss method of measuring rotation axes it is impossible to determine quantitatively how near to the plane of the section the rotation axis lies, except by cutting a second section normal to the first. The method of Powell and Treagus, of measuring the three dimensional attitude of the inclusions and deriving the axis from the measurements should avoid the necessity of cutting a thin section exactly parallel to the rotation axis, and is most useful in rocks where there is a considerable amount of variation in axis attitude and in rocks where the matrix has suffered complete .recrystallisation after garnet growth. The method has not been used in the present investigation. Fig. 7.16 is a table of the rocks from which it was possible to determine the rotation axes, and Fig. 7.17 is a plot of the axes on a stereogram. On Map 8 the axes and their sense of rotation are marked, along with the axes of folds which may be contemporary and the direction of the biotite mineral lineation. Fig. 7.18 is a series of photomicrographs of different sections through specimen 632 showing S shapes, X shapes and () shapes. Fig. 7.19 is a series of camera lucida sketches of garnets showing various sections which contain the rotation axis. Fig. 7.20 illustrates the X sections seen in specimen 599C. This rock has been strongly folded after the growth of the garnets, and a crenulation cleavage has developed. Consequently the rotation axes of different garnets are no longer parallel, as can be seen in the photograph. The good correspondence with the theoretical models of Powell and Treagus suggest that the change in orientation of the axis of rotation during garnet growth may be negligable, and that the garnets either grew during pure shear deformation in which there was some special symmetrical relationship of strain axes and schistosity or they grew during simple shear deformation.

7.12 Amount of rotation.

Another attack on the problem of the type of strain is through the study of the amount of rotation that has occured. Ramsay (1962) shows that if the amount of rotation between garnet and matrix is more than 90° then the deformation must have been by simple shear or by successive phases of pure shear. A rotation of 90° is an extreme case depending on infinite strain and a suitable initial orientation of the schistosity relative to the strain axes. In theory the amount of rotation

FIG. 7.16 Garnet rotation axes - details of thin sections used.

<table>
<tr><th>Section No.</th><th>type of pattern</th><th>axis</th><th>No. of determinations</th></tr>
<tr><td>309</td><td>S</td><td></td><td></td></tr>
<tr><td>309x</td><td>||</td><td>344/24</td><td>3</td></tr>
<tr><td>313</td><td>vague</td><td></td><td></td></tr>
<tr><td>313x</td><td>|| but only poor</td><td>298/25</td><td>6</td></tr>
<tr><td>392</td><td>||</td><td>337/14</td><td>2</td></tr>
<tr><td>392a</td><td>some random some ||</td><td></td><td></td></tr>
<tr><td>432</td><td>S</td><td></td><td></td></tr>
<tr><td>432x</td><td>||</td><td>019/19</td><td>20</td></tr>
<tr><td>508</td><td>S poor</td><td></td><td></td></tr>
<tr><td>508x</td><td>)(</td><td>284/20</td><td>1</td></tr>
<tr><td>509</td><td>)(</td><td>152/54</td><td>7</td></tr>
<tr><td>509x (parallel schistosity)</td><td>S</td><td></td><td></td></tr>
<tr><td>512</td><td>S</td><td></td><td></td></tr>
<tr><td>512a</td><td>( )</td><td>338/14</td><td>15</td></tr>
<tr><td>512b</td><td>)(</td><td></td><td></td></tr>
<tr><td>516</td><td>S, ||,)(</td><td>090/36</td><td>9 (wide range)</td></tr>
<tr><td>516a</td><td>||,)(</td><td>156/11</td><td>20</td></tr>
<tr><td>516b</td><td>S, ||,</td><td></td><td></td></tr>
<tr><td>516x</td><td>S</td><td></td><td></td></tr>
<tr><td>518</td><td>)(</td><td>150/23</td><td>?</td></tr>
<tr><td>518a</td><td>S</td><td></td><td></td></tr>
<tr><td>518b</td><td>S</td><td></td><td></td></tr>
<tr><td>518x</td><td>S and ( )</td><td></td><td></td></tr>
<tr><td>520</td><td>S</td><td></td><td></td></tr>
<tr><td>520x</td><td>( )</td><td>322/9</td><td>7</td></tr>
<tr><td>522</td><td>random & S</td><td></td><td></td></tr>
<tr><td>522x</td><td>( ) & random</td><td>350/11</td><td>5</td></tr>
<tr><td>523</td><td>|| & S</td><td></td><td></td></tr>
<tr><td>523x</td><td>||</td><td>298/11</td><td>15</td></tr>
</table>

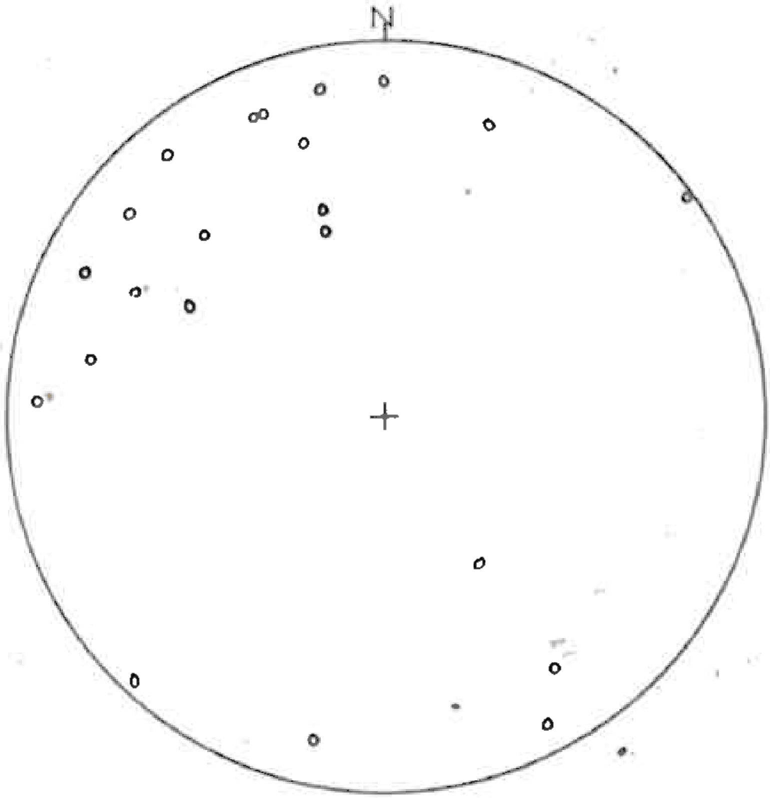
cont......

FIG. 7.16 continued from previous page.

Section No.	type of pattern	axis	No of determinations.
541	S		
541x	( )	310/13	9
593	S		
593x	)(	197/14	5
599	)(	altered by late folding.	
612	S		
612x	II	227/3	1
617	( )	342/46	2
617a	S		
618	S, II,)(	343/42	2
618a	S, II		
618x (parallel schistosity)	S and random		
619a	II, S		
619b	II	316/31	7
619c	S		
625	S, II,	too much variation	
625x	vague		
632	S		
632a	II, ( )	054/0	13
632x	)(,		
662	II	000/11	1
662a	S		
662x (parallel schistosity)	random		
681	S		
681a	S		
681b	S		
681c	)(, ( )	275/7	8
684	S		
684x	II	301/38	15

FIG. 7.17 The axes of rotation of garnets in the Furulund schist.

Determined by using the methods of Powell and Treagus (1967).



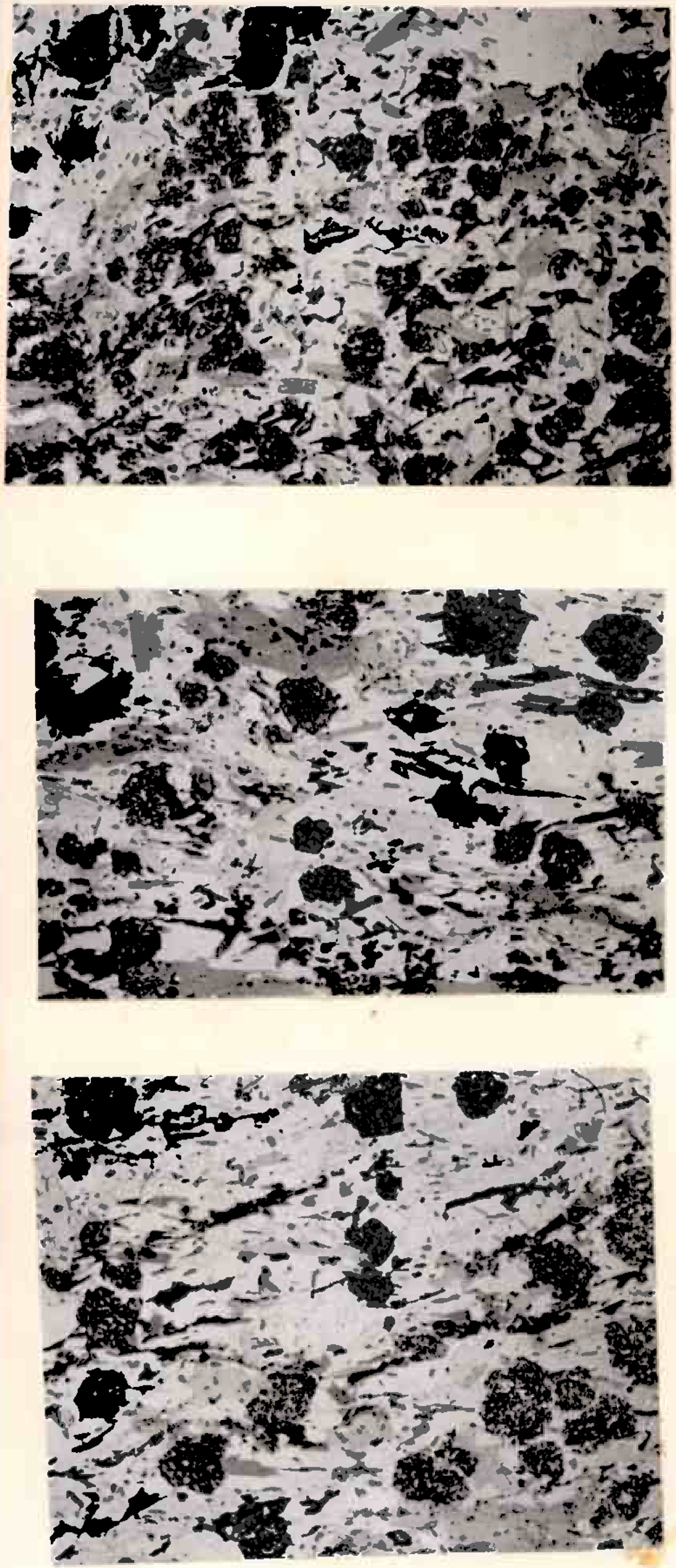
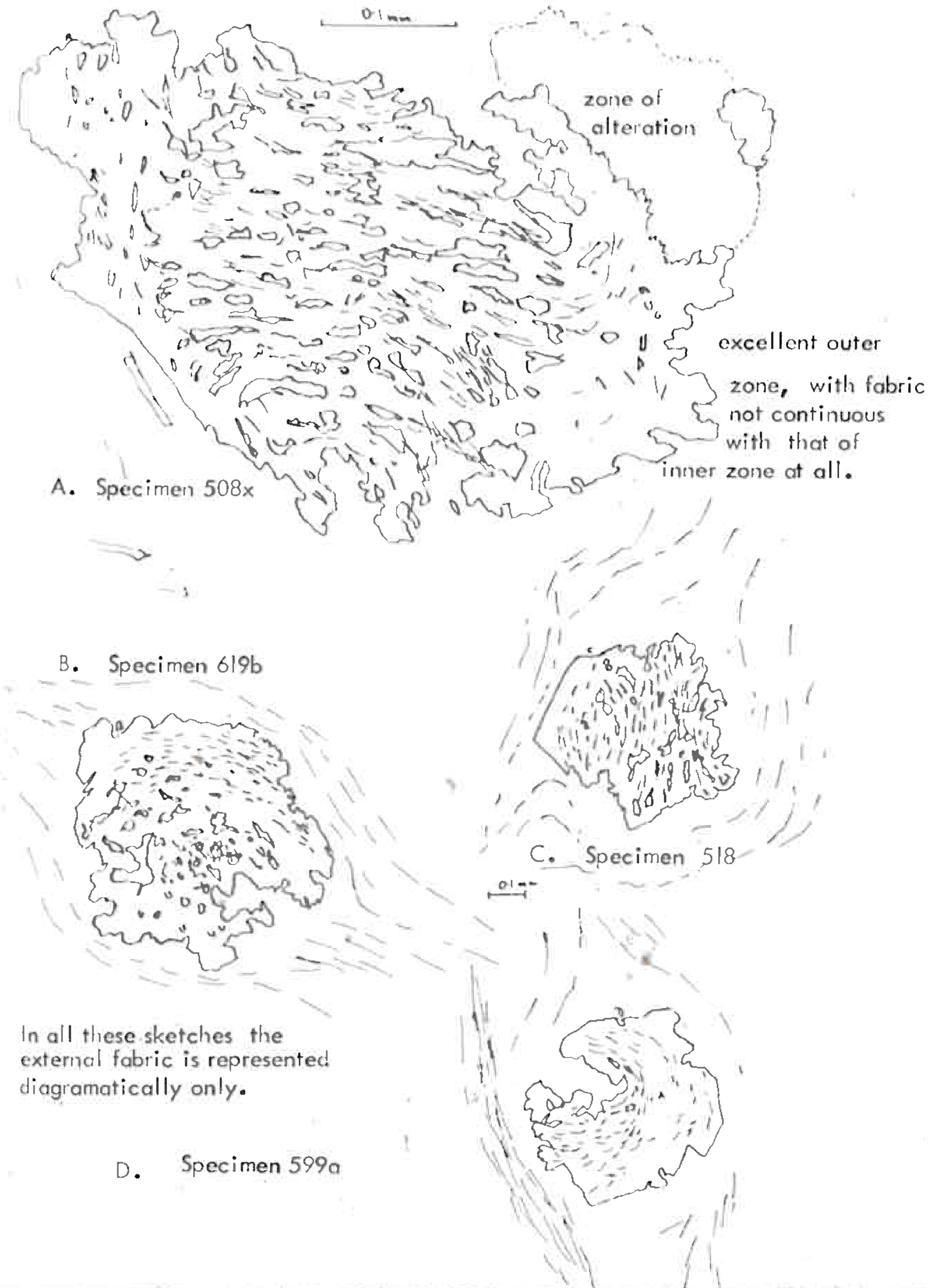


Fig. 7.18.
Specimen 632, x10, plane polarised light.
Three sections cut normal to each other.
The top section is cut normal to the rotation axis of the garnet and therefore shows S shaped trails of inclusions. The others are cut parallel to the axis of rotation of the garnets and therefore show the patterns typical of such sections as predicted by Powell and Treagus. The middle section shows () trail patterns, while the lower section shows)(patterns.

Chlorite and muscovite in the matrix lie parallel to the axial planes of folds at this locality.

FIG. 7.19 Camera lucida sketches of sections through Furulund schist garnets which contain the axis of rotation.



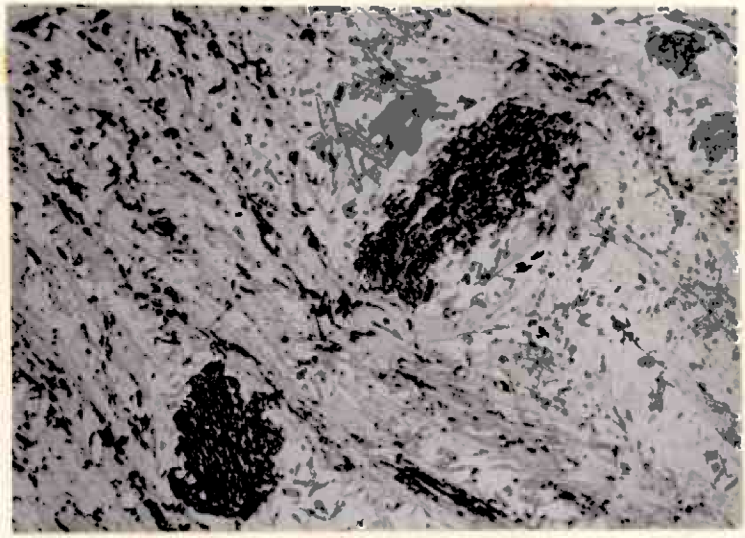


Fig. 7.20 Specimen 599, section C. x20. Ordinary light. The section is cut normal to the axis of folding. Two garnets show)(patterns of trellis, but the attitude of the rotation axis differs, due to later folding. The micas define a coarse cleavage parallell to the axial plane of the folding.

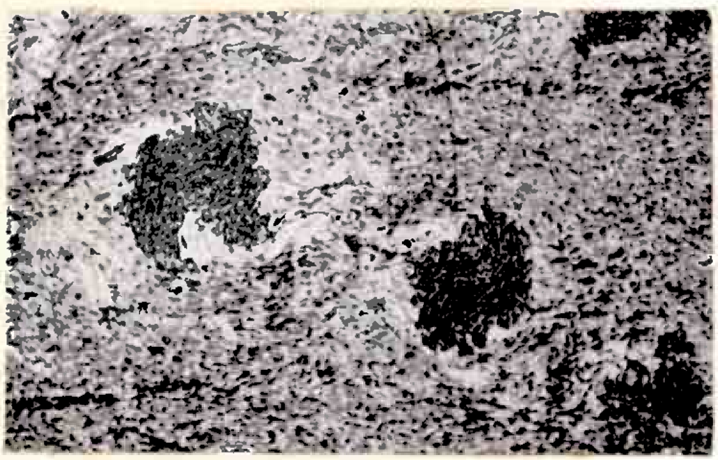


Fig. 7.21 Specimen 593, x15. Plane polarised light. The section is cut normal to the axis of rotation of the garnets, and shows the amount of rotation of the garnets during growth.

will frequently be considerably less. In the case of successive phases of pure shear with slightly different orientations of the strain axes it is not reasonable to expect to find such smoothly curving trails as would be formed during the uniform application of simple shear. There would probably be discontinuities in the degree of curvature of the trails.

It is therefore necessary firstly to measure the amount of rotation that the Furulund schist garnets have suffered, and secondly, if the angles are greater than 90° ,to determine if the S shapes are smooth or show any discontinuities.

The critical angle to measure is the angle between the attitude of the trails at the centre of the garnet and the attitude of the schistosity in the matrix beyond, out of range of the inhomogeneous strain adjacent to the garnet. This is the angle α on Fig. 7.22 below. Though the angle α is less than 90°, the angle β, (between the attitude of the trails in the garnet centre and the attitude of the trails at the garnet margin) is considerably more than 90°, and is therefore highly misleadi ng. The angles should, as mentioned by Powell and Treagus, be measured on sections through the centres of garnets, cut normal to the rotation axis.

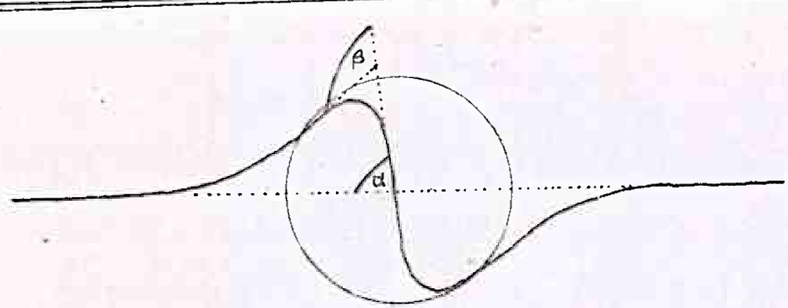


FIG. 7.22 ANGLES OF ROTATION OF GARNETS

True amount of rotation :- α . Angle β gives false amount.

In rocks where the matrix has recrystallised after garnet growth it may be impossible to measure directly the true amount of rotation, though a reasonable estimate may be made.

An attempt was made to measure the amount of rotation of the garnets in the Furulund schist. Of the 24 rocks for which attitude of garnet rotation axis had been determined, only 10 had thin sections which were cut normal to the rotation axes. As is indicated in the table, Fig. 7.23 it was apparent that in most of the cases there had been considerable deformation of the matrix after growth of the internal zone of the garnet.

FIG. 7. 23 ROTATION OF GARNETS IN THE FURULUND SCHIST

slide number	angle between plane of thin section and the rotation axis	true rotation angle α (defined in Fig. 7.22)	angle β (defined in Fig. 7.22)	garnet- matrix relationship
632	84°	?	117°-146°	matrix completely recrystallised
313	82°	?	86°-102°	matrix folded
509X	90°	?	93°-124°	matrix deformed
518A	90°	?	110°-163°	" "
593	93°	(see Fig. 7.24) > 90°	81°-119°	fabric continuous
612	103°	110°	109°	" "
619D	112°	approx 90°	109°	" "
662 A	90°	approx 80°	90°	" "
681B	95°	?	134°-159°	strong later deformation
684	99°	?	88°-154°	"

This table suggests that there was more rotation than is possible if there was one single phase of pure shear. The uniform curvature of trails in the Furulund schist garnets does not suggest that there were several phases of pure shear during the growth of the inner zones. The shape of the trails is shown in Fig. 7.21 of specimen 593. (This figure is on the same page as Fig. 7.20, several pages back.) It is therefore concluded that simple shear played a dominant role in the deformation of the matrix.

The model of Spry assumed that simple shear during garnet growth was orientated with the shear plane parallel to schistosity. In the theoretical case developed on page 67 it was assumed that simple shear would not be parallel to schistosity. ~~Certain points suggest that in the case of the Furulund schist the simple shear was orientated parallel to schistosity. The discussion of this, and of the regional significance of the garnet rotation will be discussed below when those garnets which have not been rotated have been described.~~

7.13 Garnets with non-kinematic inner zones.

These were found in 14 rocks. At least two sections were cut from each rock to ensure that the inclusion trails were planar in three dimensions. The locations of these garnets is marked on Map 8. Specimen 488 is from a schist band within the Sulitjelma amphibolites and the rock has not suffered any post- garnet deformation that can be detected. It is clear that this rock has been protected by the amphibolite and has not been deformed in the same manner as the rest of the Furulund schist.

Specimens 381, 397, 401, 392 and 682 all occur in the Ny Sulitjelma area, 381 and 401 within a band of schist on the north-west side of the amphibolite lense where it might be supposed that the deformation style would be slightly different. Specimen 401 is illustrated in Fig. 7.4 . The other specimens lie adjacent to rocks with garnets which have been rotated.

Specimens 725, 659, 672, 673 and possibly 554, all come from well down within the Furulund schist, below the band rich in garnets, though 514 from that band has some non-kinematic garnets in addition to some rotated ones. The localities of these specimens are well spread out from east to west.

Specimens 630, 633 and 634 are from Strip B at Bursi (Map 1 and 6) although other garnets from this strip (eg, in specimen 599, Fig. 7.20) are rotated. Specimens 636 and 640 are from Strip A at Bursi.

In all cases except 448 the schistosity is deformed around the garnet and the trails lie at an angle to the schistosity. Ramsay (1962) points out that when the trails are all parallel after deformation it is an indication that the deformation was homogeneous pure shear. In specimens 682, 725, 659A, 673 and 633 the trails lie approximately parallel but in others there is considerable variation. However these are rocks in which there has been folding and generation of a second cleavage. In specimen 381 for example most of the trails are parallel except in areas where there are clusters of porphyroblasts. The evidence therefore suggests that deformation after garnet growth was by pure shear.

7.14 Relationship between syn-kinematic and non-kinematic garnets.

If the above two types of garnet grew at the same time then it follows that this was a time of markedly inhomogeneous deformation. Alternatively a reason must be found to explain why some garnets might have grown earlier than others. This reason might be host rock composition. Atherton(1965) mentions that manganese rich garnets can be found outside the garnet zone and Henley, in Harte and Henley (1966) has shown that the centres of garnets in the Furulund schist are manganese rich. It may be suggested that where the host rock is rich in manganese, garnets will commence growth earlier than in places where the host rock is of normal composition. It would therefore be useful to have some chemical data for the non-kinematic garnets and their host rocks.

The problem is also one of correlating the deformations during and after garnet growth. The growth of the non-kinematic garnets was followed by deformation which was probably mainly homogeneous pure shear. The growth of the syn-kinematic garnets was accompanied by mainly simple shear deformation and was followed by deformation of unknown type. The post-garnet deformations can reasonably be correlated together and since the individual inclusions in both non-kinematic and syn-kinematic garnets are similar in shape and size the best explanation is that both types of garnet grew at about the same time.

In section 7.13 above it was suggested that the deformation accompanying garnet growth was mainly simple shear. If the shear plane was not parallel to the schistosity then inhomogeneities in shear would generate folds, and the axes of the folds would be parallel to the axes of garnet rotation. While folds which could fit this pattern do occur in the east of the thesis area (see Chapter 6.2) they are not found in the central and western parts and it must be assumed that any simple shear in these areas had the shear plane parallel to schistosity.

It may conveniently be noted here that there is some evidence of inhomogeneous simple shear parallel to schistosity from Balmi Elv, south of Langvann, where there is folding of calcite bodies, as described in Chapter 5.10. However, thin sections from other parts of Balmi Elv show only evidence of compression normal to schistosity, and no sign of simple shear, (Fig. 7.2).

7.15 Regional significance of the deformation coeval with garnet growth.

On the assumption that the matrix deformation was by inhomogeneous simple shear parallel to schistosity it is possible to determine the directions of the shear axes. The plane of shear is the 'ab' plane and the 'b' direction is the garnet rotation axis. Map 8 plots the rotation axes determined and a fair degree of parallelism can be seen. The 'a' directions can be simply derived (lying normal to the 'b' directions in the plane of schistosity) and lie east-west or NE-SW. Map 8 also marks the sense of rotation of the garnets and in all but one case the garnets give 'Z' sections when viewed from the south, indicating dextral shear. The overall sense of movement is that the higher parts of the succession have moved to the east. Evidence is reviewed in Chapter 16 which suggests that there may have been major thrust movements approximately coeval with the growth of garnet in the Furulund schist. On large scale regional evidence it is expected that such thrust movements involved the movement of structurally higher rocks over lower rocks in an easterly direction. The thrust movements may not have been restriced to non- affine slip on the thrust plane itself, but may have generated simple shear in the adjacent units, of the type which has been discussed above.

Thus while the evidence concerning the nature of the deformation during garnet growth is only conjectural, it does fit in with the thrust hypothesis as discussed in Chapter 16.

7.16 Minor structures coeval with garnet growth.

Mention has already been made of the small crinkles which appear as tails on each side of the garnets, which must have formed during garnet growth. It is possible that other crinkles in the schist having the same orientation may be of the same generation. Similarly the open folds north-east of Giken (Chapter 6.3) which are closely associated with crinkles may be of the same age.

The folds of calcite bodies in Bàlmi Elv described in Chapter 5.10 and mentioned in Chapter 7.14 above are thought to have been generated by inhomogeneous simple shear parallel to the schistosity, at the same time as the growth of garnets, although there were no garnets in the specific rocks to allow a check to be made.

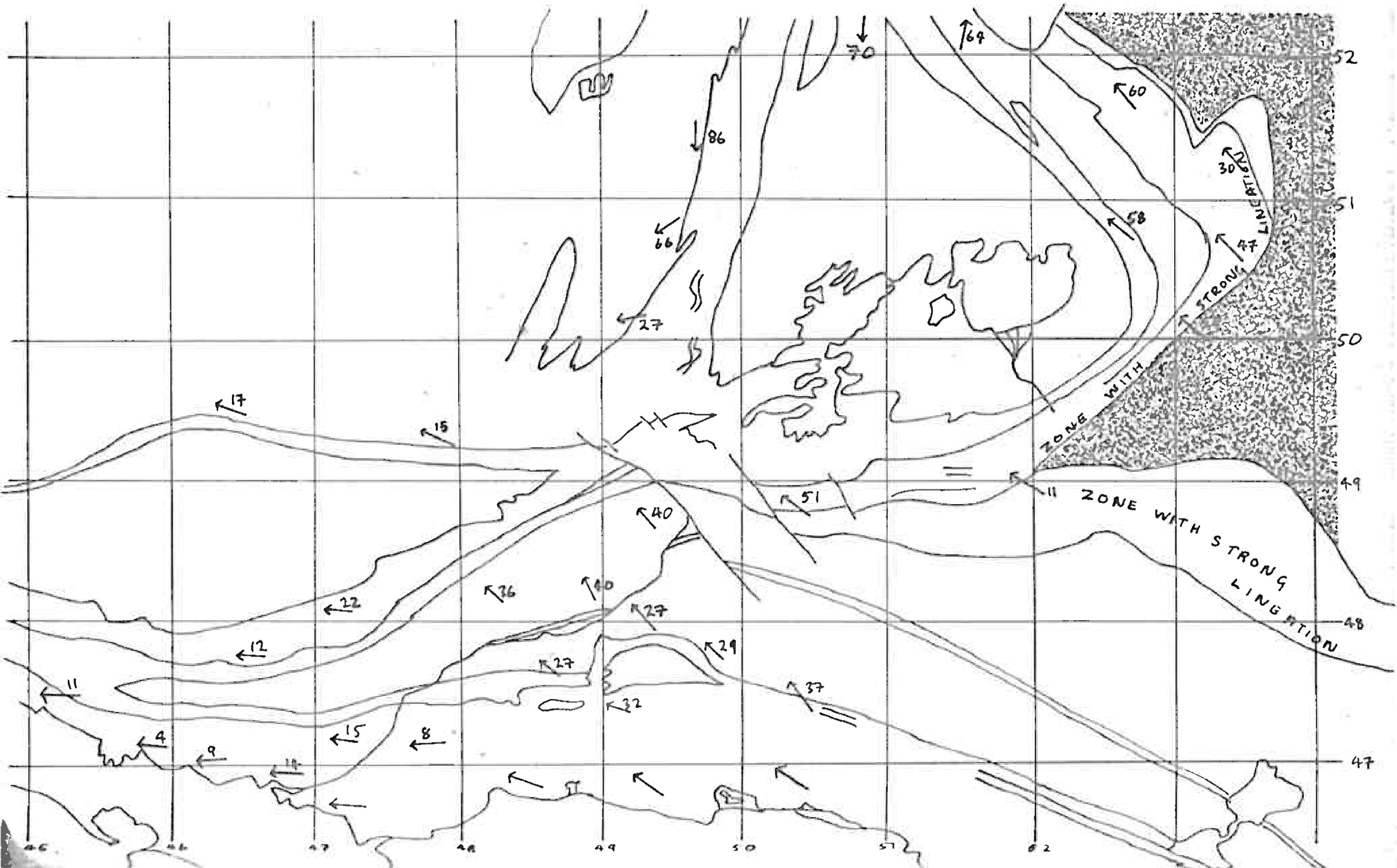
7.17 Synthesis of mineral growth.

A biotite-quartz fabric developed prior to the growth of garnet and hornblende. During the growth of these porphyroblasts there was inhomogeneous simple shear, possibly with some pure shear. Following the growth of the porphyroblasts there was compression, probably at about the time of the growth of the outer zones of the garnets. In places the growth of garnets was followed by the folding of the schistosity.

The quartz-mica fabric observed in the rock is therefore the product of three deformations of which the first was the most important. The trails within the porphyroblasts ., being relicts of the first-formed fabric give information about the later deformations when compared with the fabric outside. There is no indication that the matrix outside the garnets became coarser-grained during the growth of garnet since quartz inclusions remain constant in size across the garnets as in Figures 7.21 and 7.20 and 7.9, though they are about half the size of quartz grains in the matrix. The distance between the centres of quartz grains outside the garnet is of the same order as that between the centres of quartz inclusions, suggesting that the fabric has not become notably coarser. Since there has obviously been deformation it would appear that this deformation was mainly by re-orientation of the grains unaccompanied by coarsening of the fabric.

The nature of the deformation <u>during</u> garnet growth (that is, the second deformation) can be deduced from the rotation of the garnets, and it can be asserted that the second deformation was dominantly one of simple shear, with the shear plane parallel to the schistosity, though there will probably have been some pure shear also. Any mineral lineation originating solely from this deformation must be expected to lie parallel to the ' a ' direction of the shearing since this is the direction of maximum extension of the finite strain ellipsoid. Map 8 plots the garnet rotation axes , normal to the 'a' direction and in addition the mineral lineation direction. Although in the centre of the region 'a' is roughly parallel to the lineation it is not so in the Ny Sulitjelma region. An obvious explanation of this anomaly is that the mineral lineation has not originated solely from the

FIG. 7.24 Sketch map to illustrate the attitude of penetrative mineral lineation in the thesis area.



second deformation. A mica fabric which is the product of several deformations is related to the *total* finite strain and not to any *one* of the constituent strains. The garnet rotation axes and the 'a' directions of shearing are only related to the second phase of deformation in this case.

The information presented by the hornblendes is slightly different. The fabric of the hornblendes is theoretically the product of the second deformation (the deformation during garnet and hornblende growth) plus the final deformation, (though probably the large laths of hornblende would be more difficult to reorientate than the small biotite flakes.) Qualitative examination of hornblende fabrics in the field and in hand specimen suggest that the hornblende lineation is parallel to the mica lineation, even in the Ny Sulitjelma area in the east where there is the difference between the 'a' directions from the second deformation and the overall mica lineation. That there is a difference between the 'a' directions and the hornblende lineation can mean that either the post- porphyroblast deformation was responsible for the change in hornblende orientation or that there is some error in the derivation of the 'a' shearing direction.

Within the Furulund schist the orientation of the lineation in the Ny Sulitjelma area is somewhat of an anomaly, as is shown in Fig. 7.24. Over most of the Sulitjelma area the mineral lineation lies east-west as shown by Henley (1968). The anomaly appears to be related to the relatively competent Sulitjelma gabbro adjacent to which there has been unusually marked strain. Lineations adjacent to the gabbro plunge to the north-west at a moderate angle. In sections 14.4/5 this strain is shown to be approximately coeval with garnet growth in the Sulitjelma Schist Sequence, if not earlier.

The solution to this problem requires more work on the fabrics of the Furulund schist, especially in the Ny Sulitjelma area. In the meantime caution must be excercised in interpreting the available results.

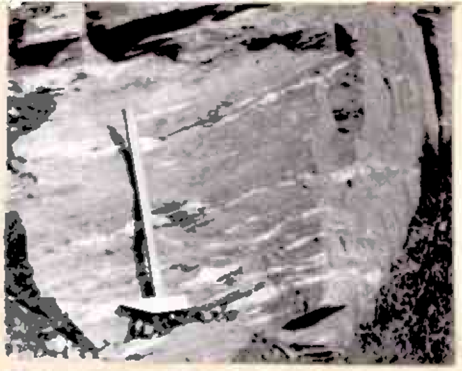


Fig. 8.1 Quartz segregations in the Furulund Schist. Just west of the bridge over Giken Elv at Giken.

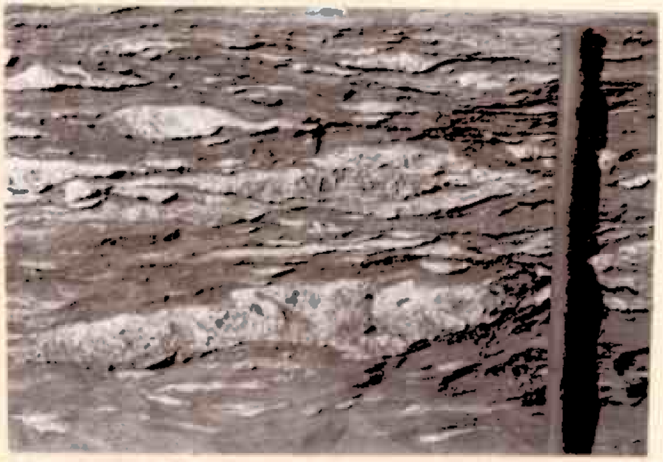


Fig. 8.2 As above.

Fig. 8.3 Quartz segregations in the Furulund Schist, crossing bedding and schistosity at a low angle. West of Giken.

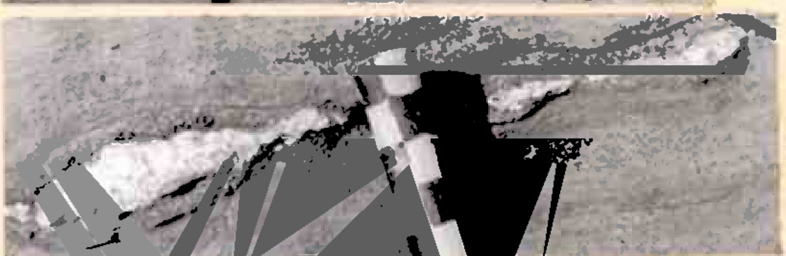


Fig. 8.4 Quartz segregation in garnet rich type of Furulund schist. Note the selvedge with coarse-grained muscovites.

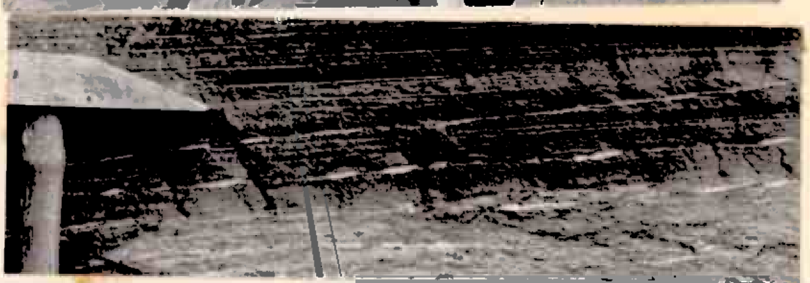


Fig. 8.5 Quartz segregations formed from quartz veins by boudinage.

CHAPTER 8

OTHER STRUCTURES IN THE FURULUND SCHIST

8.1 Quartz segregations.

The Furulund schist contains large numbers of quartz segregations. They are a chdracteristic feature of the rock in addition to its excellent banding, frequent discontinuities and smooth schistosity surfaces, as in Fig. 8.1 and Fig. 8.2.

The segregations vary in size and shape from narrow veins less than 5mm. across to highly irregular masses of coarse quartz, 10cm. by2m. The vast majority are as illustrated in Figures 8.3, 8.5, and 8.6 , lense-shaped, approximately 5cm. by 15cm. and arranged in strings crossing the schistosity and bedding at a low angle. Fig.8.4 shows how they are commonly surrounded by a selvedge rich in randomly orientated books of muscovite. The arrangement of segregations such as those illustrated in Figures 8.5 and 8.6 suggests an origin as quartz veins which at a later date have been boudined. Fig. 8.7 shows adjacent bedding and schistosity pulled into the scar resulting from such boudinage.

Wilson (1953 and 1961) describes quartz rods from Ben Hutig, Scotland. They are much more regular than the Furulund schist segregations. Wilson suggests that many of them could have developed through the deformation of originally planar quartz veins. He notes that some are quite late while others formed early in the deformation history,(1953, pg.133). The segregations have been strongly affected by post-schistosity folding, as Wilson illustrates in his Fig. 8d (1953), the quartz being concentrated in the hinges of the folds.

In Sulitjelma such concentration at the hinges of post-schistosity folds is not in evidence, as in Fig. 6.37, Chapter 6.7, but segregations are commonly elongated parallel to the mineral lineation direction, and it is suggested that most of their deformation was fairly early. Fig.5.18 shows a set of quartz segregations lying parallel to the axial plane of a syn-schistosity

Fig. 8.6 Quartz segregations formed from quartz veins by boudinage.

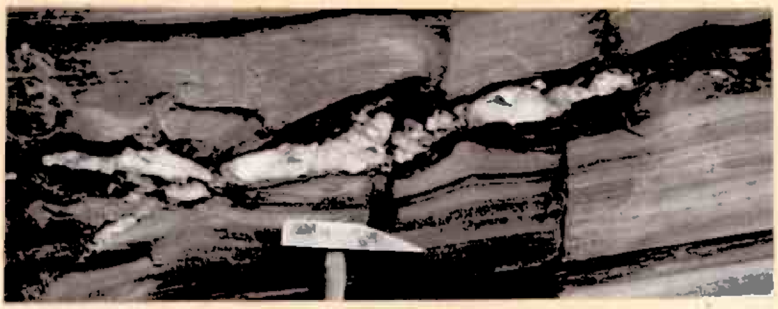


Fig. 8.7 Boudinage and quartz segregation, Furulund Schist.

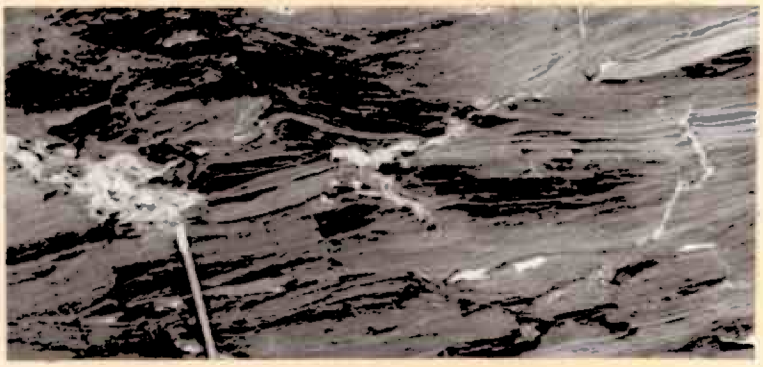


Fig. 8.8 Boudinage and quartz segregation, Furulund schist.

Fig. 8.9 Tight folding of quartz segregations, Furulund schist.

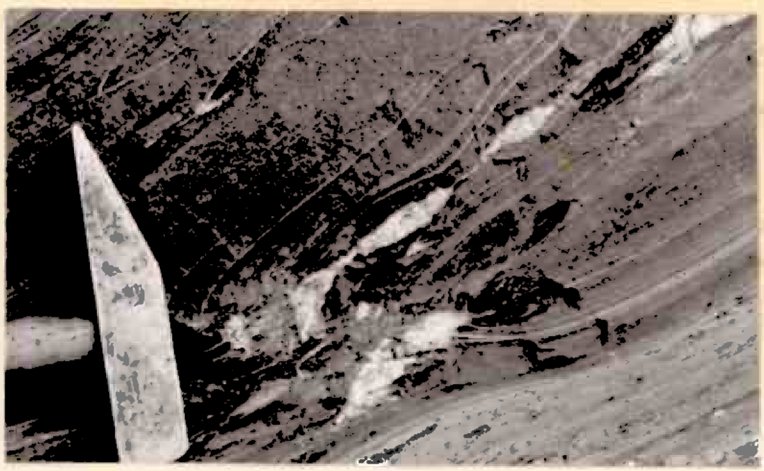


Fig. 8.10 Tight folding of quartz segregations, Furulund schist.

fold. It is evident that the original vein must have been formed after the folding. Yet some of the veins are very tightly folded, as in Figures 8.9 and 8.10. It is therefore evident that there are several generations of quartz segregations.

8.2 Boudinage.

Boudinage and other discontinuity features are well developed in the Furulund schist. The intensity of this type of deformation varies over the region. It is particularly well developed near the top of the schists but in the south-east, by Lomi Elv it is virtually absent. There are all gradations between fine examples of classic boudin shapes described by Ramberg (1955) as shown in Fig. 8.11, and discontinuities at low angles to bedding as in Fig. 8.12 and in Fig. 4.6, Chapter 4.3. The cliff feature north-east of Giken shows many discontinuities at low angles to bedding, especially in the finely-banded rocks at the base of the cliff, as is illustrated in Figures 8.12, 8.13 and 8.14. Other typical boudinage features are shown in Figures 8.15 and 8.16. Similar discontinuities are seen in the rocks in Balmi Elv (south of Langvann).

The classic shape boudins are usually between 10cm. and 2m. thick, very rarely smaller. At Bursi there is a much larger boudin some 5 or 6m. thick, illustrated in Fig. 8.17, which has caused considerable folding because of schist being dragged into the gap formed, (scar folds after Rast, 1956). A horizon of ore lies within the Furulund schist just above the level of this boudin and has been dragged down by the scar folding. This is the explanation for the body of ore on Map 6, which strikes NNE at Bursi. As was noted in Chapter 6.5 there are many isolated, open folds with large amplitude along the section between Bursi and the Church (Map 1), for example Fig. 6.29. Their isolated character, and irregular develop ment could be explained if they were drag folds for boudins which are not exposed.

Fig. 8.11 Boudinage, Furulund schist. On the railway line about halfway between Sulitjelma station and Glastunes station.

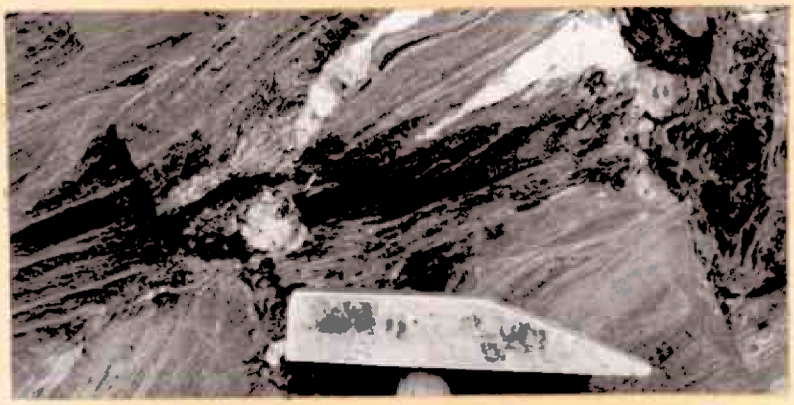


Fig. 8.12 Boudinage, Furulund Schist.

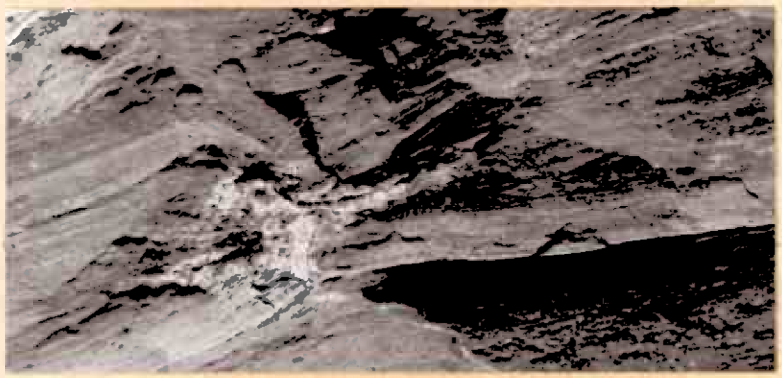


Fig. 8.13 Boudinage in Furulund Schist, in the cliff N.E. of Giken.

Fig. 8.14 as Fig. 8.13

Fig. 8.15 Boudinage, Furulund Schist. Note that these are not the regular set of boudin as in Fig. 8.11, but a much more irregular discontinuity structure.

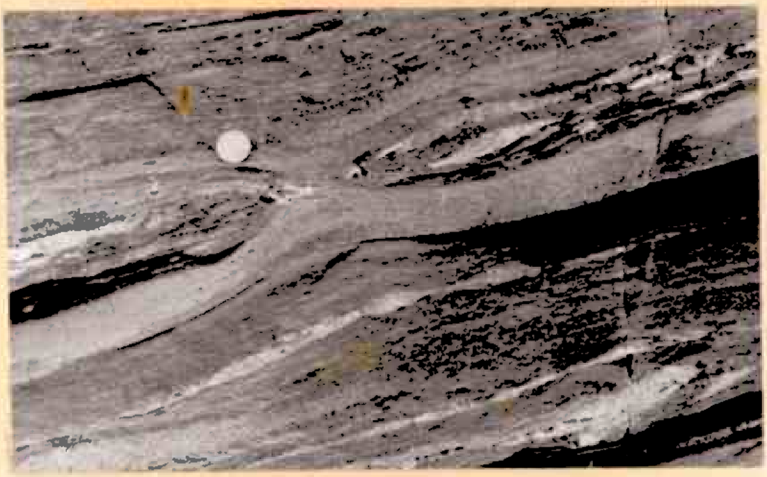


Fig. 8.16 - as Fig. 8.15

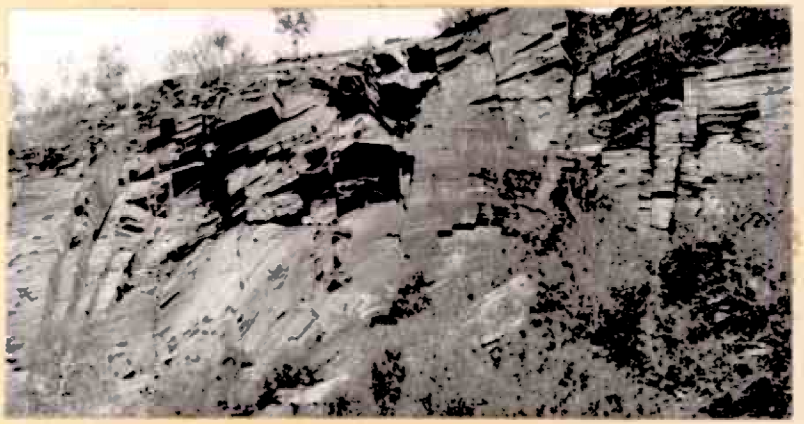


Fig. 8.17 The large boudin at Bursi. Viewed from the road to Gronlid about 100m. west of the last houses in Glastunes. This boudinage has dragged down copper ore into the neck, hence the large tonnage of ore at the Bursi mine entrance.

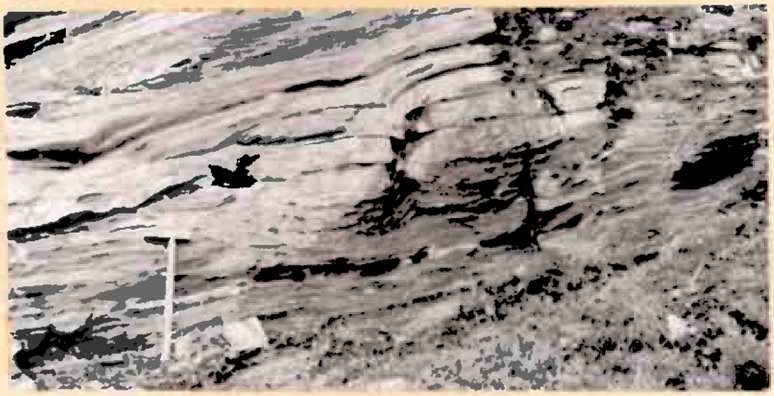


Fig. 8.18 A boudin in the east of the thesis area. An example of the rare rotated boudin.

FIG. 8.19 'Axes' of boudins in the Furulund schist.

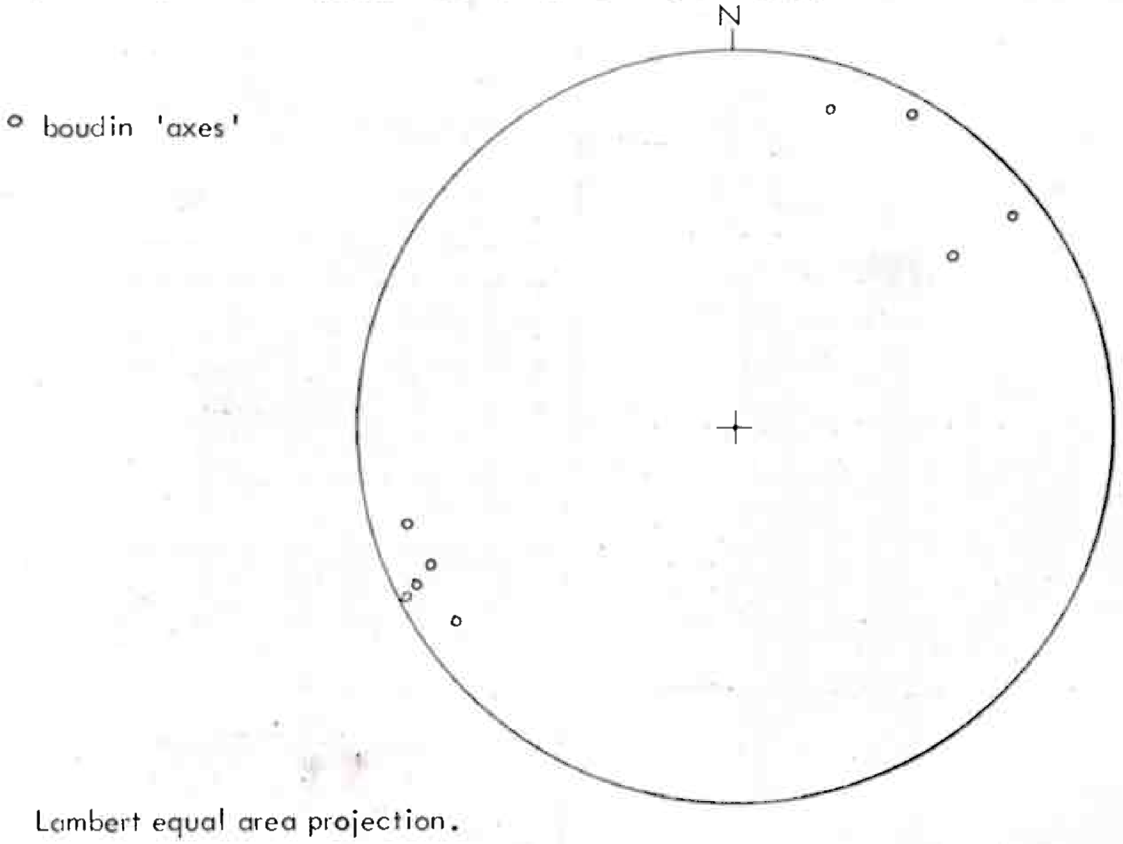
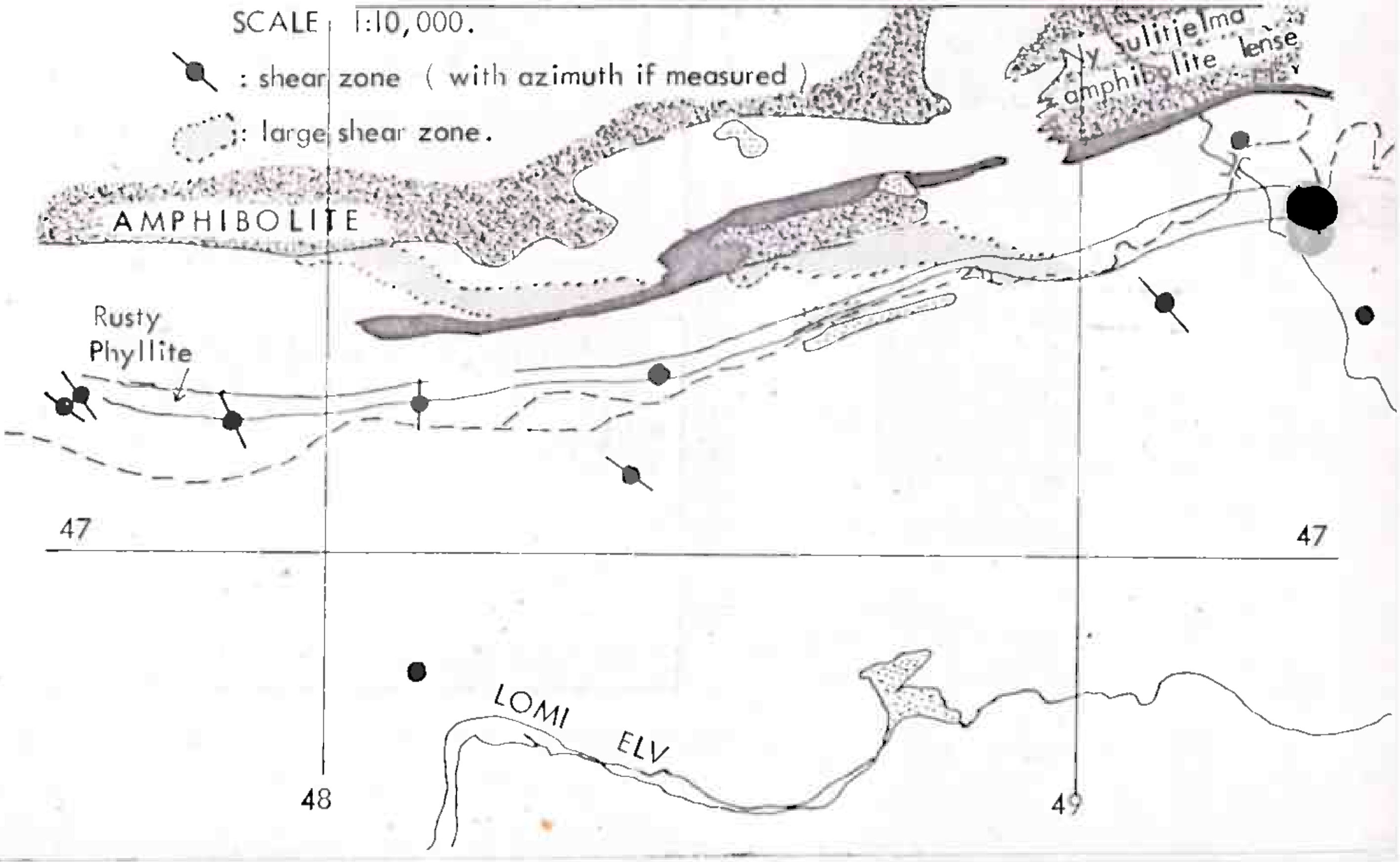


FIG. 8.20 Map to indicate locality of shear zones, south of Ny Sulitjelma.



The material which has been boudined , in all cases which have been examined carefully , is amphibolite, though first impression in the field was that it was mica schist. It is thus difficult to compare the fabrics inside and outside the boudins as a guide to the age of boudinage. Since the boudined material has a well-developed schistosity, and schistosity of the surrounding rock has flowed into the scars it is clear that boudinage is later than the development of schistosity. It is also later than the emplacement of quartz veins.

Only in one or two instances has 'rotation' of the boudins relative to the bedding occurred, indicating that usually the axis of maximum compression of the strain ellipsoid lay normal to the bedding. A normal example is shown in Fig 8.11. Exceptions are mainly seen in the east of the area, as for example in Fig. 8.18.

A clue to the age of the boudinage is that it probably correlates with the boudinage seen in the tectonic breccia which overlies it in the west. The brecciation was clearly earlier than the major folding at Bursi, which is post-schistosity, post-garnet growth.

Where possible the orientation of the boudins was measured. Most boudins were exposed on joint faces and so only nine measurements of the 'axis' were taken. These are plotted on Fig. 8.19, opposite, and they indicate near-horizontal axes, trending NE-SW. The 'axis' measured is as defined in Wilson (1961), a line parallel to the edges of separation. The orientation of this 'axis' may have little meaning if there were preexisting fractures in the rock, (Ramsay, 1967, pg. 91), or if the maximum and intermediate axes of the finite strain ellipsoid were equal, resulting in a "chocolate tablet" structure (Ramsay, 1967, pg. 112.)

8.3 Late shear zones.

South and south-west of Ny Sulitjelma there are several late shear zones (Fig. 8.20, opposite). The zones are near vertical, trending around

Fig. 8.21 A shear zone south of Ny Sulitjelma viewed along its outcrop. In this area the schist normally dips gently to the north;- to the right in the photo. In the shear zone the schistosity can be seen to be dipping very steeply to the south (to the left.)

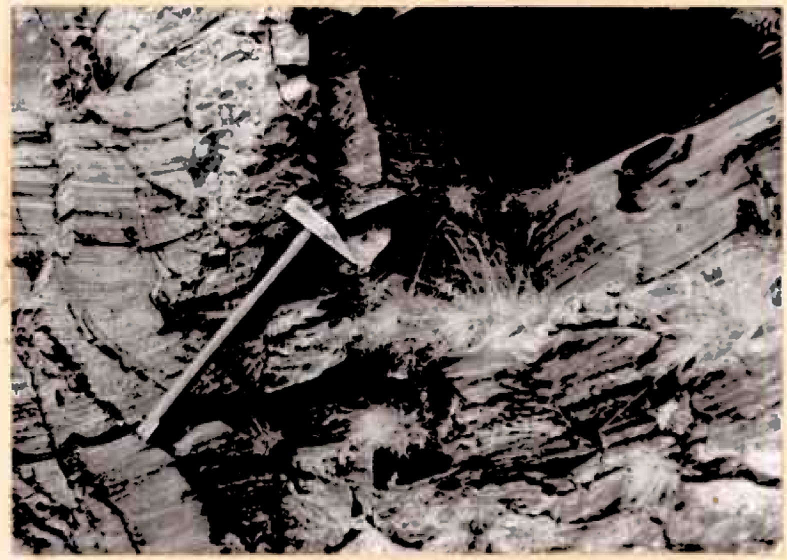


Fig. 8,22 A shear zone. Note the sigmoidal fractures.

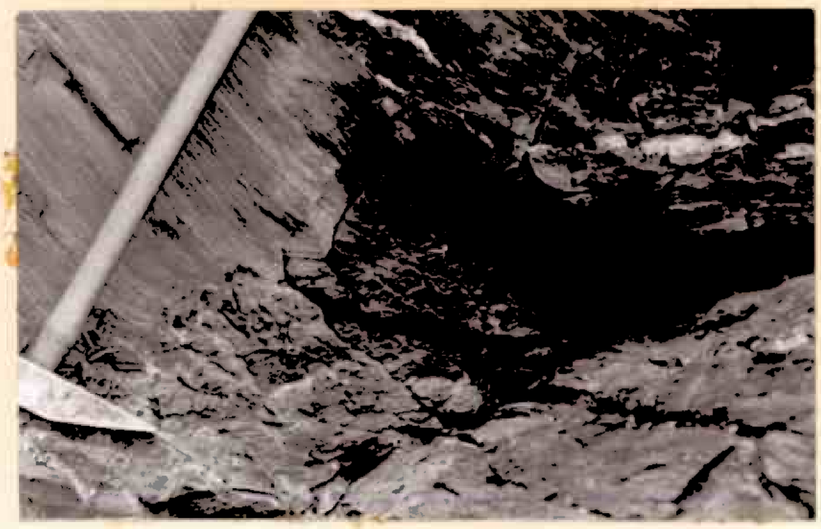


Fig. 8.23 Detail of a typical shear zone. The photograph is tilted.

Fig. 8.24 Development of fractures in a shear zone east of Ny Sulitjelma

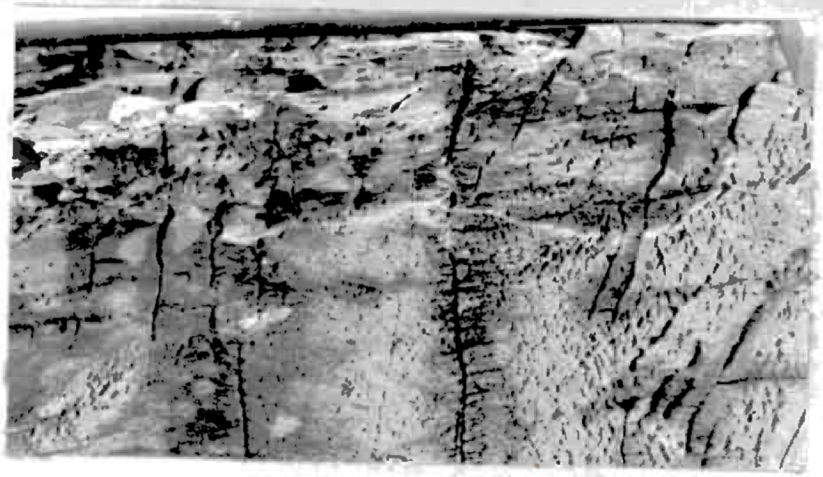


Fig. 8.25 Development of fractures in specimen 326. The white material in the fissures is carbonate. This is virtually a tectonic breccia. This is what Carlson refers to as " kalkglimmer-kiffer-breccia. "

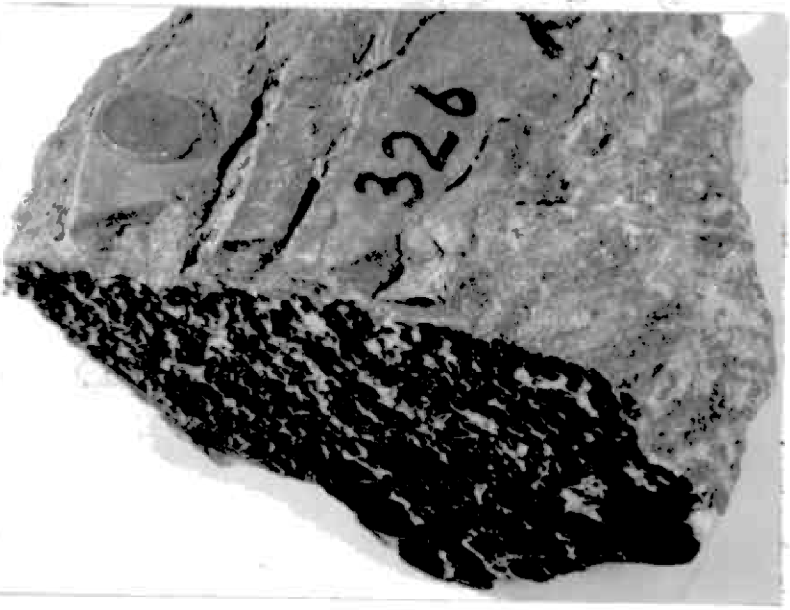
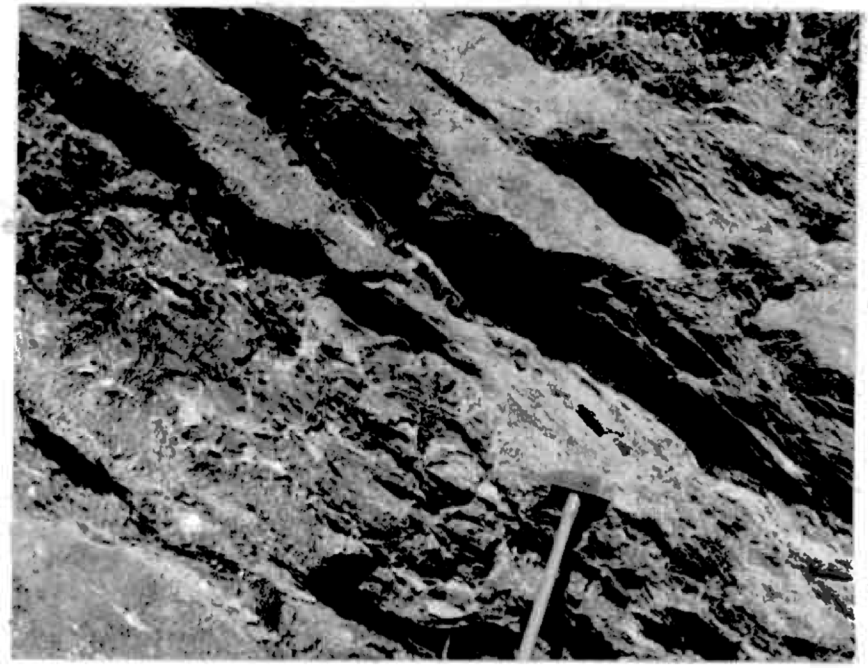


Fig. 8.26 Wide fracture zone south of Ny Sulitjelma . On the path to Giken. Above the hammer can be seen boudinage of a competent band. This is the rusty phyllite type of Furulund schist.



320° -340° and can be between lm. and 20m. wide, (Fig. 8.21). Within the zones schistosity is rotated and is cut by numerous tension gashes filled with calcite. The zones are similar to 'kink zones' or 'joint-drags' as described by Flinn(1952 Fig 2) but the hinge of the folding is wider. The sense of displacement is such that material on the north-east side has moved upwards. The shape of the tension gashes is often sigmoidal (Figures 8.22 and 8.23). It is generally accepted that tension gashes form by simple shear (Wilson 1952, Ramsay 1967,pg.88) and that the sigmoidal shape of the fissures is caused by the rotation of the first-formed parts of the fissures during the continuing deformation.

The largest of these zones is about 20m. wide and does not share the trend of the smaller zones. It runs east-west from 491 474 on the Giken-Ny Sulitjelma path south of the Hankabakken amphibolite body and north of the copper ore west of that amphibolite as far as Øvre Giken (476 474) , see Map 1 and Map 5. The rock in this zone appears to be cut by several sets of fractures at different attitudes and consequently is broken into fragments only centimetres across. There has been very little movement of these fragments relative to one another. Fig.8.24 shows the appearance of the rock in an early stage of development before the schist is actually fragmented, and Fig. 8.25, of specimen 326 illustrates the stage in which the schist is fragmented, the matrix being calcite. This large shear zone was mapped by Carlson (private map belonging to the mine company), who described the fragmental rock as " Kalk-glimmer-skiter-breccia". It has also been mentioned by Christofferson (1960) and Mellingen (1961), who do not suggest any means of formation.

The eastern part of this zone crosses the rusty phyllitic type of Furulund schist, and more competent bands within this rock have been boudined as in Fig.8.26. This is clearly seen on the footpath between Giken and Ny Sulitjelma.

PART THREE

CHAPTER 9

THE SULITJELMA AMPHIBOLITES AND THE TECTONIC BRECCIAS

A. The Sulitjelma amphibolites unaffected by brecciation.

9A.1 Introduction.

In the east of the thesis area there are some 750m. of the normal Sulitjelma amphibolites, mainly fine-grained schistose amphibolites or meta-porphyritic amphibolites. In the centre of the area the unbrecciated material has virtually thinned out completely. It is difficult to tell how much of this thinning is tectonic and how much is primary. Considerable pre-tectonic variations in the thickness of the group have been demonstrated from the east of the thesis area as is discussed in Chapter 3.4 and is illustrated in Fig. 3.2. The tectonic breccia in the west contains a small proportion of schistose amphibolites with bands of mica schist and conglomerates, indicating the presence there of the Sulitjelma amphibolites prior to brecciation. In the following sections the lithologies of the Sulitjelma amphibolites are described. Map 9 is a map of the various lithologies of the amphibolites and breccias. The location of most of the specimens referred to in the text is indicated.

9A.2 Schistose amphibolite.

The main rock type of the Sulitjelma amphibolites is schistose amphibolite, a fine-grained quartz, clinozoisite, hornblende rock, the preferred orientation of the hornblendes defining a good schistosity-lineation fabric. No traces of any igneous texture can be seen. Thin sections cut normal to the hornblende lineation display well-shaped hornblende cross sections in a matrix of quartz and occasionally, feldspar. The latter is very fine-grained and rarely shows twinning or cleavage. The clinozoisites are present as small grains, well-shaped. Chlorite is rather rare. Patches of calcite are occasionally seen. Typical textures are seen in Fig. 9.1. A feature of specimens 427 and 379 illustrated in Fig. 9.2 is that there are thin continuous zones only a few grains wide in which the hornblendes show a much higher degree of preferred orientation and are relatively concentrated. This is an indication that the deformation was far from homogeneous. The schistose amphibolites are clearly banded as is illustrated in Fig. 9.3. Bands of slightly different modal composition are commonly about 30cm. thick though bands 2.3cm. thick occur in many parts of the area, as shown in Fig. 9.13 . Not all the schistose amphibolites may be igneous in origin. Specimen 427 from one kilometre east of Ny Sulitjelma contains several large grains of quartz, now highly strained and made up of several sub-grains, as shown in Fig. 9.5 .In a basic igneous lava or sill, large phenocrysts of quartz certainly would not be expected and so it may be that this is a meta-sedimentary amphibolite. In appearance it otherwise resembles the other fine-grained schistose amphibolites.

9A.3 Meta-porphyritic amphibolite.

Within the schistose amphibolites there are thin bands (10-60cm. thick) of meta-porphyritic amphibolite. This rock is similar in mineralogy and fabric to the schistose amphibolite except that it contains large plagioclases or pseudomorphs after plagioclase. Their appearance as rectangular phenocrysts is shown in Fig. 9.4. In this photograph the amphibolite is seen to be cut by two sets of quartz veins, one set apparently associated with boudinage. Quartz veining is quite common in the amphibolites.

The appearance of the meta-porphyritic amphibolite in thin section is shown in Fig. 9.6. The pseudomorphs are composed mainly of clinozoisite and fine-grained feldspars or, as in the case of specimen 442, of clinozoisite

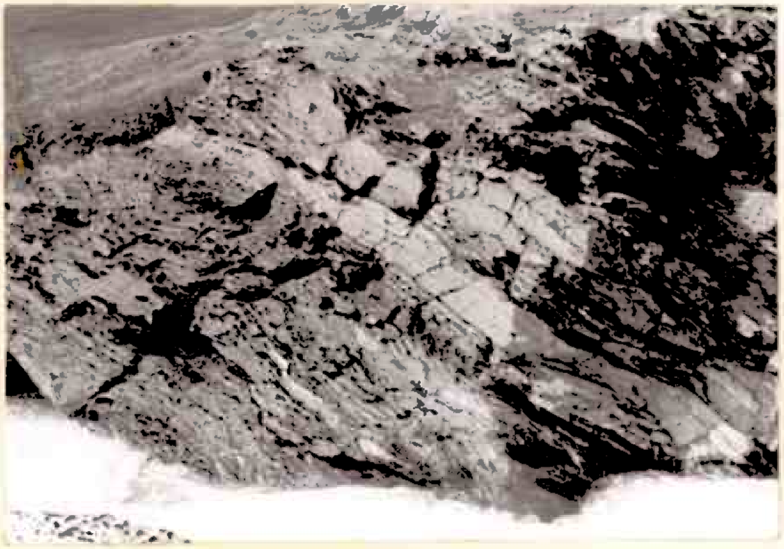


Fig. 9.3 The banded character of the schistose amphibolites. Giken Elv. Light band of rock is mica schist.

Fig. 9.4 Meta-porphyritic amphibolite cut by two sets of quartz veins.

and quartz. The plagioclases and their pseudomorphs show a slight preferred orientation, defining a lineation. The matrix in specimen 332 does not show any obvious preferred orientation, and is composed of hornblende, plagioclase and quartz, with traces of epidote and possibly axinite.

Bands of meta-porphyritic amphibolite are not very common within the thesis area, and are marked on Map I as P.A. East of the thesis area the section of amphibolite lying above the schist strip at 500 484 contains increasing numbers of bands of this type in its upper parts and consequently the unit was split by Mason (1967, Fig. 2) into two parts, the lower part being the schistose amphibolite, the upper the porphyritic amphibolite.

9A.4 Coarse amphibolite.

Bands of coarse amphibolite are seen occasionally within the schistose amphibolites. They comprise hornblende and quartz, both visible to the naked eye, and minute grains of clinozoisite and chlorite. The hornblendes display a preferred orientation which can be good as in specimen 404A or only moderate as in specimen 390. Inside the hornblendes are quartz inclusions , not arranged in any pattern.

These rocks are assumed to be schistose amphibolites in which recrystallisation has proceeded further than normal.

9A.5 Deformation of the schistose amphibolites in the centre of the area.

Map I indicates that the schistose amphibolites narrow to the west. At 460 476 the rocks are notably more deformed than to the east, being conspicuous for thin 3-5mm. bands of very dark amphibolite lying parallel to schistosity. In thin section (specimens 456 and 459), these zones are seen to be composed entirely of hornblende showing a very high degree of preferred orientation, which suggests that these zones have suffered unusually high strain. In addition the rock has been cut by shears lying oblique to schistosity, which have favoured the growth of calcite and clinozoisite. This clinozoisite is different from that in the normal amphibolites , which has anomalous blue birefringence, since it shows second order yellow birefringence (which is the normal case for clinozoisite). The large grains of clinozoisite found in the tectonic breccias show similar second order birefringence. The clinozoisite in these schistose amphibolites may be of the same generation.

9A.6 Quartzites.

Quartzites occur at several horizons within the schistose amphibolites, as is shown in Map 9 and Map 1.

A three metre thick band of quartzite is seen near the top of the succession at Fjeldsgrube (487 487). This marker horizon is useful in indicating faulting (see Map 4).

At Ny Sulitjelma quartzites are seen at the base of the lense of schistose amphibolite which lies within the Furulund schist (Map 5). About 120m. of schistose amphibolites and quartzites thin to virtually nothing here, and this must be a sedimentary feature . The quartzites are streaky and fine-grained as in specimen 403, showing a variety of grain sizes, but no minerals other than quartz, except chlorite, ore minerals and some very fine-grained indeterminate material. Specimen 389 was taken from slightly higher in this lense and is a fine-grained quartz-mica rock, poorly schistose with stubby biotites. Quartz-quartz grain boundaries are straight.

Just west of Hankabakken the base of the main amphibolite is similar to the base of the Ny Sulitjelma lense, being made of interbedded schist, quartzite and amphibolite. This sequence can be found even west of Giken Elv where it underlies the tectonic breccia. In specimen 411 from west of Giken Elv the main mineral is quartz in tightly packed interlocking grains with hornblende, chlorite, biotite, cross-cutting muscovite porphyroblasts, ore, garnet, calcite and cross-cutting seams of epidote.

In the area west of Giken Elv the quartzites are broken up into small lenses, a few centimetres long. Specimen 501, from here, is mainly of quartz with traces of plagioclase. Grain boundaries are interlocking but the grains show no strain shadowing. Occasional grains of hornblende, biotite and ore (rectangular) occur. The ore seems to have grown quite late since it is well-shaped and does not have any pressure shadows (Ramsay, 1967, pg. 181). The quartzite is cut by several veins of hornblende which in part is altered to chlorite, indicating that chloritisation is later than the fracuring of the quartzite.

Mason (1966) describes micaceous quartzites from just below the schistose amphibolites east of Otervann. The equivalent level in the thesis area is above the schist band at 502 483, but no quartzites were seen.

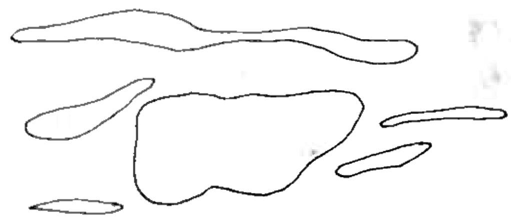
9A.7 Mica schist in the Sulitjelma amphibolites.

Mica schist bands are present at various places. Already described in Chapter 3.4 are the three strips of schist at Bursi (Map 6, Fig. 6.32). It is most reasonable to suppose that strip B originally lay partly within the amphibolite breccia since it is underlain by amphibolite breccias as well as ore, though its eastern end is probably attached to the main mass of Furulund schist. Strip C may have been attached to stri p B, but may have always been isolated. Even less can be said about the original position of strip A.

Also mentioned in Chapter 3.4 is the strip of schist which runs from Otervann to Giken Elv. It cannot be traced further west because of poor exposure due to deposits of glacial material on the valley side. Exposure in the valley bottom here is also bad. This band of schist is very similar to Furulund schist and is noted for its internal folds in the banding. This rock is further described and illustrated in Chapter 4.3, Figures 4.8 and 4.9.

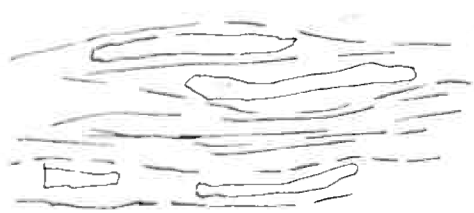
FIG. 9.7 Quartzite conglomerates at base of amphibolite lense, Ny Sulitjelma.

(traced from sketches in field notebook No 10.)



(x 1)

quartzite fragments in matrix of garnet-mica schist (x 1).



flattened pieces of pure quartzite in amphibolitic matrix (x $\frac{1}{2}$)

quartzite fragments in matrix of fine-grained muscovite (x $\frac{1}{2}$)

Immediately above the strip of mica schist just described there is a thin series of finely banded rocks which seem to be of sedimentary origin. Specimen 333 from here is a strongly lineated rock composed of successive bands showing the following mineralogy:-

	hornblende	biotite	quartz	plagioclase	calcite	sphene	epidote
1.	X	X	X	X			
2.			X	X	X	X	
3.	X		X	X	X		
4.			X(coarse)	X	X		
5.			X(fine)		X		X
6.			X	X	X		X

Isolated bands of mica schist occuring elsewhere in the amphibolites are marked on Map I and on Map 9. Fig. 9.3 shows the appearance of one such band in Giken Elv. This is a fine-grained quartz-biotite rock with clinozoisite and chlorite and a porphyroblast of microcline (specimen 438)

9A.8 Conglomerates and possible pyroclastic rocks.

Within the schistose amphibolites there are occasional conglomerates and what may be pyroclastic rocks.

Near the base of the lense of amphibolite at Ny Sulitjelma are several outcrops of rocks in which there are rounded fragments of quartzite. Map 5 marks localities, and Fig. 9.7 shows their appearance. The matrix material varies. At one outcrop in the actual settlement of Ny Sulitjelma the matrix is fine-grained muscovite (specimen 377). In this specimen the fragments of quartzite show very intricate quartz-quartz grain boundaries.

West of Giken Elv at 473 473 there are several outcrops of undoubted conglomerate at the base of the breccia. They are illustrated in Figures 9.8 and 9.9.

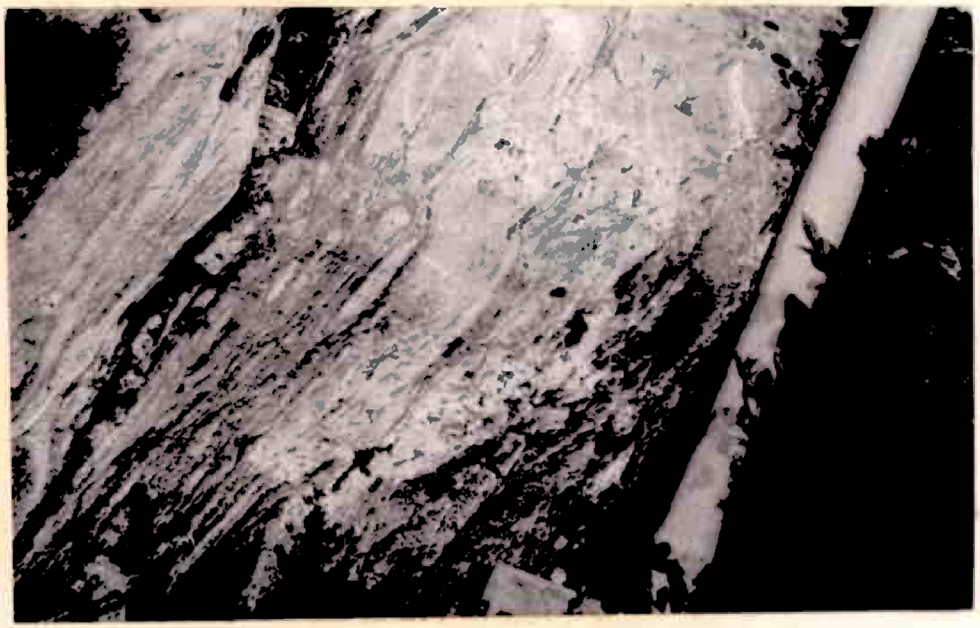


Fig. 9.8 Conglomerate at base of tectonic breccia just west of Giken.

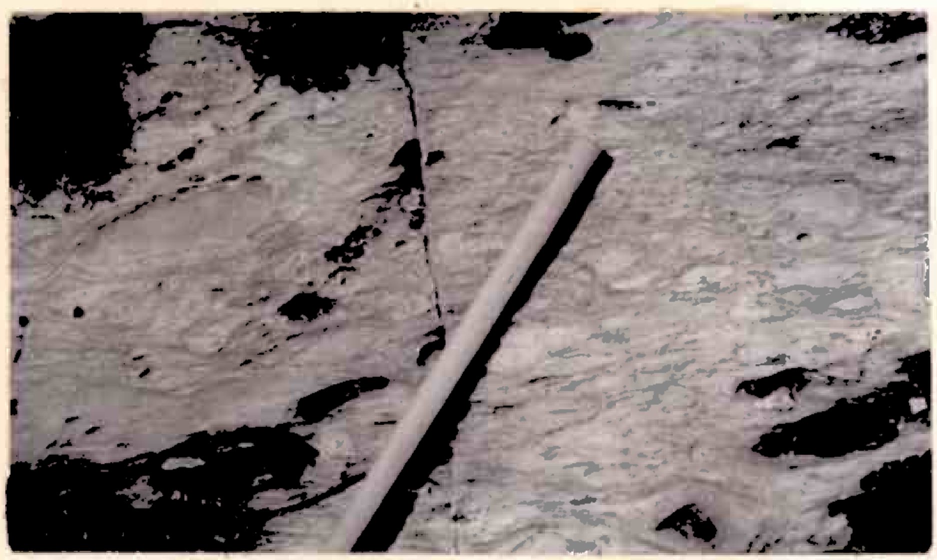


Fig. 9.9 As above.

The fragments vary in composition, some being quartzitic, some being hornblendic.

West of grid easting 460 there are several rocks of presumed conglomeratic origin at the base of the tectonic breccias, but there is confusion here since tectonic brecciation is capable of producing very realistic imitations of conglomerates. Fig. 9.24 is undoubtedly of tectonically originated breccia, but closely related rocks such as illustrated in Fig. 9.32 and 9.33 are problematical. Figures 9.10 and 9.11 illustrate conglomerates at 433 490, at Bursi. Specimen 635 is from the photgraphed outcrop and the fragment sectioned is a fine-grained quartzite with clinozoisite and muscovite in a matrix of finely comminuted quartz, chlorite, muscovite and coarse-grained clinozoisite. There is not much difference between matrix and fragment in this specimen, but other fragments appeared to be of slightly different composition. Outcrops of tectonic 'pseudo-conglomerates' are quite extensive north of the village. The 'agglomerate' referred to by Kautsky and illustrated by him in his plate 90 (1953) is probably a highly chloritised example of tectonic 'pseudo-conglomerate.

Conglomerates are found at other levels, apart from the base of the amphibolites. Just below the strip of schist at 502 483 (Map 9) there are conglomerates, which were originally mapped by Mr Roger Frankland for Mason(1966), and the occurance was confirmed in the present work, the conglomerates being illustrated in Fig. 9.12.

At 503 487 in the east of the area, just below the Flaser gabbro, (the tectonic breccia), the normal schistose amphibolite can be seen to contain rounded and flattened quartzite fragments, as in Fig. 9.13.

In addition to the above described examples of conglomerates there are several exposures of what are possibly pyroclastic rocks. In Giken Elv, at 494 484 there are two outcrops of a rock with rounded nodules of amphibolite which are strongly e longate parallel to the mineral lineation. The nodules are zoned, being darker at the edges and lie in a matrix of either amphibolite or,

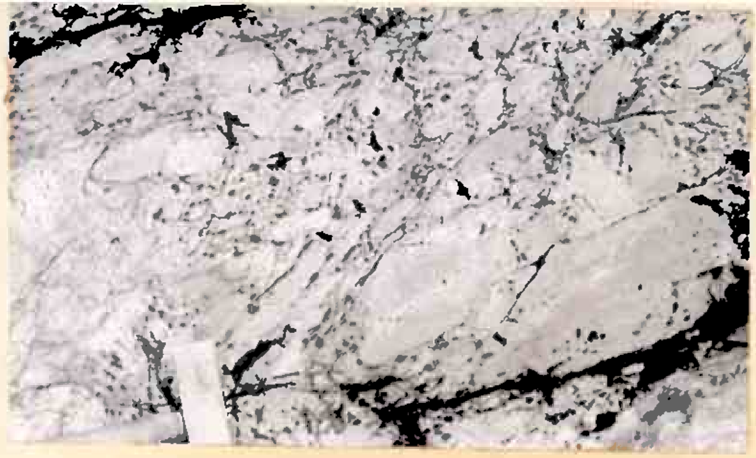


Fig. 9.10 Conglomerate in the amphibolite breccia at Bursi. It lies in the the tectonic breccia immediately above schist strip B on the nose of the recumbent fold.

Fig. 9.11 as fig 9.10

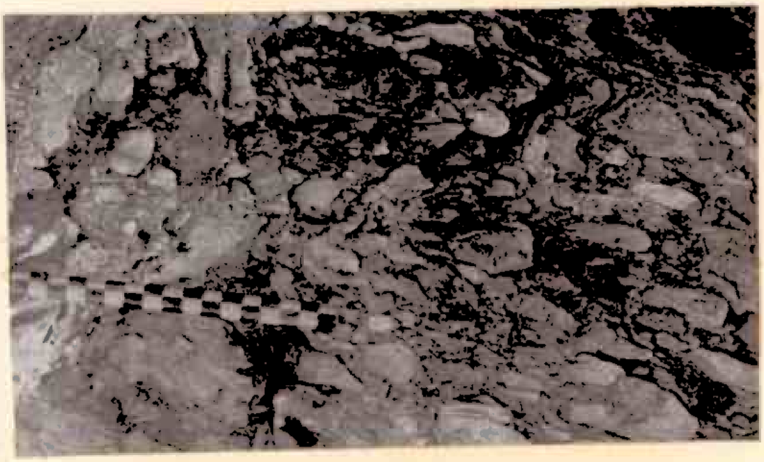


Fig. 9.12 Conglomerate in schist strip within amphibolite in the east of the thesis area. Grid ref. 502 483

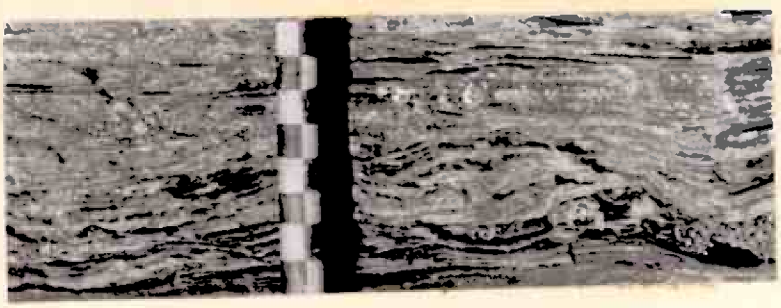


Fig. 9.13 Deformed quartzite fragments at the top of the Sulitjelma amphibolite unit in the east of the thesis area.

as in specimen 443, a rock composed of the following minerals - quartz, feldspar hornblende, calcite and biotite. These are illustrated in Figures 9.14 and 9.15. The shapes of twelve nodules were measured, and an average ratio of 1 : 6.5 : 22 was derived, but since the original shapes of the fragments are not known and since the shapes are so irregular it is doubtful whether this accurately indicates the finite strain.

9A.9 Brecciation of tectonic origin.

Within the Sulitjelma amphibolites there are occasional small patches of fragmentary rock which are tectonic in origin. These areas are mainly around Ny Sulitjelma. Patches of schistose amphibolite are seen with irregular random gashes filled with orange carbonate. Where the amphibolite has poor schistosity as in some of the coarse amphibolites (see section 9A.4, page 85) an irregular breccia is the result, but where the rock has a strong lineation, masses of rock tend to separate out as rods parallel to the lineation.

9A.10 Structural history of the Sulitjelma amphibolites.

The most obvious event has been the development of a lineation-schistosity fabric which is defined by the preferred orientation of the hornblende grains. This deformation has been noted to be inhomogeneous, since rocks such as 427 and 379 show thin zones in which the hornblende has a very high degree of preferred orientation.

The deformation of the fragmentary rocks in the Sulitjelma amphibolites provides one of the few possibilities of determining the amount of finite strain suffered by the rocks in the whole Sulitjelma area. Unfortunately the conglomerates are usually so poorly exposed that it is not possible to determine the strain in more than two dimensions. The only rock in the thesis area for which it was possible to make measurements was the nodular amphibolite in Giken Elv described in

Fig. 9.14 and 9.15 Nodules of amphibolite in a quartz-mica matrix in Giken Elv. This is evidence that the amphibolite series was not a sill, but was exposed to the surface at some time before the metamorphism and deformation. Note the dark margins to the irregularly shaped nodule.s.

Chapter 9A.8 on page 89. The ratio of 1 : 6.5 : 22 obtained from this rock is, as has been discussed above, not reliable. At Lomi, 7km. east of the thesis area, in the underlying Furulund schist, fossils are preserved apparently undeformed (see plate 20 in Vogt, 1927), within 3km. of a conglomerate consisting of "very much elongate quartzite and marble pebbles " (Nicholson 1966). According to Vogt (pg. 60) the tuff conglomerate near the fossil locality contains pebbles 5cm. by 15cm. by 50cm. It is therefore clear that the deformation has been notably inhomogeneous.

Minor structures are rare in the amphibolite. Boudinage is the most common, and is better developed towards the base, but it was not possible to measure any axes.

Folds were very rare. Kinking was seen near the top of the succession at 465 477, though no data could be collected. Specimen 453 from here showed that the kinking actually breaks hornblende grains.

B. The tectonic breccias.

9B.1 General.

The problems that these breccias present are firstly the derivation of the lithologies involved, and secondly the nature and the reason for the brecciation. In non-genetic terms the breccia is made up of the following rock types:- coarse-grained feldspar rock, quartz-feldspar-hornblende rock, coarse-grained quartz-feldspar rock, fine-grained quartz-feldspar rock and fine-grained quartz-hornblende-plagioclase rock (schistose amphibolite). In addition there are in places small quantities of unaltered gabbro, granite, mica schist and conglomerate.

The structure of the breccia is of two types. Firstly there is the mass

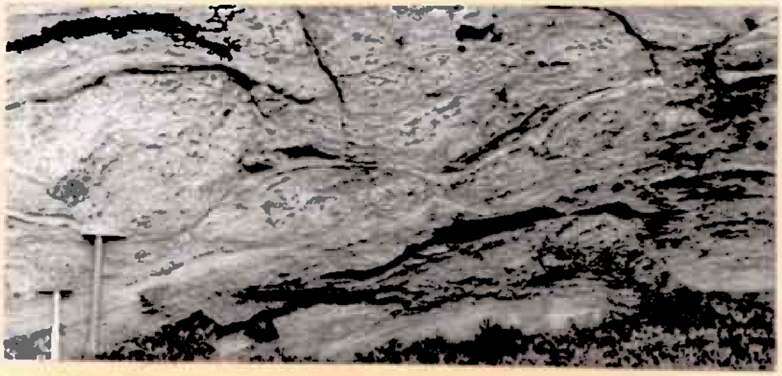


Fig. 9.16
The tectonic breccia at Bursi. Coarse-grained quartz-feldspar-hornblende rocks are boudined and tectonically lensed.

Fig. 9.17
as Fig. 9.16

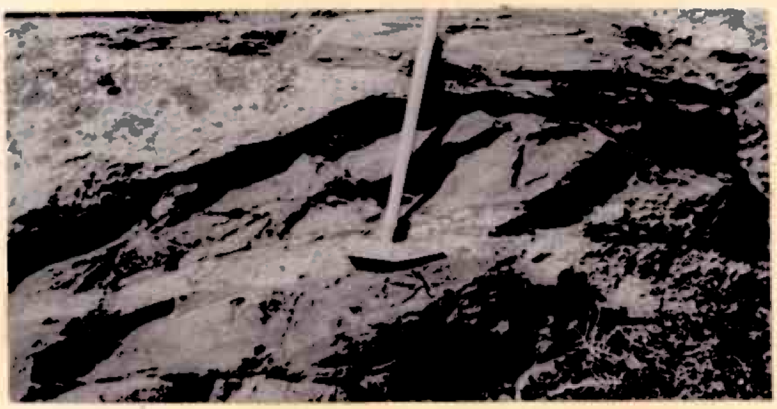


Fig. 9.18 Tectonic breccia immediately west of Giken Elv.

Fig. 9.19 The tectonic breccia at Bursi.

Fig. 9.27 Sedimentary conglomerate within the tectonic breccia at Bursi. Folding takes place at the contact with schist strip B.

Fig. 9.28 Conglomerate within tectonic breccia at Bursi.

Fig. 9.29 as Fig. 9.28

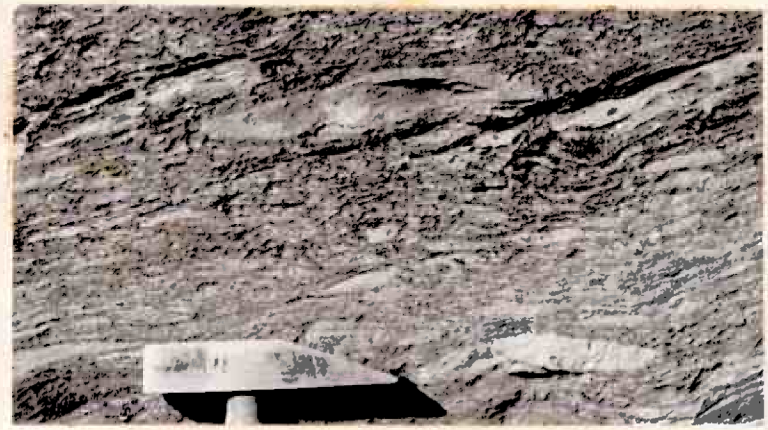


Fig. 9.30 Boudins of schistose amphibolite within the "conglomerate" at the base of the tectonic breccia. This shows that definite tectonic brecciation has taken place, and that the breccias are not all sedimentary in origin.

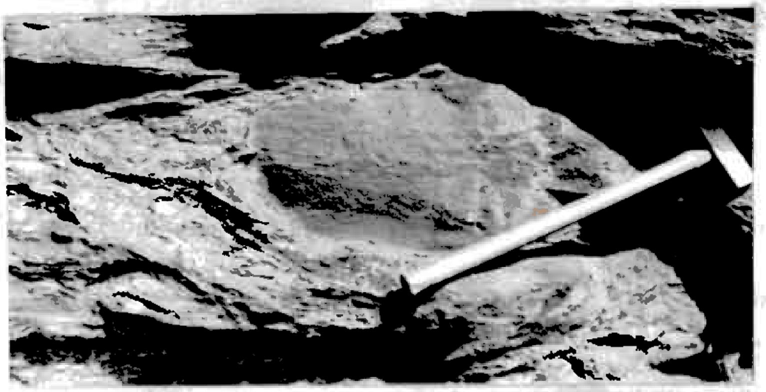
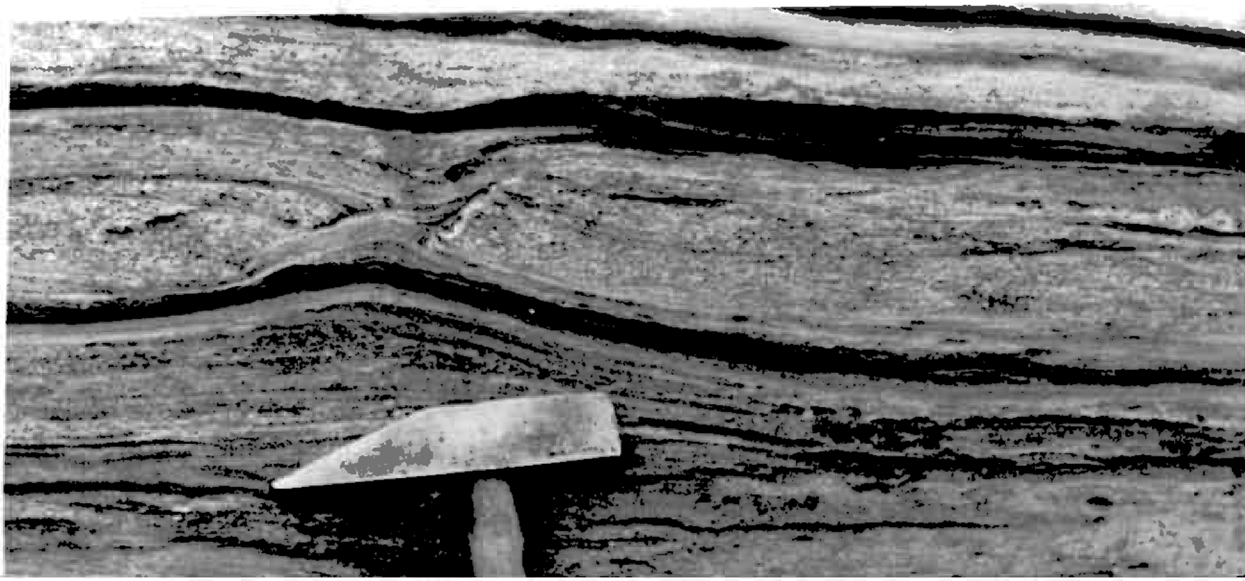


Fig. 9.31 as Fig. 9.30

Fig. 9.32 The basal unit of the tectonic breccia at Byrsi. It is impossible to tell if this unit is tectonic or sedimentary in origin, or both.

Fig. 9.33 As Fig. 9.32

Fig. 9.20 and 9.21 Boudinage features in the tectonic breccia at Kurdi.



SPARE

Fig. 9.22 Boudinage in the tectonic breccia at Burgi. Immediately below schist [illegible] C.

Fig. 9.23 Tectonic breccia near the top of the unit east of Burgi. A medium-grained quartz feldspar rock is fractured, the fissures being infilled with chlorite.

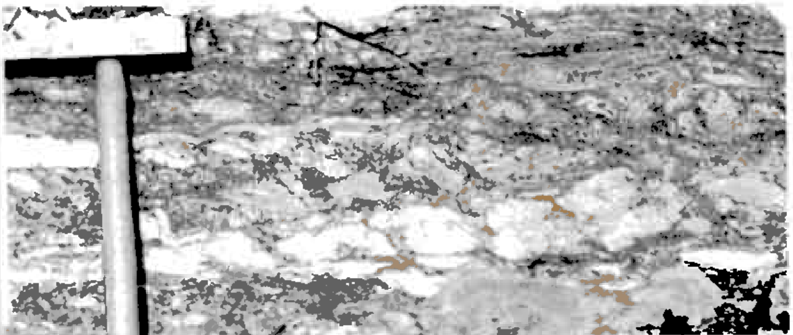


Fig. 9.24
Small-scale brecciation at Burgi. Large strips of rock have clearly been pulled apart. The end product looks like a breccia produced by sedimentary means.

Fig. 9.25 as Fig. 9.24

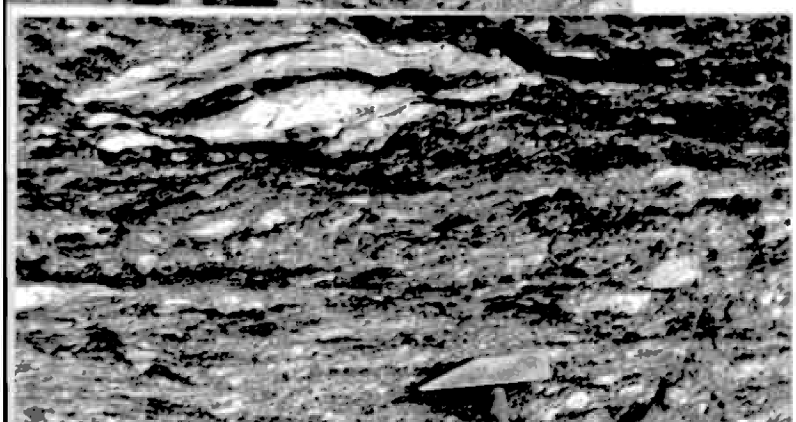


Fig. 9.26 Small-scale tectonic brecciation at Furuhamnen.

of the breccia in the west, which is built up of bands of the above rock types, some 1-3m. thick which have been strongly deformed by boudinage and by pinch and swell so that their general appearance is as in Figures 9.16 to 9.22. Secondly there is brecciation on a smaller scale at the margins of the unit. It is frequently evident that fracturing and boudinage is the mechanism, but these marginal breccias differ from the central type in several ways. Fracturing is developed on a smaller scale, as in Fig. 9.23, where massive medium-grained quartz-feldspar rock is crossed by tension gashes infilled with chlorite, or as in Figures 9.24 and 9.25 where thin bands of quartz-plagioclase rock are broken up. In addition the marginal rocks are rich in chlorite, so much that in places it is referred to by the local miners as 'chlorit'. It is also impregnated with copper ore, large cubes of pyrite up to 2cm. long being found. In addition these rocks bear coarse clinozoisites, often visible to the naked eye. Figure 9.26 from Furuhaugen is typical of the appearance of this rock. Fig. 9.42 is a photomicrograph of the same rock as in Fig. 9.26.

A complication with the marginal breccias on the underside of the breccia unit is that some of the rocks underneath the central breccias are presumed conglomerates, and these are involved in the brecciation. Such rocks are seen in Figures 9.27 to 9.29, and also 9.10 and 9.11. Some of the rocks which appear to be conglomerates also contain large fragments of schistose amphibolite similar in mineralogy and fabric to the schistose amphibolites of the Sulitjelma amphibolites. As is shown in Figures 9.30 and 9.31, the fragmentation is clearly tectonic, the fragments representing boudins. It is certainly very difficult to decide with some of the lower marginal breccias whether their fragmentation is tectonic or sedimentary. Such problem cases are shown in Figures 9.32 and 9.33.

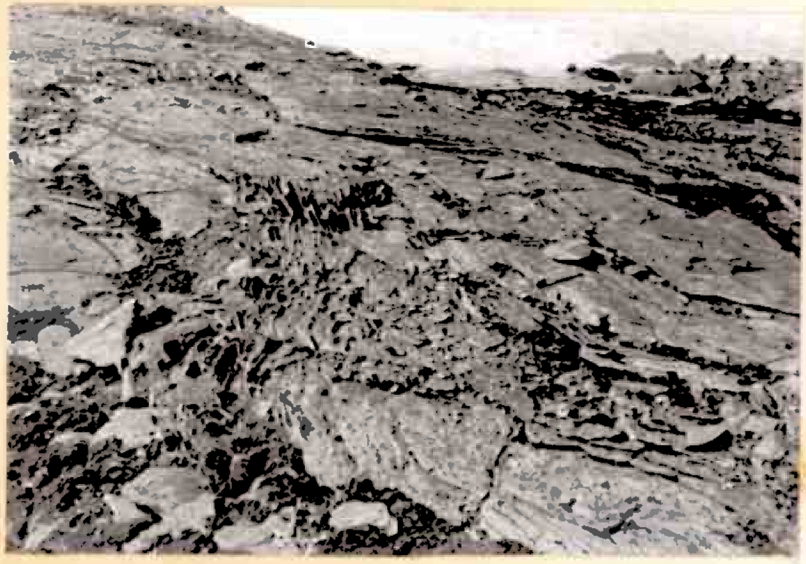


Fig. 9.34 Lensed character of the tectonic breccia in the far east of the thesis area.

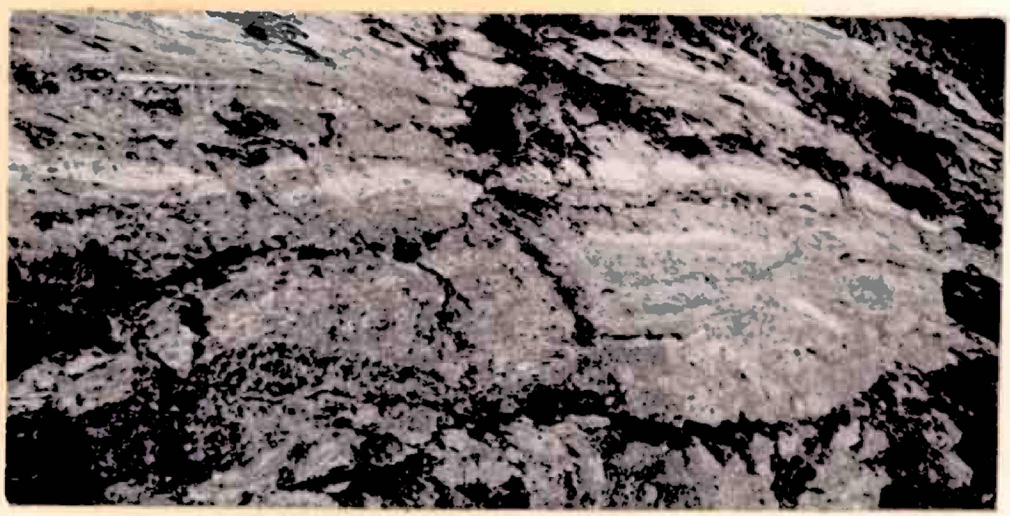


Fig. 9.35 Boudinage of light-coloured member of the tectonic breccia, Lappholleren.

9B.2 The tectonic breccias in the east of the thesis area.

In the east of the thesis area the tectonic breccias have been described by Mason, who terms them Flaser Gabbro, though he does not intend that the term should imply that the Flaser Gabbro is related to the Sulitjelma gabbro in particular, merely that they are highly deformed meta-basic rocks (pers. comm.) (Note that in Mason 1966, the Flaser gabbro is referred to as Dioritic Gneiss). Mason describes the rock as being characterised by the presence of large lenses of coarse-grained amphibolite which show a strong lineation defined by the preferred orientation of the hornblendes. Between the lenses there is a fine-grained amphibolite also with a lineation. According to Mason,the upper parts of the unit contain lenses of unaltered gabbro which are distinguished by orange-yellow weathering. Immediately east of the thesis area the Flaser Gabbro is overlain by amphibolitised gabbro which is similar to the Flaser Gabbro except that it does not show the characteristic strong lineation.

The lower parts of the Flaser Gabbro contain lenses of the underlying rock unit , the meta-porphyritic amphibolite (Mason, Pers. comm), while in the middle part of the Flaser Gabbro there are lenses of coarse-grained amphibolite of no obvious derivation. Mason chemically analysed a coarse-grained amphibolite from a lense near the base of the Flaser Gabbro and found it to have a different composition from the gabbros of the Sulitjelma gabbro complex, being notably richer in silica and iron and poorer in magnesia (1966, pg. 107).

A traverse was made across the tectonic breccias in the east, along easting 503 (Map 9), which is just within the area mapped by Mason. The unit was made up of lenses of mainly amphibolitic rocks, with lenses of granite and unaltered gabbro at the top, the lense structure being apparent in Fig. 9.34. The amphibolites were coarse-grained, well lineated, in lenses, with occasional bands of fine-grained schistose amphibolite. Near the base is a rusty coloured quartzo-feldspathic rock which can be traced west to Fjeldsgrube (Map 1). The above description of this unit tallies with Mason's account of it (1966, pg. 27). Sjögren (1895) described a north-south section through this particular area (Table 5, Fig. 3) but did not mention the lensed character.

9B.3 The brecciaot Lapphelleren (471 480).

The tectonic breccias overlying the Sulitjelma amphibolites are well exposed here. The succession below the lowermost Lapphelleren schists is as follows:-

7. Lapphelleren schist.
6. 6m. of rounded fragments of white rock. The fragments are 4-6cm. across, and are separated by medium-grained chloritic material.
5. 20-30cm. of fine-grained quartz-feldspar rock showing a slight foliation. Specimen 468 is from here. The rock contains at least 20-30% plagioclase with less than 10% of chlorite, clinozoisite and muscovite. The quartz and the feldspar are intricately inter-grown, but the grains themselves are not now strained, indicating that the deformed areas have recrystallised, but there has not been overall grain growth. The clinozoisite, present as a few large grains, is zoned, and sometimes has myrmekitic intergrowths at grain boundaries.
4. 2-3m. of medium-grained well-lineated amphibolite. The above band cuts out against this. Represented by specimens 469 and 40. In thin section this rock appears to be a fairly normal amphibolite composed of quartz, clinozoisite and hornblende.
3. 20-30cm. of fine-grained white rock with knots of hornblende.
2. 2-3m. of coarse massive rock, composed of large hornblendes and feldspars as in specimen 470. Within the unit are deformed slices of well-banded quartz-feldpar rock as shown in Fig. 9.35, and represented by

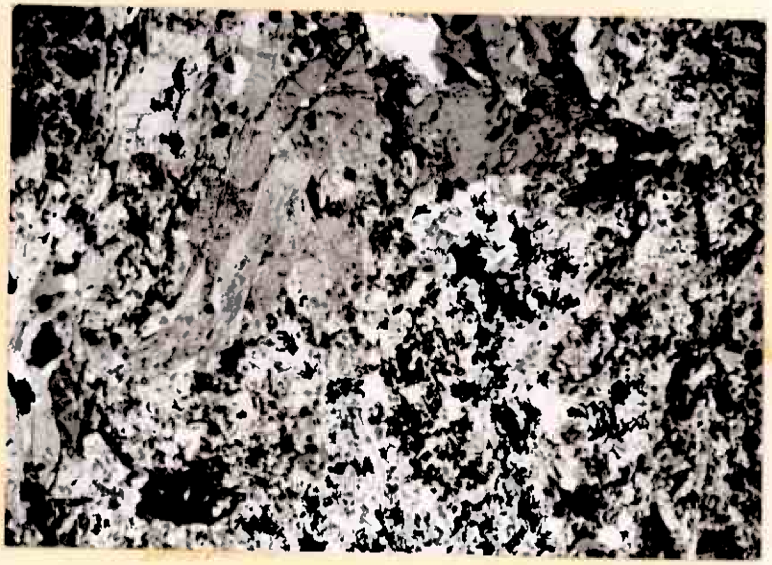


Fig. 9.36 Specimen 470 x12, crossed polars.
Large hornblende grains in a fine-grained matrix of quartz and feldspar.

Fig. 9.37 Specimen 41 x50, crossed polars.
Large zoned clinozoisite growing across chlorite.

specimen 41.

Specimen 470 (Fig. 9.36) contains zones of relatively undeformed rock separated by zones of cataclasis. The relatively undeformed parts consist of clusters of coarse hornblendes with smaller grains of plagioclase and hornblende. The large hornblendes are ragged in shape and show internal strain. The cataclastic zones are made up of fine-grained quartz and plagioclase, with highly intergrown grain boundaries, though the grains are strain free. There are also fine-grained hornblendes, well orientated. This rock is typical of the Flaser gabbro found east of here at the same structural level.

Specimen 41 (Fig. 9.37) is taken from the white rock which occurs in slices in the coarse amphibolite described above, and is made of fine-grained quartz with a little plagioclase, and is cut by late chlorites. It is finely banded, there being bands with about 10% hornblende in small grains. The particular band sampled has been boudined, and the neck of the boudin is filled with coarse chlorite, clinozoisite and quartz. The clinozoisites are well-shaped and are zoned and appear to cut across the chlorites as is shown in Fig. 9.37.

I. 7-10m. of rounded lumps of white rock and amphibolite separated by thin seams of chloritised amphibolite with folded strips of white rock.

The specimens , 471, 473, 474, 472 and 475 are varieties of rock made up of quartz, clinozoisite and chlorite. 474 and 475 also contain a fair proportion of hornblende and seem to be derived from schistose amphibolite. In 471 the fabric of the clinozoistes (fine-grained) and the chlorite is folded. Usually the ~~chlorites~~ clinozoisites are coarse-grained, well shaped and zoned, as in Fig. 9.37.

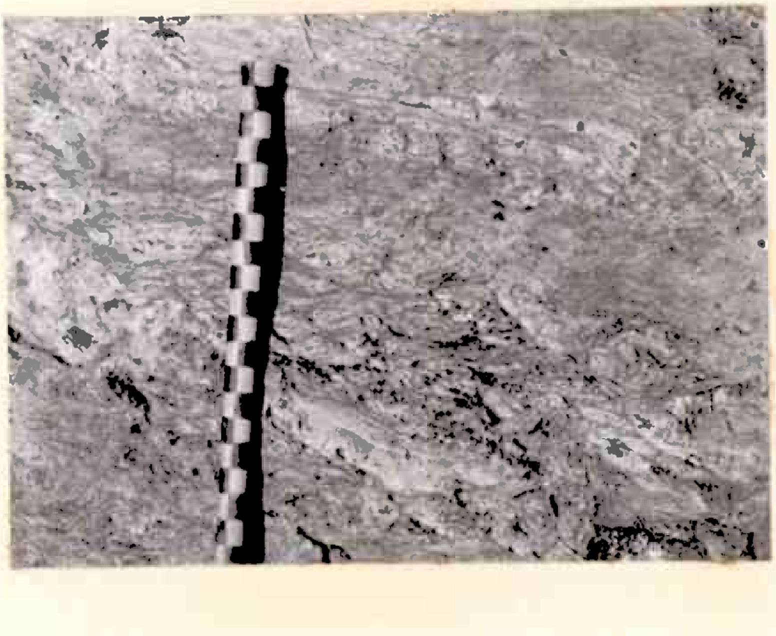


Fig. 9.38 . The tectonic breccia below schistose amphibolites near Qikan Elv.

Fig. 9.39 As above. Rounded masses of coarse amphibolite in a matrix of chloritised amphibolite.

9B.4 The Tectonic Breccias below the unbrecciated Sulitjelma amphibolites.

In many respects the breccia below the Sulitjelma amphibolites is very similar to that developed above. In particular the same coarse-grained feldspar-amphibole rocks are present, almost as far east as Ny Sulitjelma (Map I, Map 9). If these were derived from gabbro then a real problem is how they got into that position. The nature of the breccia in this area is shown in the following north-south section across the breccia west of Giken Elv (at 467 474).

5. Schistose amphibolite
4. A white or rusty coloured rock, with needles of amphibole. It has streaks and stringers of amphibole rich rock which are often chloritised. Specimen 488 from here is mainly composed of plagioclase and quartz. The grain boundaries are usually intricate, and the quartz grains are strained. Chlorite, muscovite, biotite, clinozoisite and garnet are also present.
3. A layered series of meta-porphyritic amphibolite, schistose amphibolite, acid rusty rock and strongly chloritised amphibolite. The general appearance is as shown in Fig. 9.38. The porphyritic amphibolite is in veins being boudined. Embedded in the rock are quite large masses of quartzite, again slightly rusty coloured. Specimen 487 is of the quartzite and can be seen to consist of quartz, clinozoisite and chlorite and hornblende. The clinozoisites are full of small inclusions suggesting that the mineral grew before the rock fabric was so coarse. The areas of quartzite are separated by sheaves of chlorite.
2. Well banded meta-porphyritic amphibolite.
1. Coarse green and white amphibolite, with no preferred orientation of its minerals, present in masses 30-40cm. across, separated by a fine-

Fig. 9.40 Specimen 484 x 15 crossed polars. This specimen is taken from a rounded fragment such as is shown in Fig. 9.39. Note the large altered plagioclases.

Fig. 9.41 Specimen 485. x10. Plane polarised light. Fine-grained hornblende, chlorite, clinozoisite and quartz.

grained pale green rock showing strong schistosity folded round the coarse-grained masses. This matrix material is often highly chloritised, the chlorite being parallel to the schistosity and present in massive books. Fig. 9.39 illustrates the appearance of the rock.

Specimen 484 is typical of the coarse-grained material in the lenses, and is composed of masses of medium to coarse amphibole and chlorite, separated by areas with large grains of plagioclase, now partly altered. These plagioclases are shown in Fig. 9.40. There is virtually no quartz in the rock; hornblende, chlorite and clinozoisite making up the rest of the rock. The many small grains of chlorite and clinozoisite give the rock the impression of being fine-grained, but most of the rock can be accounted for by the coarse plagioclases and hornblendes. The rock thus seems to be a coarse meta-basic rock.

Specimen 485 is typical of the fine-grained matrix material. It is composed of equal proportions of hornblende, chlorite and clinozoisite. Some of the hornblende is partly altered to chlorite. There is a small quantity of plagioclase. The rock texture is rather like a typical schistose amphibolite from the Sulitjelma amphibolites above, but compositionally the rock is richer in clinozoisite. See photomicrograph in Fig. 9.41.

In summary this section contains the following rock types:- schistose amphibolite, meta-porphyritic amphibolite, fine-grained acid material, coarse feldspar amphibole rock, fine-grained quartz rich rocks. It shows the breaking up of bands by boudinage, and the filling in of the boudin scars by chlorite, and the breaking up of massive coarse-grained bands into large rounded masses. There has been chloritisation and growth of clinozoisite.

Derivation of the material in the breccias – a summary

The origin of some of the brecciated material is quite clear as has been discussed above. For example, the lenses of unaltered gabbro in the east and, by inference, much of the coarse-grained amphibolite in the east must be derived from the Sulitjelma gabbro. Similarly the fine-grained schistose amphibolite and the meta-porphyritic amphibolite in the east and the conglomerates and mica schist bands in the west must belong to the Sulitjelma amphibolite group.

There remains much material which is of indeterminate origin. As described above, on page 93, Mason has found that some of the coarse-grained amphibolite in the east is not of the composition of gabbro. In the west of the area there are bands of coarse-grained quartz-feldspar rock which show no affinities with gabbro. Coarse-grained amphibolites are found below the Sulitjelma amphibolites nearly as far east as Ny Sulitjelma. If these were to have been derived from the Sulitjelma gabbro it is not easy to explain why they occupy their present position.

On the very limited evidence at present available it is therefore concluded that many of the rocks in the breccia are not derived from the gabbro, but represent a series of thinly banded basic and acid bodies of different primary origin to the other amphibolitic rocks in Sulitjelma. There is clearly need for further work here, to determine the mineralogy and petrology of these bodies before there can be further speculation about their origin.

9B.6 Age of the brecciation.

Fragments within the breccias are schistose, indicating that the tectonic separation was post-schistosity. The breccia unit as a whole is folded in the Bursi area by folds which are later than the growth of garnets. Thus the brecciation event may be placed in the succession of tectonic events after the development of schistosity, possibly around the time of the growth of garnets in the Furulund schist, with the modification to schistosity which occured then, but before the folding of schistosity which followed garnet growth.

Chloritisation post-dates the brecciation on the evidence of several thin sections, especially 501 and N67 54. The evidence from the latter specimen is shown in Fig. 9.42, where biotite can be seen to be partly replaced by chlorite. The chloritisation is best developed at the margins of the breccia unit, where the rock also is ore-bearing and rich in clinozoisite.

9.8.7 Cause of the brecciation.

In 1927 Vogt regarded the breccias as igneous intrusion structures, evidence for several phases of intrusion of basic magma. In 1949 he stated in response to a question by Kautsky, that the breccia formations may represent minor thrust planes, but not the major thrusts suggested by Kautsky.

Kautsky (1953) pg. 203, ascribed much of the brecciation to the presence at the base of the amphibolites of a major thrust plane. The fine-scale breccias he described as agglomerates.

Mason (1966, 1967) regarded the Flaser Gabbro as a zone of extreme strain, suggesting that the zone represents a thrust.

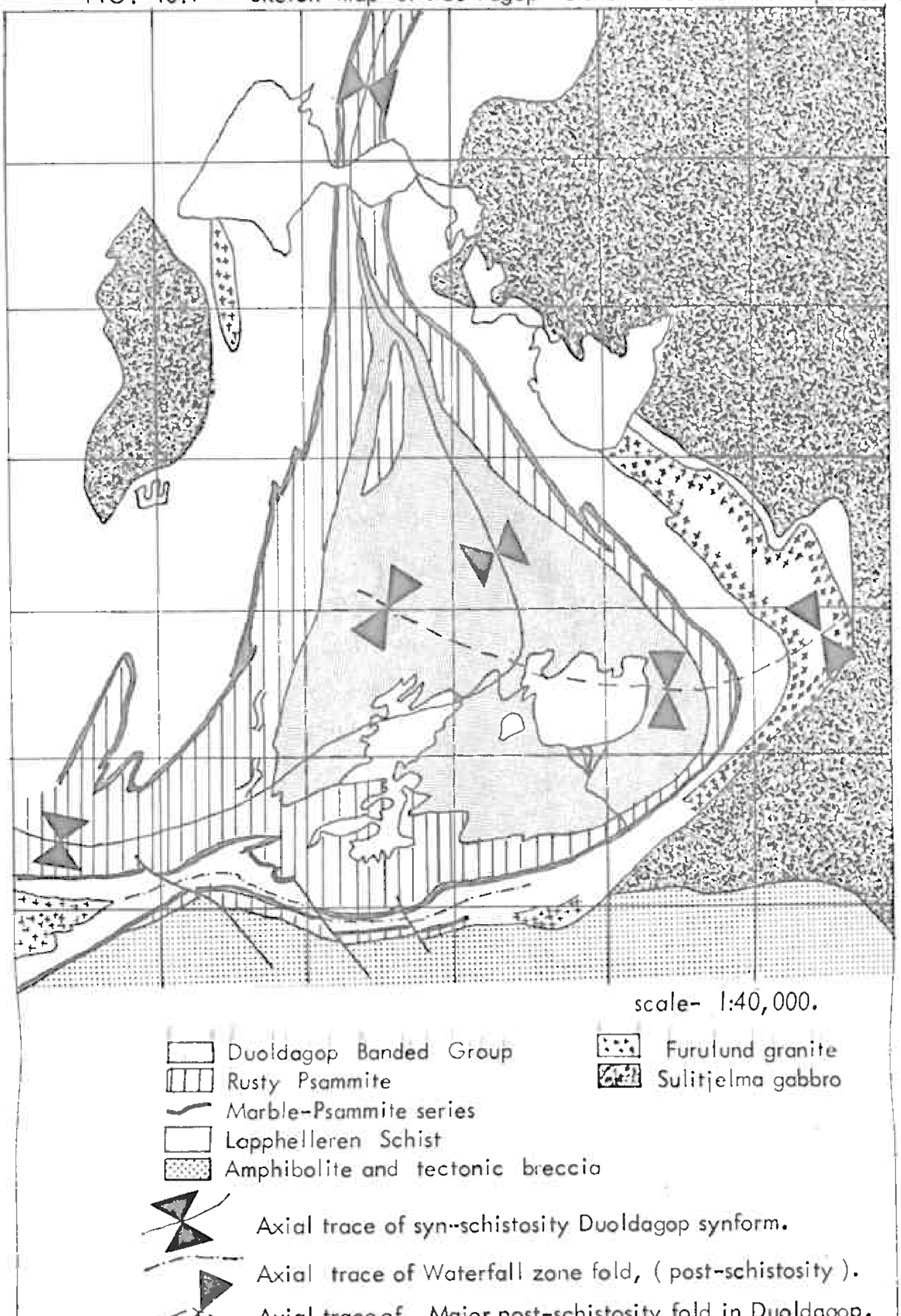
It will be observed from the photgraphs that the main type of deformation suffered in the breccias is boudinage of a symetrical type, a simple response of the rock to flattening where the plane of extension is parallel to banding where different bands have different competences. Such a zone of intense boudinage could have developed either because the zone suffered more strain than adjacent areas, or because the lithologies are very different from those of adjacent areas and have reacted differently. Boudinage is common in the upper parts of the Furulund schist, as is described in Chapter 8.2 , and illustrated in Fig. 4.6, and the competent material that has boudined is usually amphibolite, the mica schists usually having behaved relatively incompetently. There are within the breccia zone a variety of rock types, very likely with different competences. It may be that these varying rock types reacted in this way to the same stress as was imposed on the schist below.

There is no evidence either way concerning displacements across the zone, to give a clue to the deformation. As the photographs show the brecciation has caused separation of the rock into fragments, but there is no sign of much relative movement after separation.

There are no characteristics of the brecciation which suggest that it could have formed in response to thrust movements.

Fig. 9.42 Specimen N6754. x20, plane polarised light. The tectonic breccia at Furuhaugen. Fragments of quartzite in a biotite rich matrix. The biotite is partly replaced by chlorite.

FIG. 10.1 Sketch map of Duoldagop to show the effects of repeated folding



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PART FOUR - SULITJELMA SCHIST SEQUENCE

CHAPTER 10

INTRODUCTION AND LITHOLOGICAL DESCRIPTIONS

10.1 Introduction.

The outstanding feature of the Sulitjelma Schist Sequence in the thesis area is the large eyed fold in Duoldagop (Fig. 10.1, opposite) in which the bedding is probably arranged in a basin form as suggested by Mason (1966). It will be demonstrated in the following chapters that this has formed through the interference of an early synform (the Duoldagop synform) and a post-schistosity fold whose axis plunges to the north-west and which opens to the west. This is not the only major folding of the Sulitjelma Schist Sequence. In the Waterfall zone (Map 4) there is a major fold which can be detected through the repetition of lithologies across the fold trace as in Fig. 10.1, opposite. It is apparent from the behaviour of bedding that the fold axis is nearly horizontal, with an east-west azimuth. At first sight the fold appears to hinge in the Waterfall zone but it is more probable on regional grounds that the fold is a "Z" type fold (Elliot, 1968 pg.172), with a definite short limb, the lower limb having thinned out and become dislocated. As a result of the major fold the outcrop of the Lapphelleren schists becomes much narrower in the Waterfall zone. The age of this folding is not known for certain. There is a notable concentration of minor folds in the Waterfall zone which are of post-schistosity age, and this suggests that the major fold is also of post-schistosity age.

To understand the structural history of the Sulitjelma Schist Sequence in Duoldagop it is necessary to consider the evidence for the existence of the major folds, particularly the one in the Waterfall zone, to study the different phases of minor folding, the growth of porphyroblasts and matrix minerals and to relate these to the intrusion and deformation of the Sulitjelma gabbro and the Furulund granite. When these are all considered there are several alternative possibilities for the sequence of events, but the most probable sequence is as follows. The earliest event was the formation of the Duoldagop synform, a closure of which can be seen in the north and is illustrate in Map 7. This was accompanied by the generation of schistosity in the metasediments. Following the early events the gabbro and granite were intruded, and a schistosity imposed upon the granite and upon the margins of the gabbro. Possibly at about this time there was post-schistosity folding on a major and a minor scale in the Waterfall zone, with an associated slide which removed part of the lower limb, though the form and age of this folding is a matter for discussion. Following the minor folding there was garnet growth. In a third phase of folding the granite and gabbro were folded. Finally there was faulting in the Waterfall zone (Map 4).

Other possible sequences arise from uncertainties concerning the age of intrusion of the Furulund granite, the correlation of major and minor folds and the form of the major fold in the Waterfall zone.

In the next section is discussed the evidence concerning the form of the major fold in the Waterfall zone, and a description of the lithologies of the Sulitjelma Schist Sequence. Later chapters describe the mineral textures, the early and late folding on all scales and the igneous intrusions. Finally a synthesis of these descriptions is attempted.

10.2 Evidence of major folding in the Waterfall zone.

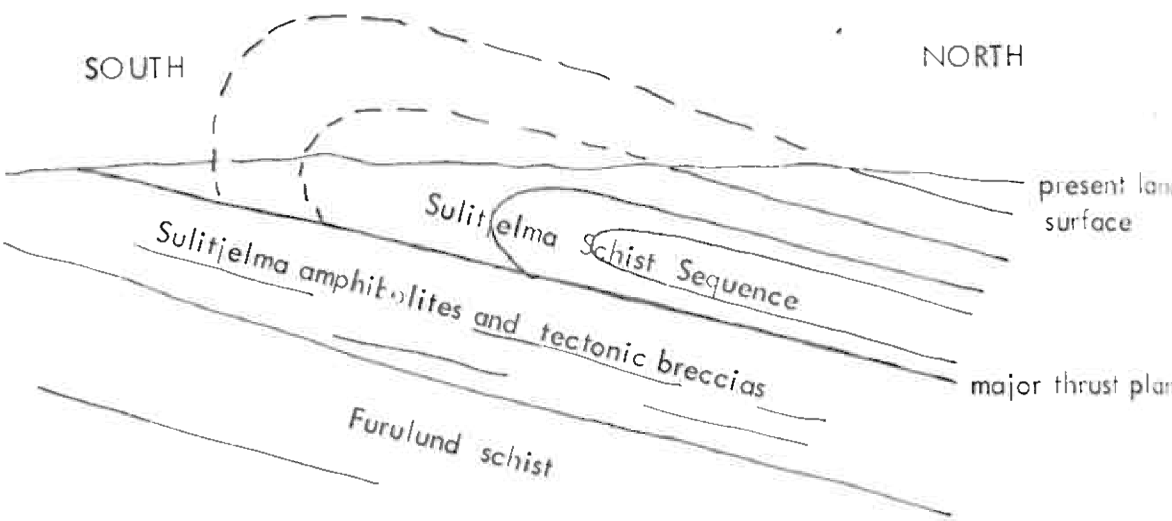
The major fold in the Waterfall zone can be identified by following the outcrops of the marble-psammite series as on Map 4. This Marble-Psammite series is a thin group. of marbles and white psammites usually arranged with a marble on the side adjacent to the Rusty Psammite. The series is tightly folded in the Waterfall zone and during the intense deformation of the rocks the variations in competence within the series and between the series and the surrounding schists have resulted in considerable variations in the thickness of the series and in the thickness of individual members. In places the entire series is absent, and in others individual members are missing. Where the series is not intensely folded it is between 3 and 6m. in thickness and is commonly made up of three members :- a marble lying adjacent to the Rusty Psammite, a white psammite and a series of very thinly bedded marbles and psammites, each unit of the latter being only a few centimetres thick. This latter group is rich in light-green calc-silicate minerals, and at several places is represented by about half a metre of calc-silicate rock whose mineral components show no preferred orientation. In several places the sequence is more complicated than that mentioned above, but there is sometimes evidence that there is repetition by folding. On Map 4 a series of sections across the Marble-Psammite Series at the scale of 1:200 indicate the variations seen. It would seem most reasonable to assume that all the isolated outcrops of interbedded marble and psammite at the junction of the Rusty Psammite and the Lapphelleren schist marked on Map 4 are in fact part of the same sequence, and can be correlated with one another.

If this is assumed then a major fold is defined in the Waterfall zone, opening to the south, with an east-west, horizontal axis, culminating in this zone. Apparently the Marble-Psammite Series surface outcrop does not close completely round this fold, actual surface outcrop closures being somewhere within the Lapphelleren schists, but relations in this zone are complicated by faulting and imperfect exposure. The Lapphellern schists can be followed east from point 500 490 (Map 4) where they are very thin. Exposure is very irregular but they seem to connect eastwards with the large body of grey schist which curves round the eastern margin of Duoldagop.

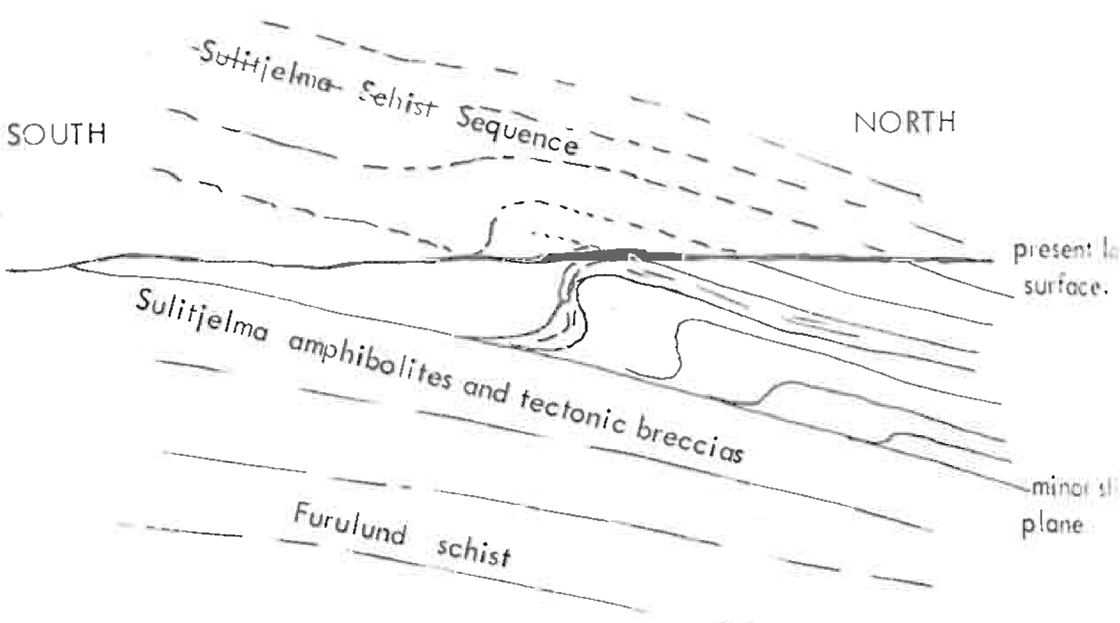
Relationships are particularly complicated in the area just east of the Waterfall zone at 508 490 where the sequence RustyPsammite, marble,

FIG. 10.3 Alternative forms for the major fold in the Waterfall zone

'M' type major fold



'Z' type major fold



psammite, interbedded marble and psammite is repeated without inversion. This is clearly illustrated in Fig. 10.2 and in Map 4. The situation at the level of the Lapphelleren schists in the whole of this zone east from Fjeldsgrube is obscure, the thickness and number of lithological units between the Marble-Psammite series and the Tectonic breccias varying as in Map 4. Since the Sulitjelma amphibolites and breccias are not represented on the northern limb of the major fold defined by the Marble-Psammite series it is clear that there must be some kind of discontinuity at this level. This might be a major thrust or could be a much smaller slide with thinning out of the lower limb of the fold. The two alternatives seem to be that the major fold is an 'M' type fold (terminology as in Elliot, 1968 pg. 172), with two long limbs and one hinge, this alternative necessitating a major slide with considerable movement, or is an 'Z' type fold having a short limb and two hinges, in which case part of the bottom limb is missing. The two alternatives are illustrated in Fig. 10.3, opposite. It may be suggested that at the locality figured in Fig. 10.2 it is the middle limb that is missing, only the upper and lower long limbs being preserved thus giving the repetition without inversion. Minor fold evidence suggests that the fold is post-schistosity and as is discussed in Chapter 12.7 (page 122) a post-schistosity 'M' type fold implies a much more complex set of events. In addition evidence from outside the thesis area is not in favour of a major fold at this level (Nicholson, pers. comm.) and so the 'Z' type fold interpretation is favoured.

10.3 Lithologies of the Sulitjelma Schist Sequence - The Lapphelleren schist.

The lithologies of the Lapphelleren schists have been investigated in detail around Lapphelleren (471 480) and internal divisions within the schists mapped east and west for a kilometre or so. The Lapphelleren schists on the perimeter of the Douldagop basin are well exposed but have not been studied in detail except in the Waterfall zone (Map 4) where the structures were

FIG. 10.4 Mica fabrics in the Lapphelleren schist, Lapphelleren.

FIG. 10.4a 100 poles to biotite cleavage in specimen 37.

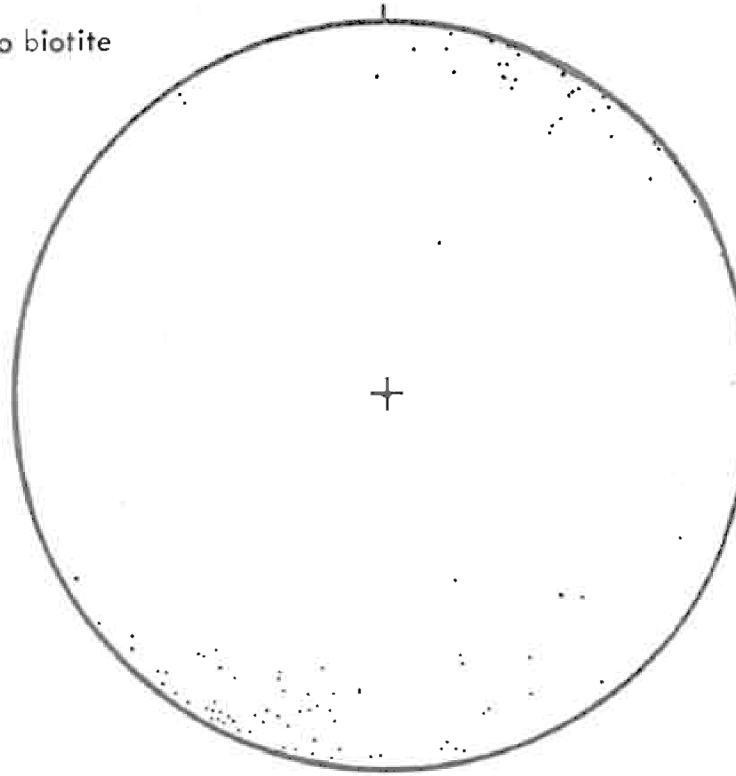
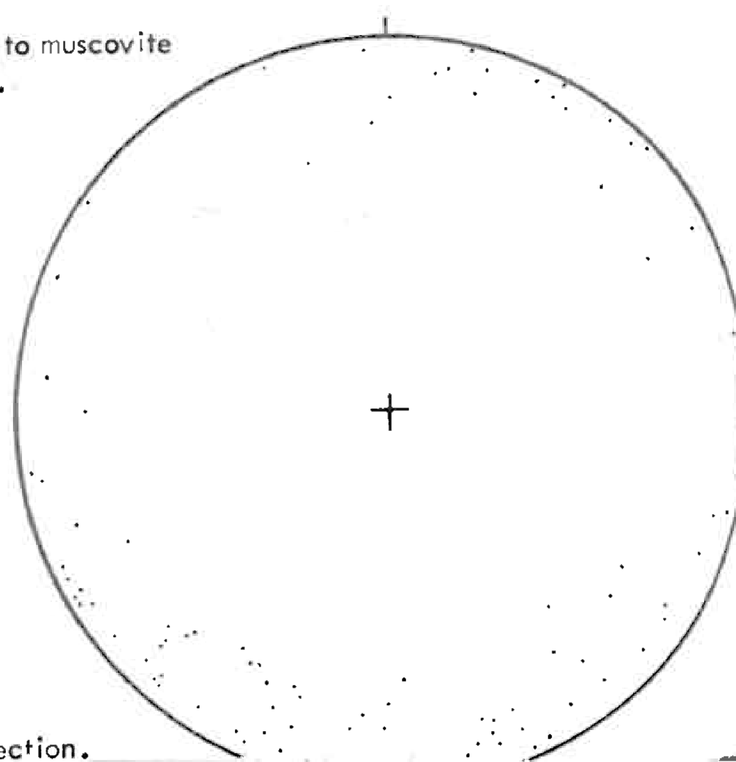


FIG. 10.4b 100 poles to muscovite cleavage in specimen 37.



Lambert equal area projection.

investigated.

The character of the Lapphelleren sc hists varies considerably. The rocks are usually medium-grained, grey in colour, with schistosity surfaces rather irregular on a small scale, the whole rock being quite unlike the Furulund schist or the Duoldagop Banded Group. Porphyroblasts of garnet and kyanite are quite common, though kyanite is usually altered to muscovite and quartz round the margins of the grains. The main minerals visible with the naked eye are quartz, biotite and muscovite. Clinozoisite, sillimanite , ore minerals and staurolite are commonly present. In general the schists are not as calcareous as the Furulund schists. Varieties of Lapphelleren schist can be quite coarse-grained as in the central part of the succession at Lapphelleren, though fine-grained varieties occur. Partings along schistosity are characte ristically greyish, but occasional bands with higher than average contents of ore-minerals tend to weather to give a rusty colour. Some bands are rich in hornblende and are often quite tightly folded. In the north of Duoldagop there occur varieties of Lapphelleren schist containing large (5-6cm. diam.) nodules or pods of green material, generally made of calc-silicate minerals (Mason, pers. comm.)

The succession of Lapphelleren schist around Lapphelleren.

At Lapphelleren (471 480 on Map I, see also Fig. I.6) there is a well-exposed stream section across the Lapphelleren schist below the Furulund granite. The schists can be divided into four units.

The lowest unit is finely banded fine-grained schist composed of quartz, biotite, occasional muscovite, clinozoisite (abundant, with anomalous blue birefringence), occasional calcite and ore minerals. It is represented by specimens 35, 38 and 39. Fig. 10.4 is a stereogram of 100 poles to muscovite cleavage in specimen 37 and illustrates the L-S tectonite fabric developed. This unit is approximately 30m. thick and is succeeded by about 50m. of rather gneissic schists, coarse-grained with quartz segregations and kyanite pseudomorphs. The upper part of this unit has only small segregations, some 1cm. by 5cm., but the lower part has segregations up to 30cm. thick. Some of the segregations are pegmatitic in character, being rich in coarse muscovite as well as quartz. Representatives are specimens 32, 33, 34, 206, 92 and 93. They are all quartz-biotite-muscovite schists with garnets and occasional grains of plagioclase, clino-zoisite and ore minerals. Large masses of quartz and muscovite occur as pseudomorphs after kyanite, and, occasionally, kyanite is seen. Staurolite is present in specimen 33.

Above these coarse-grained rocks lie some 20m. of fine- to medium-grained schists, which are characteristically very well banded and are extremely flaggy. The top of this unit is impregnated with copper ore and the rock is tightly folded, the axial planes of the folds being parallel to the northerly dipping schistosity. A characteristic of these folds is that one set of closures is consistently missing, the rock being divided into a number of synformal units separated by shear planes, the folds in every unit opening to the south. Specimens 30, 31 and 37 represent the rocks in this unit and are composed of quartz, biotite, muscovite, sillimanite, garnet, plagioclase, ore minerals and a little clino-zoisite. The garnets have slightly curved inclusion trails, though the external fabric is not folded at all, indicating that there was slight deformation (probably only flattening oblique to schistosity) during garnet growth. Specimen 30 is notable for its marked banding which is caused by a variation in the modal proportions of biotite and quartz, alternating every 5mm. In specimen 37 the lineation element of the L-S tectonite fabric is quite strong, and Fig. 10.4 is a plot of poles to biotite cleavage measured parallel and normal to the lineation. There is a well-developed girdle.

The uppermost unit below the granite in this stream section is about 40m. thick, being mainly highly hornblendic and garnetiferous schists. Some thin bands such as sampled in specimen 29 are almost entirely amphibole.

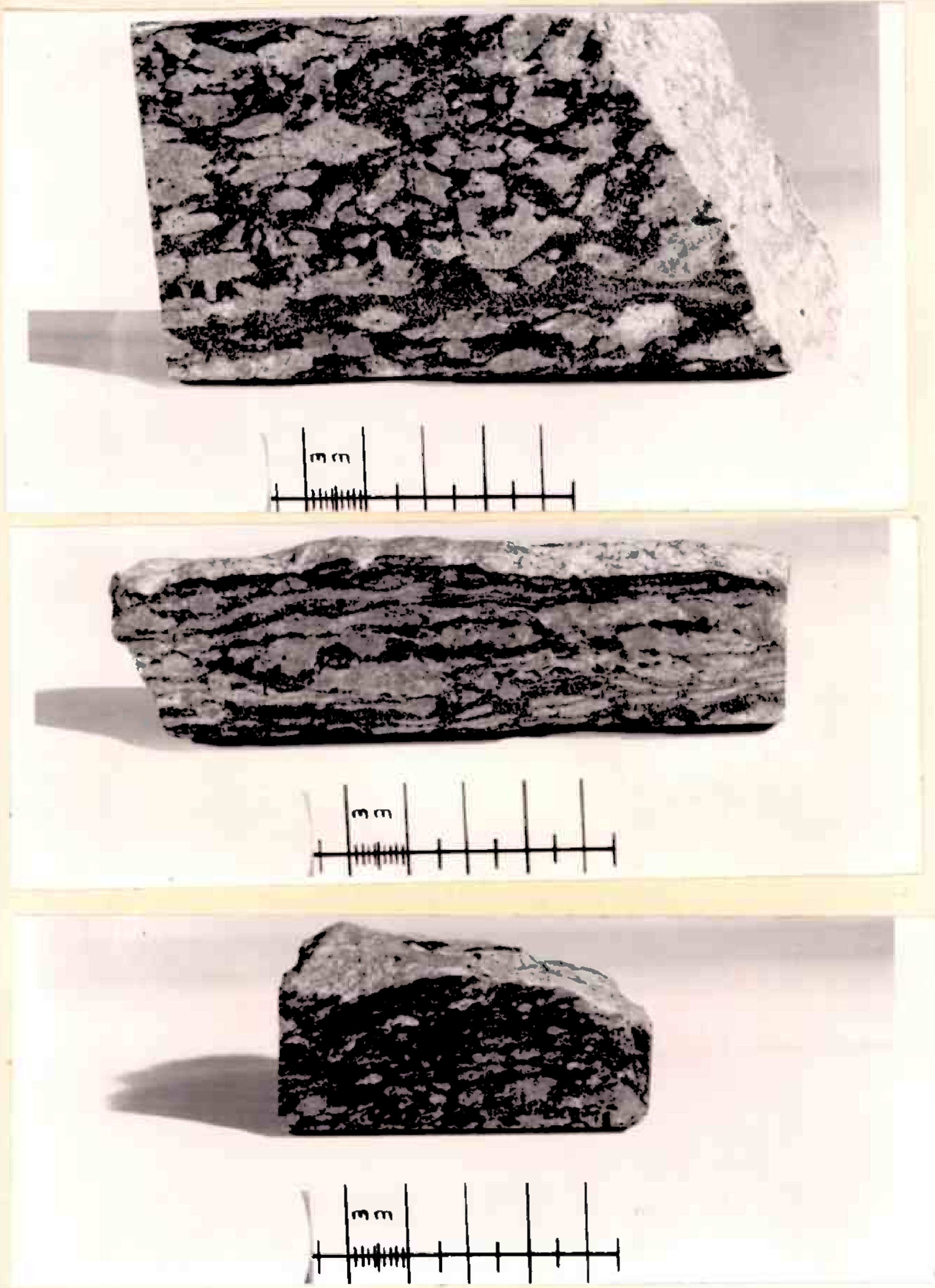


Fig. 10.5 Specimen 646 , x1 approx. Diopside rich rock from N.Du[illegible]. Some diopsides are granulated, and the aggregates are elongated by strain. Top- parallel to schistosity, bottom, normal

Granite veins are seen here,(specimens 25 and 26). Other specimens are 22 to 28 and 207. In most of these medium-grained schists the hornblende is not present as porphyroblasts as is common in the Furulund schist, but as a groundmass mineral. In the hornblendic bands there is virtually no biotite. The rocks in immediate contact with the Furulund granite are represented by specimens 1,7,11 and 17. In these the biotite grains are more stubby than is usual and there is considerable late growth of muscovite porphyroblasts, unusual in the Lapphelleren schists. Further discussion of this is included in the sections on mineral growth.

About one kilometre to the west of Lapphelleren the contact of the granite cuts across the lithologies and there is exposed a notable band of highly hornblendic schists which lie above those just described.

The lithologies described above from the Lapphelleren stream section can be traced east for about half a kilometre until the rocks are obscured by a large patch of moraine and continuity is lost.

In the Waterfall zone most of the folded rock is kyanite rich.

Specimens described from the north of the western Furulund granite were generally medium-grained quartz, biotite schists rather similar to the schists immediately below the granite at Lapphelleren. The lithologies are not really well enough known to determine whether there is any major repetition of strata within the Lapphelleren schists. It is more probable that there is not, thus arguing in favour of the interpretation of the major fold in the Waterfall zone as being a 'Z' type fold.

In the north of Duoldagop there occurs a band of grey schist within the Rusty Psammite, on the eastern limb of the early Duoldagop synform(Map 7). Parts of this band appear in the field to be conglomeratic, the 'fragments' being gravel sized and showing an apparent grading. This feature is well shown in Figures 13.1 and 13.2. A cut and polished hand specimen of the rock is shown in Fig. 10.5. The 'fragments', however, are diopside crystals and obviously are of metamorphic origin. The grading effect is therefore of no value in determining the younging direction, since the significance of the original compositional differences is not known. Specimens 646 and 647 are of this rock and are composed of over 60% diopside, occuring both as large crystals some 5mm. by 10mm. and as aggregates of small crystals, the aggregates themselves being elongated parallel to the lineation in the rock. The aggregates are clearly large crystals which have broken up. The large crystals do not show any immediately apparent preferred orientation of shape but their margins are notably fractured, the fractures being filled with muscovite. The matrix is mainly biotite with a little quartz. The biotite shows a slight schistosity, which is occasionally deflected around the diopsides.

The most reasonable explanation for these diopsides is that they are the product of the regional metamorphism of a rock of rather unusual composition. The alternative, that the diopside has grown as a response to the contact metamorphism of the gabbro magma, is unlikely since Mason describes the thermal aureole of the gabbro as being a narrow zone up to 30m. wide (1967, pg. 243), and the outcrop described above lies over 300m. away from the gabbro (Map 1). Furthermore, Mason's map (1967, Fig. 2) shows the hornfelsing concentrated in re-entrants of schist within gabbro, while this outcrop is opposite a bulge of the gabbro within the schists.

10.4 Lithologies of the Rusty Psammite.

The Rusty Psammite is a fine to medium-grained rock consisting mainly of quartz with 20-30% biotite and muscovite and minor amounts of clino-zoisite and ore minerals. The two most obvious characteristics are its fissile nature and its rusty colour, especially along fractures parallel to the schistosity. This sections of specimens such as 345 show that the ore minerals are concentrated near the fractures. In specimens 650, 350, and 345 there are late, randomly orientated muscovites.

One peculiarity seen in the north of Duoldagop is that the rocks contain aggregates of fine-grained muscovite which are shaped as triaxial ellipsoids (prolate). In specimen 640 from 502 535 there are syn-schistosity folds whose axes are parallel to the mica fabric lineation. The longest axis of the aggregate ellipsoid lies parallel to the axis of the folding, the plane of flattening of the ellipsoid lies parallel to the axial plane of the fold. A similar situation is seen in specimen 679, and is illustrated in Figures 13.16 and 13.17. Fig. 13.17 shows the ellipsoids on a surface of the hand specimen normal to the fold axis, and Fig. 13.16 shows the ellipsoids in thin section (x 10) in a similar orientation.

In the Rusty Psammite in the Waterfall zone there is a band, 30-60m. thick, of a very fine-grained greyish psammite, a very coherent rock. This is only observed between 497 491 and 507 490, just north of the marble band which lies adjacent to the Rusty Psammite. The rock, marked on Map 4 by a thin black line, is thrown into tight folds of quite large amplitude.

10.5 The Marble-Psammite series, and marbles within the Rusty Psammite.

Psammite bands:-

The psammite bands can either be massive, looking almost like a granite, or quite flaggy, being strongly banded every 3-6cm. Specimen 352 is mainly composed of quartz, (80%) and diopside (20%). Quartz-quartz boundaries are rather irregular, and quartz grains show moderate strain shadowing.

Marble bands :-

The marble bands are not pure marbles, but contain thin seams of calc-silicate material, psammite and schist. As is described later, these calc-silicate seams are thrown into tight folds. The psammite layers tend to boudin. Fig. 10.7 shows a block of Rusty Psammite within the marble and Fig. 10.10 shows the boudinage of some Psammite layers in the north

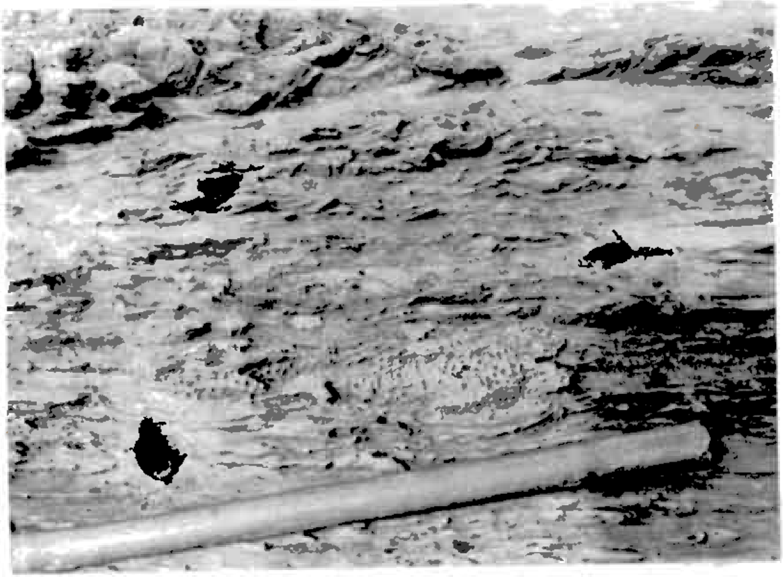


Fig. 10.6 Marble band, south Dueldagon. The marble contains rods of calc-silicate material and in this photograph, some rather organic looking material.

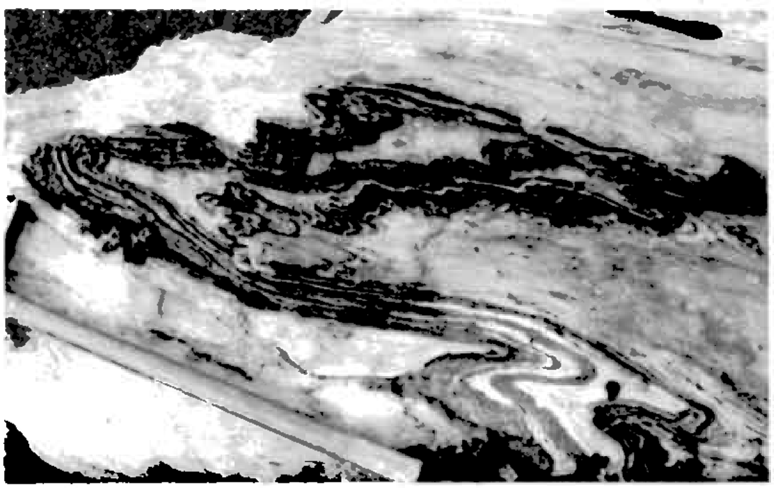


Fig. 10.7 Marble band, south Dueldagon.

Fig. 10.8 . Typical Duoldagop Banded Group

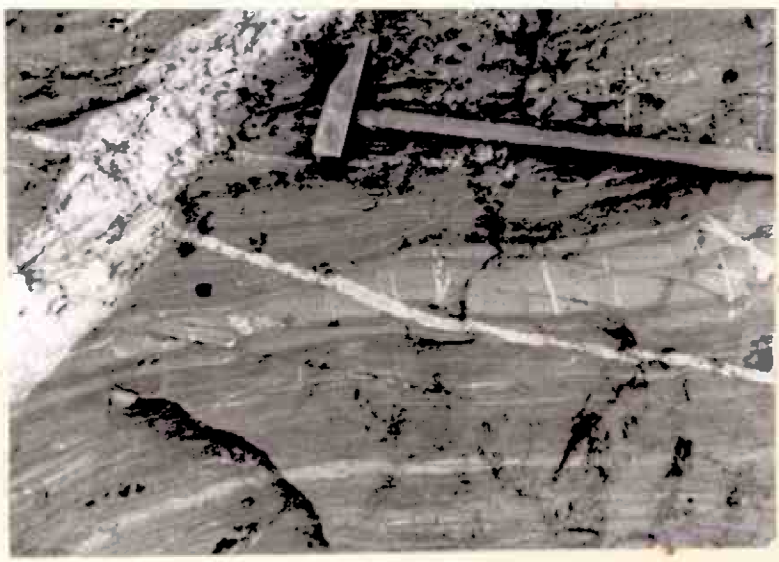
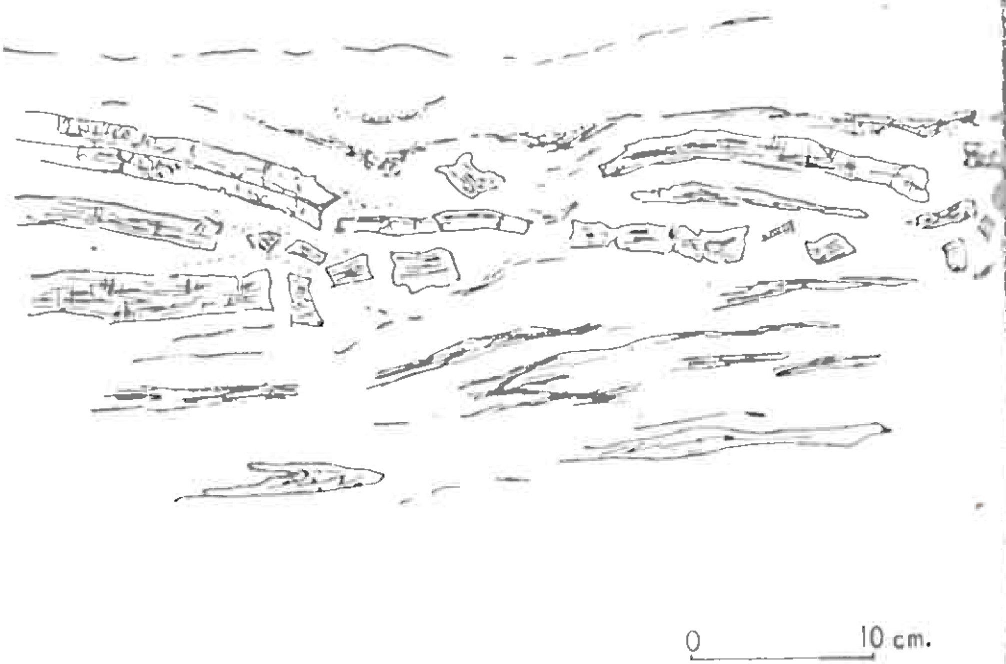


Fig. 10.9 To show the banded character of the Duoldagop Banded Group . Note several generations of quartz segregations.

FIG. 10.10 Boudinage structures in marbles within the Rusty Psammite, N.Dub

Traced from sketches in field notebooks (Book No. 15)

A. Hinge of syn-schistosity fold of psammitic material. ($\times \frac{1}{2}$)



B. Boudinage of thin bands of psammitic material.

of Duoldagop. Fig. 10.6 shows an irregular mass which has an organic appearance. Specimen 636 is from a highly folded band of calc-silicate material in the marbles at 496 492 and is composed of about 50% calcite with twin lammellae, the rest consisting of randomly orientated stubby grains of biotite, together with white mica and quartz, plus some very fine-grained opaque matter. Specimen 351 is a marble from 493 491. The main mineral is calcite, with about 10% of a colourless amphibolite, possibly tremolite-actinolite. There is a trace of white mica. The calcite grains are irregular in shape and unequal in size.

Calc-silicate bands:-

There occur in some places thin bands of medium-grained rock, comprising light-green calc-silicate minerals. These minerals have a random orientation. Specimen 353 (see section G on Map 4) is from such a band and is made up partly of tremolite-actinolite, and partly of very large clinozoisites (1-2mm.). The clinozoisites are very close-packed together, forming white patches in the rock.

Marble bands within the Rusty Psammite:-

These marble bands sometimes contain calc-silicate and psammite layers which are folded or boudined, as in Fig. 10.10. In the north of Duoldagop marble bands are more common, as is shown in map 7, (marbles marked in black). The bands in the north are frequently good pure marbles, white to light blue in colour.

10.6 Duoldagop Banded Group.

This rock group has a uniform distinctive lithology. Layering is the most obvious feature, being unusually regularly developed, the colour alternating slightly every 3-8cm. as in Fig. 10.8 and Fig. 10.9, and in Figures 13.22 and 13.23 of folds. The rock is usually grey, very coherent, with only a very poor schistosity. The main minerals are quartz and biotite, with occasional aggregates of muscovite. Despite Mason's name for these rocks - the calc-silicate group of Duoldagop - minerals such as clinozoisite or calcite are extremely rare.

Specimen 677 is the closure of a minor fold in the north of Duoldagop at 507 524. Over 90% of the rock is quartz and biotite, these two being present in equal proportions. There is about 5% muscovite in ellipsoidal aggregates. Also present are a few grains of clinozoisite and two garnets. The quartz and mica are present as small equant grains, the biotites showing only the slightest trace of preferred orientation. One of the garnets has small equant quartz inclusions, the other garnet is like an atoll garnet (Sturt and Harris, 1961), only present as a ring, the centre being filled with quartz. The adjacent matrix is biotite rich.

Specimen 603 is also taken from the hinge of a fold, south of the upper Duoldagop lake at 520 497. Again over 90% of the rock is biotite (in stubby grains) and quartz. Represented by only one or two grains are ore minerals, hornblende(porphyroblasts), calcite, clinozöisite and kyanite. It is a rock with a definite schistosity, parallel to the axial plane of the fold. In hand specimen there appear to be large grains of biotite, but these are in fact clusters of small biotites. The random equant inclusions in the hornblendes suggest static post-schistosity growth.

10.7 Rocks above the Rusty Psammite west of Kobbertoppen.

These rocks have only been given the most superficial examination. In the area NW of the Furulund granite (western body) a traverse was made across the first 200m of schists above the granite. After about 10m. of fine-grained clino-zoisite - mica schists representing the uppermost part of the

Lapphelleren schists, and about 3m. of rusty weathering schist representing the Rusty Psammite, there are a variety of schist types, the most common being very coarse-grained, almost a gneiss. Also very common is a medium-grained, grey flaggy quartz-mica schist. The highest levels examined were a thin series of marbles, with rusty weathering psammites, amphibolites and schists. This series, and rocks higher in the sequence have been affected by minor scale post-schistosity folding.

Specimen 481 is an example of the coarse-grained gneissic rock. It is composed of about 40% quartz, 20% biotite and 20% garnet, with lesser amounts of muscovite, chlorite and plagioclase. The plagioclase, with some of the quartz, forms segregations which are strongly deformed, the schistosity being compressed around them. The garnet is in small euhedral grains, with no inclusions round the edge, but a few minute quartz grains in the centre. The chlorite is replacing the garnets, some garnets not being completely replaced.

CHAPTER 11

MINERAL GROWTH IN THE SULITJELMA SCHIST SEQUENCE

11.1 Introduction.

The Lapphelleren schists usually show a good schistosity-lineation fabric though characteristically the surfaces are not as smooth or as regular as those in the Furulund schist. The Rusty Psammite shows a moderate schistosity-lineation fabric, the rock being poor in mica. The Duoldagop Banded Group appears only to develop a schistosity in the hinges of early folds. It is, however, quite a micaceous rock.

In the Sulitjelma Schist Sequence porphyroblasts are virtually restricted to the Lapphelleren schist. Aggregates of small muscovite grains, probably representing deformed muscovite porphyroblasts do occur, however, in both the Rusty Psammite and the Duoldagop Banded Group. Therefore most of the discussion in this chapter will be restricted to the Lapphelleren schists, and to samples collected in the area around Lapphelleren and the Waterfall zone.

In the Lapphelleren schists are porphyroblasts of garnet, staurolite and kyanite, though the latter is more usually represented by pseudomorphs. Fig. 15.2 relates mineral growth to deformation.

Biotite.

The L-S tectonite fabric of the Lapphelleren schists is clearly displayed in Fig. 10.4, a plot of poles to biotite cleavage in a specimen from Lapphelleren. These rocks, near to the Sulitjelma gabbro, show a fabric nearer to an L tectonite, though no measurements of intensity have been made. The lineation formation is discussed in Chapter 16.4, pg. 151.

Within 20-30m. of the Furulund granite the shape of the biotite grains is unusual, the grains being quite stubby, with length two or three times thickness, as compar ed with ten or twenty times thickness elsewhere. The degree of preferred orientation was also less.

11.3 Muscovite.

In the majority of specimens there is a small quantity of muscovite orientated to give an L-S tectonite fabric as in Fig. 10.3. Occasionally muscovite is more abundant than biotite. Specimens from within 2-3m. of the Furulund granite contain large numbers of randomly orientated porphyroblasts. Elsewhere porphyroblasts of muscovite were absent, in contrast to the Furulund schist.

11.4 Chlorite.

Chlorite is rare in the Lapphelleren schists. It is seen in specimens from the Waterfall zone in which garnets were altered, though such alteration was exceptional.

11.5 Clinozoisite.

Clinozoisite is not a common mineral in the Lapphelleren schist. It is found in some of the finer-grained biotite-rich schists near the bottom of the sequence at, and east of Lappehlleren, (see Chapter 10.3 , page 105). It is present as small well shaped grains with no inclusions, and has anomalous blue birefringence.

11.6 Garnet.

Garnets in the Lapphelleren schist are distincly different from those in the Furulund schist on the grounds of their inclusion fabric, and their relation to the external fabric. On these grounds several different types of garnet can

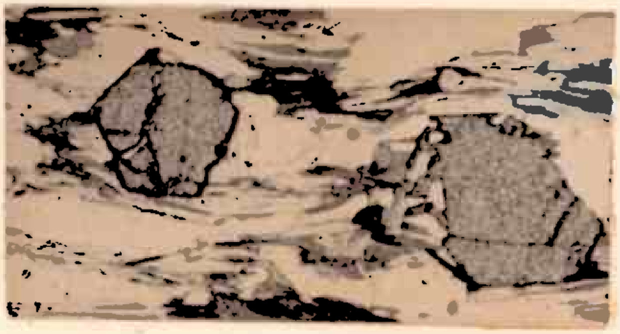


Fig. 11.2 Specimen 32 x20.
Small garnets with well-developed crystal faces. No inclusions. Lapphalleren schists.

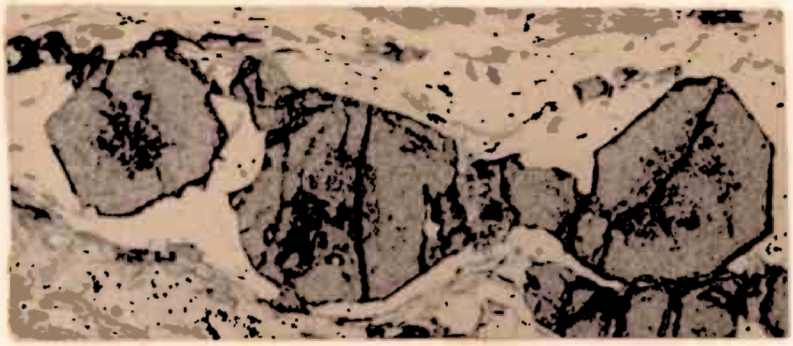


Fig. 11.3 Specimen 92, x60 ordinarly light. Garnets with well developed crystal faces and small inclusions in their centres.

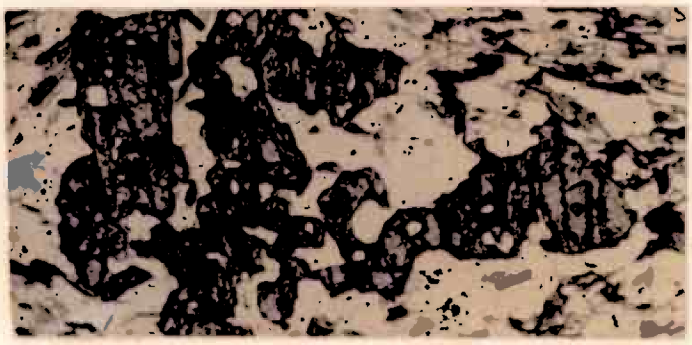


Fig. 11.4 Specimen 63, x40. Garnet with large inclusions having a spongy appearance. Lapphalleren schist.

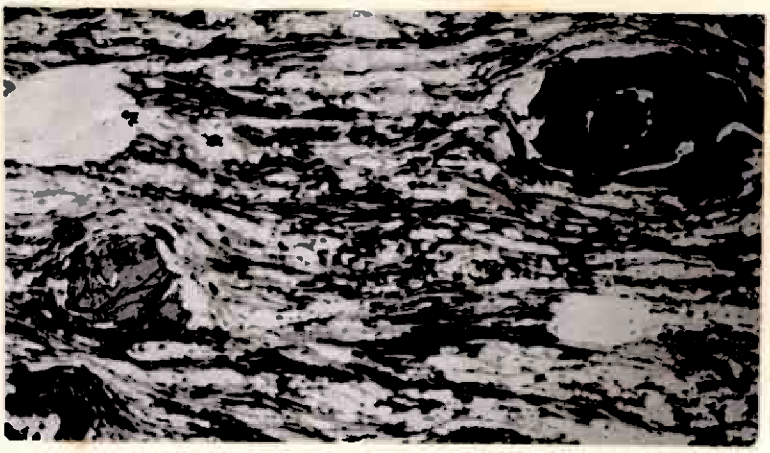


Fig. 11.5 Specimen 206, x 10. Garnets with large inclusions. The trails indicate syn-kinematic growth.

be seen within the Lapphelleren schist. Firstly there are small euhedral garnets without any inclusions. These are usually so small in relation to the schistosity that there is no evidence of post-garnet compression in the majority of cases, such as in Fig. II.2.

Some rocks have slightly larger garnets, with minute inclusions in the centres, having a random pattern. There is more evidence of post- garnet compression in these, as is shown in Fig. II.3, from specimen 92. Specimen 734 contains a euhedral type of garnet with fine inclusions which indicate that this garnet grew after folding of the biotite fabric (fig. II.9).

Distinctly different are large garnets with inclusions of quartz and sillimanite which are the same size as quartz grains in the external fabric. As a consequence these garnets have a somewhat spongy appearance, as is shown in Fig. II.4. The inclusion patterns sometimes indicate more or less static growth, as in specimen 17, static growth followed by compression, as in specimen 63 or growth during a slight deformation, specimen 47- non-rotated, specimen 30, rotated.

In the Waterfall zone are garnets which have a few large inclusions, and these garnets, illustrated in Fig. II.5, appear to have grown during deformation. The schistosity is clearly compressed around these garnets. Also in this area are garnets such as are illustrated in Figures II.6, II.7 and II.8, which appear to have grown over the very sparse coarse grains of biotite in this rock. Where the biotites are folded the garnet has overgrown the folds.

Virtually all the garnets have grown before a slight compression. Two distinctly different types of garnet have overgrown post-sc histosity folds in the Waterfall zone- specimens 359 and 734 , shown in Figures II.8 and II.9, and this evidence narrows the available time for the growth of these two types of garnets. It is probable that all the garnets are approximately coeval, and that local differences in grain size and rate of growth may have resulted in different styles of garnets.

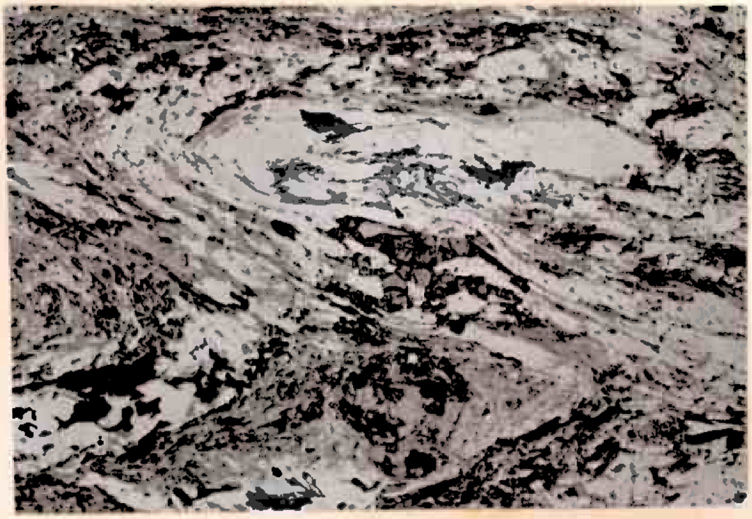


Fig. 11.6 Specimen 732 x15. Plane polarised light. Tight fold in Waterfall zone (south Duoldagop) Lappholleren schist.

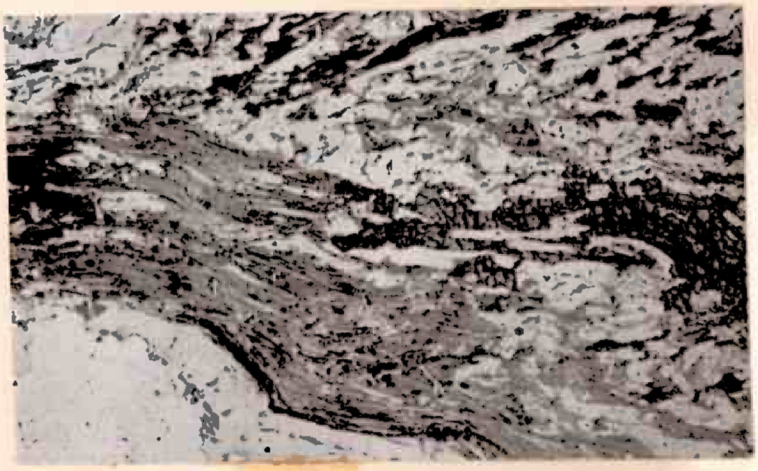


Fig. 11.7 Specimen 359. x20. The garnet here appears to have replaced the large biotites in this rock and consequently has a stringy appearance.

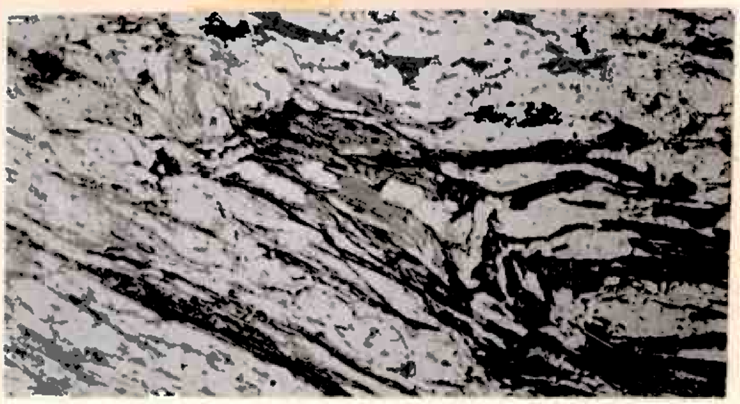


Fig. 11.8 Specimen 359. x 20. The garnet has grown over a post-schistosity fold of biotite. Lappholleren schist, south Duoldagop.

Fig. 11.9 Specimen 734. The garnet has grown over a post-schistosity fold. The outline of the fold can be seen in the inclusion trail pattern .

11.7 Hornblende.

Hornblende porphyroblasts were not seen. Groundmass hornblende was seen in rocks at Lapphelleren, as is described in Chapter 10.3.

11.8 Staurolite.

Staurolite is only occasionally present. It is seen as porphyroblasts with inclusions but there is not sufficient evidence to determine the time of its growth with certainty. In specimen 33 (Fig. 11.10,) staurolite has grown over biotite which is compressed around kyanite pseudomorphs, suggesting that staurolite growth was later than kyanite. Alternatively Mason (1966, Fig. 5.11) and Henley (1968) regard staurolite and kyanite growth as approximately coeval. In particular Mason found staurolite with kyanite in the hornfels zone of the Sulitjelma gabbro indicating that the two minerals had grown prior to gabbro injection. In most of the samples examined the staurolite had straight inclusion trails. Although the evidence is not at all conclusive, the staurolite growth is marked on Fig.15. 2 . as being early.

11.9 Sillimanite.

Needles of fibrolitic sillimanite are frequently seen, and show a high degree of preferred orientation. In specimen 11 fibrolite needles are seen as inclusions within garnets. In specimen 359 , illustrated in Fig. 11.11, sillimanite is seen to be orientated with the needles lying in the plane of a post-mica fold, one of the minor folds of the Lappehelleren schists in the Waterfall zone. Fibrolite is especially common as felts around kyanite grains . Mason placed the growth of prismatic sillimanite immediately after the intrusion of the gabbro complex and before the development of the D2 deformation event, as discussed in Chapter 13 .5 . The growth of fibrolite he regarded as a late event.

11.10 Kyanite.

Pseudomorphs after kyanite are very common in the Lapphelleren schist. They occur particularly in a band about half-way between the Sulitjelma amphibolite and the Furulund granite (western body), and are very common in the Waterfall zone. They are very common round the eastern margin of Duoldagop and Mason maps the Lapphelleren schists here as 'kyanite schists '. The pseudomorphs are usually well orientated parallel to the mica lineation. In the Waterfall zone they are folded by the tight post-schistosity folds, as can be seen in Fig. 14.13. In thin section the pseudomorphs are made up mainly of quartz and muscovite with occasional grains of kyanite still preserved in the middle. In the cutting of thin sections these kyanites tend to be torn out, since they are surrounded by relatively soft muscovite.

Since Mason finds kyanite in the hornfels zone around the Sulitjelma gabbro he places the growth of kyanite as pre-gabbro, and this is followed here.

CHAPTER 12

IGNEOUS INTRUSIONS

Intruded into the Sulitjelma Schist Sequence are the Furulund granite, the Sulitjelma gabbro and several small granitic dykes.

12.1 Granitic dykes.

Dykes or veins of granite up to 2m. thick are found in the north of Duoldagop and are marked on Map 1. Though they clearly cut across bedding and schistosity, it is impossible to tell if they are earlier or later than the post-schistosity folding. No specimens were collected. Sjögren (1900) marks some dykes of tourmaline granite in the south-west of Duoldagop and also to the west of the thesis area. Holmsen(1917) found them to the north-east in Skagmadalen (pg. 15). The dykes are mentioned by Vogt (1927 pg. 84 and pp. 268-270). Vogt suggests that their lack of any schistosity indicates that they are perhaps the youngest igneous rocks in Sulitjelma. He refers to them as tourmaline-rich granite.

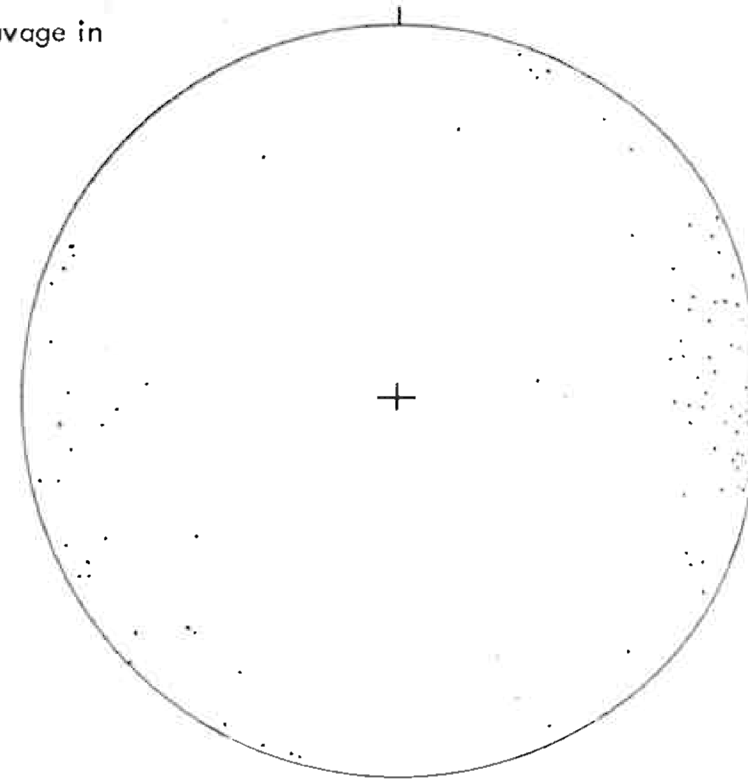
12.2 The Furulund granite.

Mentioned by Vogt (J.H.L.) in 1890, the granite was described in detail by Nordenskjöld in a separate paper in 1895. Vogt (Th.) (1927) described it in detail (pp. 155-160, form and intrusive relationships, pp. 249-256, petrology and petrography.)

Extent:- The granite occurs as two separate lenses as shown on Map 1, which are referred to here as the eastern and western bodies. A third body of granite occurs on the western side of Duoldagop in the far north and is marked on the 1:40,000 index map with Map 1. Sjögren suggested that the highly deformed character of this third body indicated an Archæan age, but Vogt(1927) did not think that this was so. He did not, however, include this granite with

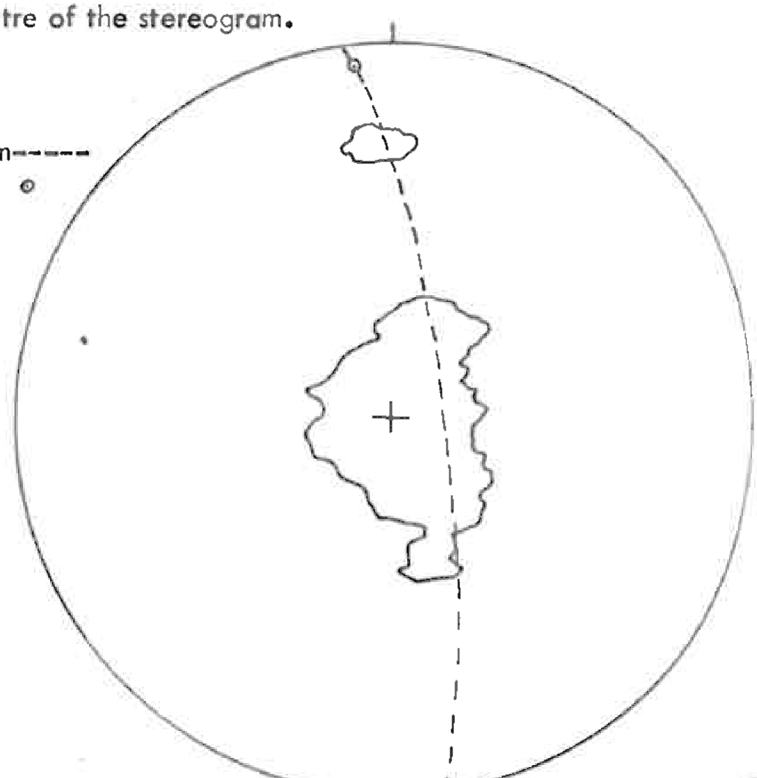
FIG. 12.1 Biotite fabric of the Furulund granite (western body).

100 poles to biotite cleavage in specimen J23.



5% contour of above plot rotated so that the maximum concentration of poles lies at the centre of the stereogram.

Primitive on above diagram-----
'north' on above diagram ⊙



the Furulund granite. It appears to be a similar rock and probably is related to the Furulund granite, though only one brief visit has been made to its outcrops in the course of this investigation.

West of Bursi the western granite body thins to a matter of tens of metres and can be seen in Map I and Fig. I.3 to continue as far west as Rupsi Elv. Fig. I.3 shows that between Bursi and Grönli the granite appears to be in the form of a series of small lenses. Sjögren has mapped the granite as far west as north of Hellarmo, but according to Nicholson (pers. comm.) the granite is not present when all the Sulitjelma rocks dip steeply under the Fauske marbles east of Sjönstå. South of Langvann the granite can be traced as a series of lenses some tens of metres thick right round the Baldaoive plateau according to the maps of Sjögren (1900), Vogt (1927) and Dybdahl (1951). The 'sill' therefore has considerable areal extent.

12.3 Contacts.

As previous workers reported, the granite margin is usually parallel to the bedding and schistosity outside, but there are exceptions, particularly above Fjeldsgrube, at the eastern end of the western body where the lense thins out completely, and the margin cuts across both bedding and schistosity (see Map 4). One kilometre west of Lapphelleren (at 462 480) and two kilometres west of Lapphelleren (at 455 480) the contact cuts across bedding as shown on Map I. The concordant character of the contact at 440 490 is shown on Map I .

The intrusive character of the contact is demonstrated by the frequent apophyses of granite. Veins of similar granite are frequently found in the adjacent schists. These are boudined or folded. The actual contact is always knife sharp.

There is very little trace of any contact effects on the country rock. At the contact north of Lapphelleren the adjacent schists are much tougher rocks than is usual and this is partly due to the high proportion of random muscovite, unusual for the Lapphelleren schist and partly because of the low degree of preferred orientation of the biotites.

12.4 Mineralogy.

The main part of the western body is notably massive and homogeneous. The granite is usually white and medium to coarse-grained with large conspicuous microclines. Other minerals present are quartz, plagioclase and biotite, with accessory amounts of muscovite, clinozoisite, sphene and garnet, though the latter is rare. Occasionally seen are varieties lacking the coarse microclines or of slightly different grain size. The western body shows a marginal facies which lacks the coarse microclines and is finer-grained than usual. Bands of slightly differing appearance at the margin appear to be sheared out, and the margin as a whole appears to have suffered greater deformation than the rest of the granite. The eastern granite is notably less homogeneous than the western body.

12.5 Fabric.

The mica shows a preferred orientation giving the rock an L-S tectonite fabric as is shown for the western body in Fig. 12.1. In this western body the lineation element is not apparent in hand specimen. Xenoliths lie with their longest dimensions parallel to the schistosity of the granite. The eastern body is notably lineated, though this has not been analysed by petrofabric measurement. Xenoliths in the eastern granite lie with their longest dimension parallel to the lineation. The granite commonly shows a mullion structure. This eastern granite lies adjacent to the Sulitjelma gabbro and the strong lineation seen in rocks adjacent to the gabbro is interpreted as being caused by the unusually high strain suffered by rocks adjacent to the relatively undeformed gabbro. The lineation is parallel to the axis of the fold which has folded the

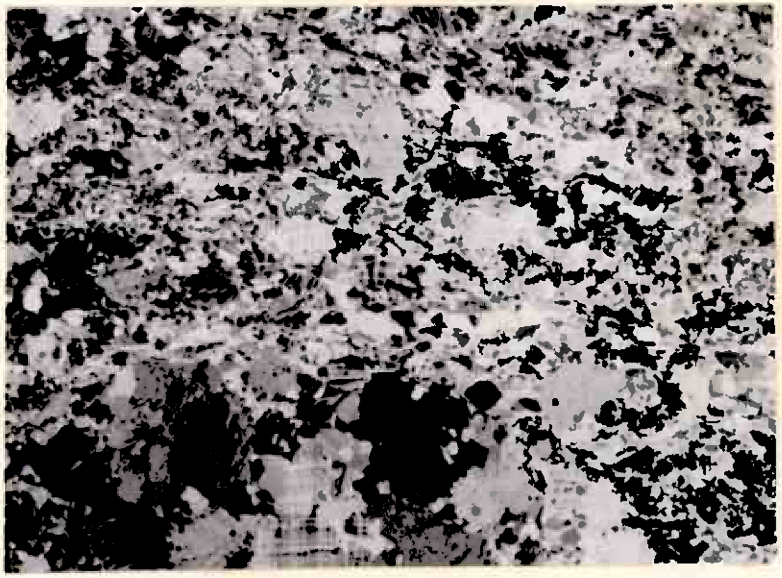


Fig. 12.2 Specimen 186 x15 Crossed polars.
Fabric of the Furulund granite, eastern body.

granite and the schistosity of the granite. The appearance of the granite in thin section (Fig. 12.2, of specimen 186) suggests that much of the deformation is quite late; the large grains show strain shadowing, development of fractures and granulation at the edge, while the fine matrix is sometimes so intensely granulated that the finest grains cannot be resolved under the microscope. Not much recrystallisation has followed the deformation. It is therefore suggested that the lineation may be of a different generation from the schistosity, having been imposed upon it during the post-schistosity folding episode.

The western granite is crossed by frequent shear zones and joints. There are frequent small veins of lighter coloured granite parallel to the joints. These features are nearly all vertical and generally have an azimuth in the range 314- 145°. This is parallel to one of the main directions of jointing in the schists as recorded by Holmquist in Vogt(1927). It is also parallel to the faults in the Waterfall zone, the azimuths of which are around 315°.

12.6 Xenoliths.

As mentioned by Nordenskjöld the granite contains a considerable number of xenoliths, (for example, 2cm. by 10cm.) with a few larger ones occasionally. The two largest ones are marked on Map I. One of these, in the east of the western body at 476 489 is a band of schist about 5m. thick and some 10m. long, length parallel to schistosity, its ends not exposed. It consists of fine-grained epidote-biotite-garnet schist similar to that found above and below the granite and contains boudined granite veins. There is no folding to be seen within it. In the west of the western granite there is a long strip of schist completely within the granite. Small xenoliths were difficult to extract, often lying in the middle of flat ice-smoothed surfaces. Specimens 12 and 13 are of a small xenolith of graphitic schist (graphite, quartz, muscovite and biotite). The graphite occurs as long streaks which have been folded, the axial plane of the folding being parallel to the schistosity of the enclosing granite. This suggests that the fragment was folded after incorporation into the granite. Considerable deformation of the granite after intrusion is indicated by its penetrative fabric, by the above mentioned folding inside a xenolith, and by the orientation of the xenoliths.

12.7 The age of the intrusion of the granite.

That the granite has suffered considerable deformation after intrusion has been established above. The main evidence for the age of the granite comes from its relation to the Sulitjelma gabbro, the age of which is known (Mason, 1966). On the evidence of veins of granite cutting into the gabbro the granite is taken to be younger than the gabbro. This is discussed by Holmquist (in Vogt, 1927), by Holmsen (1917), Vogt (1927), and Mason (1966). Some of Vogt's evidence must be discounted since he is describing (on page 158) involvement of the granite within the Flaser gabbro, a tectonic unit developed much later than gabbro or granite intrusion. Mason, however, has described veining of the true gabbro by granite. An alternative here could be that this is back-veining caused by remelting of the granite by the heat of the gabbro magma. Since Mason (1966) has described folds inside xenoliths which lie in undeformed gabbro, the granite almost certainly was intruded after the first deformation and prior to the second major deformation.

The relation of the granite to the problematical fold in the Waterfall zone depends on the interpretation adopted of the form of that fold (see page 104). If the fold is an 'M' type fold then the granite lies near to its axial plane and intrusion must be later than the folding. If, on the other hand, the fold is a 'Z' type then the granite could be earlier than the folding and indeed the relative inhomogeneity of the granite may have been a factor in the generation of the fold. Evidence discussed in section 10.2 suggests that the fold is more likely to be a 'Z' type fold. The implications of a post-schistosity 'M' type fold are that the granite was intruded after two phases of deformation and prior to two, thus requiring a total of four periods of deformation for the Sulitjelma Schist Sequence. The complexity of such a scheme argues against it.

12.8 The Sulitjelma gabbro.

According to Mason, the Sulitjelma gabbro complex consists of a body of olivine gabbro with primary igneous layering preserved in parts. This layering is discordant with the bedding and schistosity outside the gabbro and with the contacts. Xenoliths and rafts within the gabbro contain early folds indicating that the gabbro was certainly intruded after the first deformation. Contact hornfels zones contain relict kyanite and staurolite indicating that intrusion came after the growth of these minerals. The southern margin of the gabbro has been highly deformed and now forms part of the flaser gabbro zone. This zone shows an unusually intense development of the regional lineation and schistosity fabric. Mason(1967) suggests that this zone of intense deformation represents the Gasak-Vasten thrust horizon of Kautsky. Later unpublished work suggests that this interpretation may be incorrect since in Sweden Mason (pers. comm.) has found the gabbro cutting across the level at which Kautsky suggested that there was thrusting. The critical area for this assertion, however, has not yet been mapped in detail.

Mason suggests that although the gabbro has not been deformed to the same extent as the country rock, it has been folded. Mason, however, has a different interpretation of the age relations in Duoldagop from that developed in this thesis. He postulates that the gabbro was intruded after the D1 deformation, during which the structures in the rafts and xenoliths were formed. Then followed a D2 event which was much more intense, the result of which was to form the early Duoldagop synform, and to give the rocks their penetrative schistosity. During this deformation all traces of the earlier deformation were lost ouside the protected xenoliths. Finally there was a D3 deformation in which the gabbro was folded and the Duoldagop synform was converted into a basin structure. Discussion of this will be delayed until the folding has been fully described.

FIG. 13.1 Bands of diopside rich schist within the rusty psammite in North Duddingston (see map 7). Photograph taken looking west. Fig. 13.2, below , shows the false graded bedding suggesting younging to the south

FIG. 13.2

CHAPTER 13

EARLY FOLDS OF THE SULITJELMA SCHIST SEQUENCE

13.1 Introduction.

A major fold, which is interpreted to be a synform, can be identified in Duoldagop, and is termed the Duoldagop synform. Minor folds related to the major structure lie with their axial planes parallel to the regional schistosity, and so the major fold is assumed to be of syn-schistosity age.

The styles of the minor folds vary considerably in the different lithologies, and in the following sections the styles developed in the different lithologies are described, while in the concluding section the attitudes are discussed.

13.2 Styles of minor folds in the Lapphelleren schists.

Syn-schistosity minor folds in the Lapphelleren schists are only rarely seen, but as Map 1 indicates, examination of the Lapphelleren schists in many parts has only been of a cursory nature and it is estimated that the folds are likely to be more abundant.

Folding was seen in the north of Duoldagop, in the diopsidic band described on page 107. Their position on the major fold suggests that they should be overturned to the north-east (see Map 7), but they appear to be on a hinge, opening to the south. The style is illustrated in Figures 13.1 and 13.2. Some of the diopside crystals in the rock have been granulated, the aggregates having their longest dimension parallel to the fold axis and their shortest dimension normal to the axial plane of the fold. This deformation can be seen in the photographs of the hand-specimen cut at different attitudes, Fig. 10.5 .

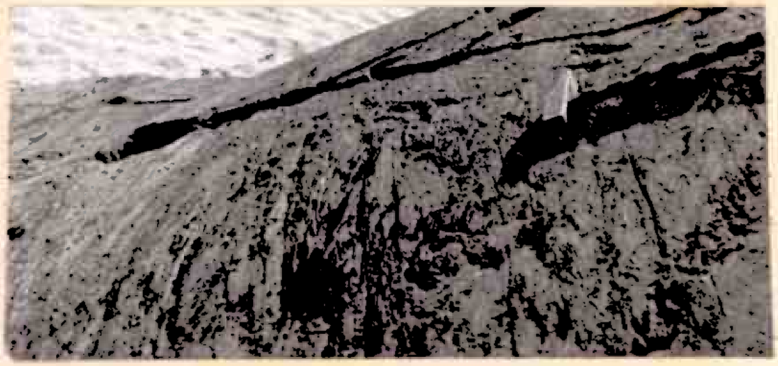


Fig. 13.3

Tight folds in the Lapphelleren schists just west of Lapphelleren

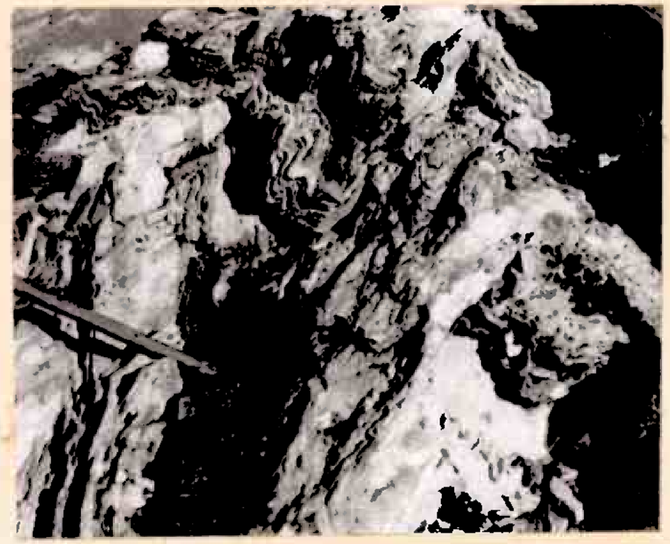


Fig. 13.5 Marble bands in the " waterfall zone"- south Duoldagop. The folds are of relatively competent calc-silicate bands.

Fig. 13.6 As Fig. 13.5

Fig. 13.7

Specimen 649, x1
Marble with calc-silicate bands. Photographed along the axis of folding.

Specimen taken from locality in Fig. 13.5.

the boundaries with other units. For this reason the folds are described as " internal folds ". The folds can be described as "elasticas " (Ramsay (1967), Wilson (1952a)) and are illustrated in Figures 13.8 and 13.9. In some exposures the hinges of the folds are plainly visible and the limbs, considerably thinned can be seen to join adjacent hinges, as in Figures 13.8, 13.9 and 13.10. In most of the exposures the limbs have been completely thinned out, the rock containing isolated hinges in a streaky matrix, as in Figures 13.11, 13.12 and 13.13. In these rocks it is difficult to determine the sense of overturn of the folding, but there is scope for more field-work here. In some of the exposures of marble not even the hinges of the folds could be positively identified, the rock merely containing linear rods of calc-silicate material.

The available evidence suggests that these internal folds are of syn-schistosity age. In specimens 735 and 736, the axial plane of the folds appears to lie parallel to the schistosity fabrics of the biotites, but the fabric is indistinct in these rocks. At one locality there are folds of marble and of Rusty Psammite in which the axis of the internal folding of the marble is parallel to the axis of the fold in the Rusty Psammite (see Fig. 13.14). The vergence of the internal folds agrees with the position of the small minor folds on the larger fold of Rusty Psammite. In this case it is certain that the fold of Rusty Psammite is syn-schistosity and therefore it follows that the folds of marble are syn-schistosity also.

In addition it may be argued that a rock showing such a variation in competence, having relatively competent thin bands in a weaker matrix would respond readily to deformation. The first deformation phase would result either in boudins or folds and subsequent deformations would only modify the structure formed in the first event.

These internal folds are not restricted to the Waterfall zone, and are found in the marbles lying within the Rusty Psammite. Their wide distribution makes them of great use in studying the variation in axial attitudes over the area.

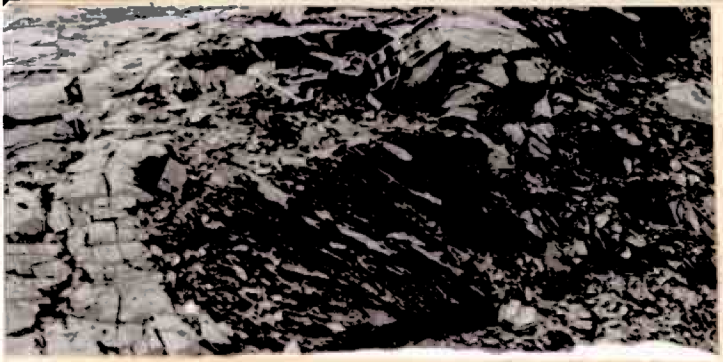


Fig. 13.14 Fold of Rusty-Psammite and marble. 'Internal' syn-schistosity folds in the psammite agree in attitude and sense with the the large fold. Nath of Kobbertoppen.

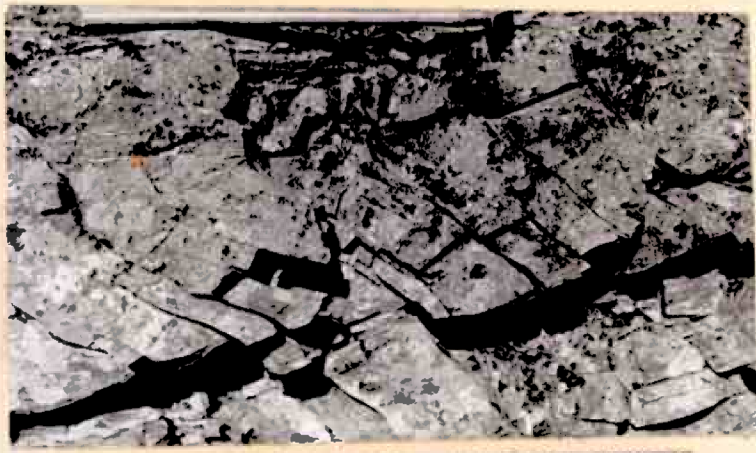


Fig.13.15 Fold in Rusty Psammite Waterfall zone.

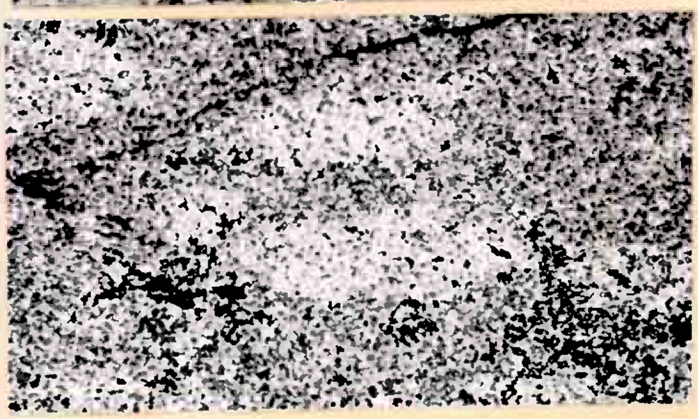
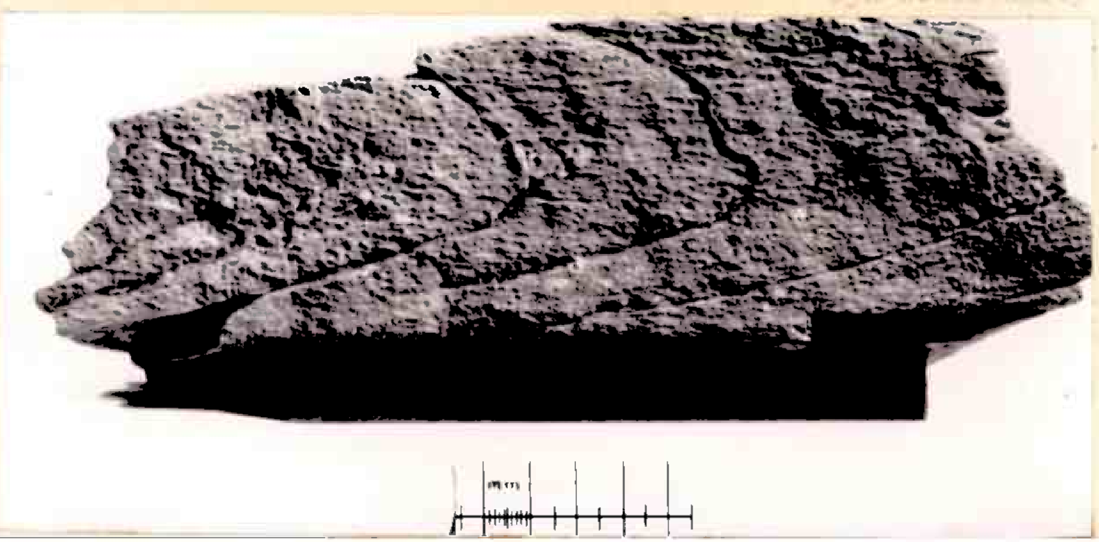


Fig. 13.16 Specimen 674, x7, crossed polars. Mostly quartz and biotite and biotite, but there are ellipsoidal aggregates of quartz and muscovite.

Fig. 13.17(below). Specimen 679. Showing aggregates of qtz. & muscovite as in fig 13.16. Syn-schistosity fold.

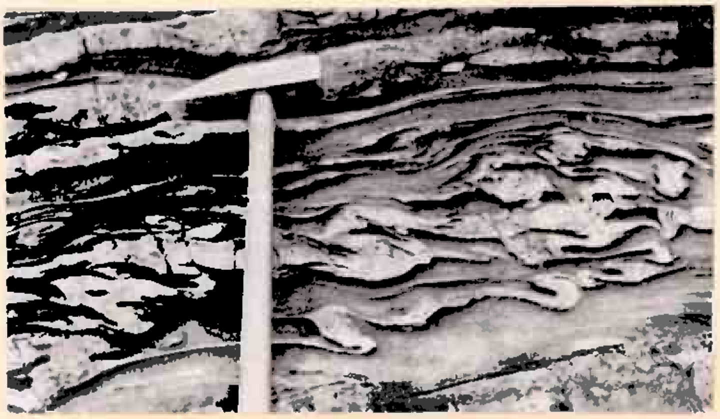


The only other folds of this age in the Lapphelleren schists are in the Lapphelleren area. The lowest lithology seen in the stream section (see page 105) is a biotite-clinozoisite-quartz schist and there is a small fold, collected as specimen 35. The fold has an east-west axis and is overturned to the north. Nearby there is a considerable amount of folding on glacially smoothed surfaces, as is shown in Fig. 13.3 but axes could not be measured or specimens collected. Other early folds are illustrated in Fig. 13.4, and had an east-west azimuth.

13.3 Styles of minor folds in the Marble-Psammite Series.

The major folding of this group, discussed in Chapter 10.2, page 102, is illustrated in Map 4 of the Waterfall zone. Minor folds are very common. One type of closure occurs when the whole of a marble or a psammite band is folded. It is not easy to tell if such folds are syn-schistosity since the schistose fabrics of such rocks are not well-developed. Figures 13.5 and 13.6 illustrate the type of fold. Fig. 13.7 is of specimen 649 , the photograph being taken parallel to the axis. Such folds are only developed in the Waterfall zone in southern Duoldagop, and their location, and axial attitudes are shown on Map 4. Fig. 13.32 is a stereogram showing the axes of folds of the different units. The wide spread of axes between azimuths 315 and 050 is notable, and axes from several single outcrops are just as divergent, those from one specific locality being marked thus ⊕ . At this locality the folds were of thin calc-silicate bands within the marbles, the bands being up to 5cm. thick, folded in the same manner as the external contact of the marble. This is therefore an intermediary type between the folds of whole units and the " internal " folds which are described below.

The thin bands of calc-silicate material that are common in the marbles have been tightly folded on a small scale, the folds not affecting



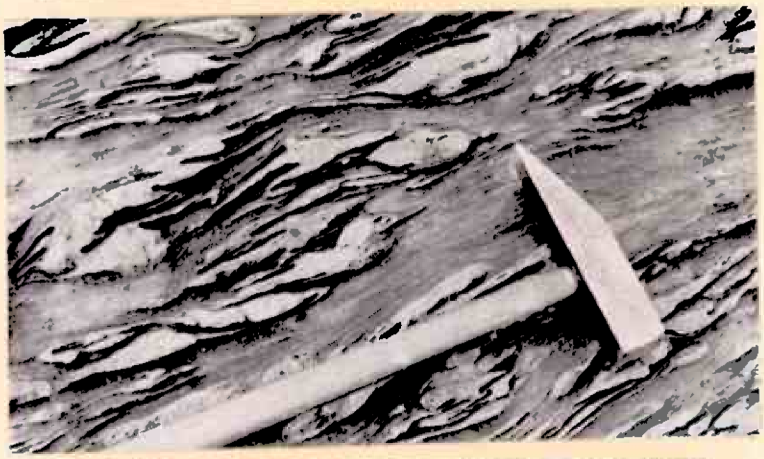


Fig. 13.8,9.Elasticas folds of calc-silicate layers in marble, Waterfall zone.

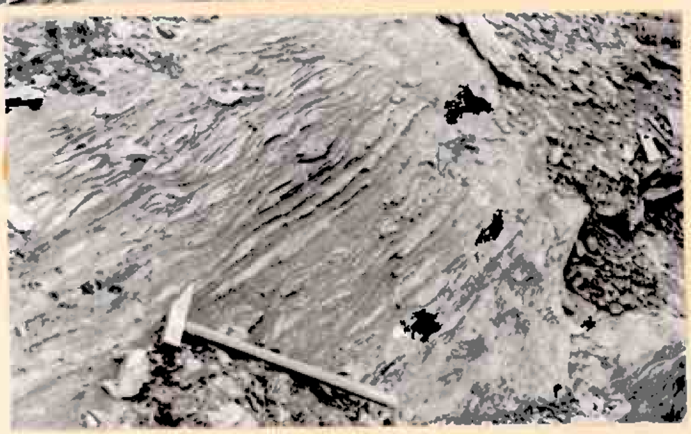


Fig. 13.12, Folds of calci-silicate layers in marble, Waterfall zone. The limbs between the closures have almost sheared out.

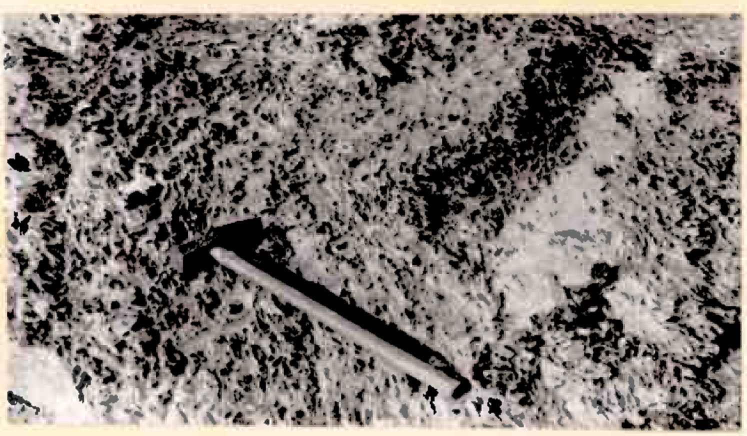


Fig. 13.13 As in Fig. 13.12, but the limbs have apparently been sheared out.

Fig. 13.18 and Fig 13.19

Syn-schistosity folds of Rusty Psammite in north Duoldagon. Fig. 13.18 is looking to the south, thus indicating a major closure to the east. See map 7.

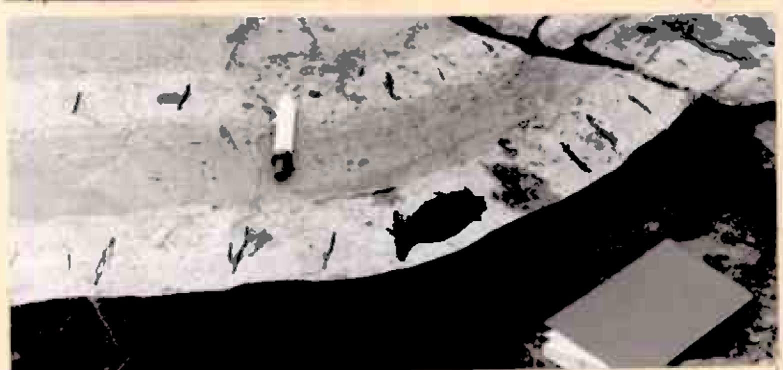


Fig. 13.20

Gentle fold of Duoldagon Banded Group. North-east Duoldagon. Note the development of two sets of tension gashes.

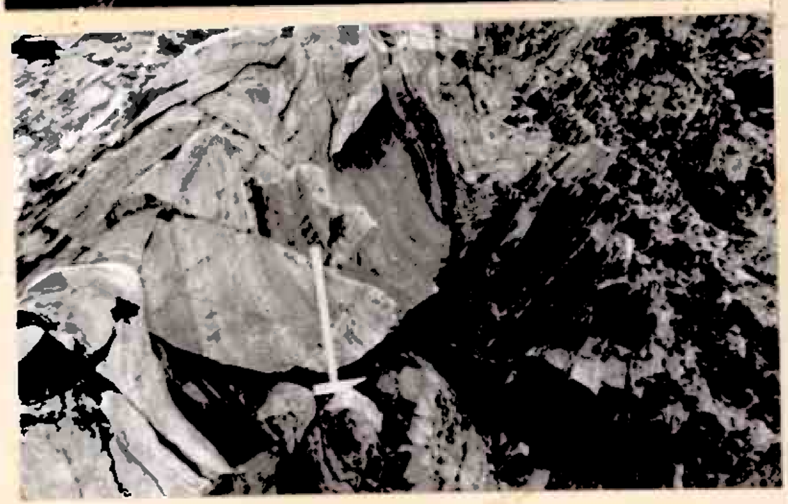
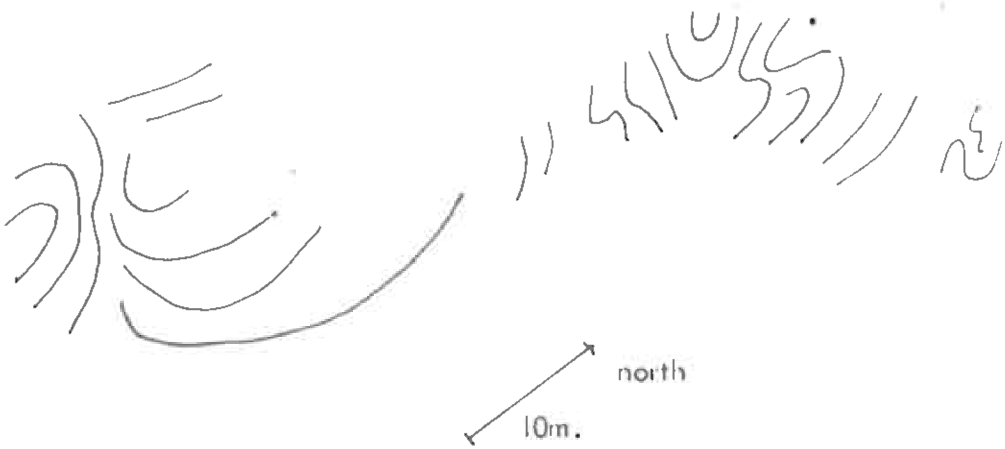


Fig. 13.21

Syn-schistosity fold of Duoldagon Banded Group., south of the Upper Lake, Duoldagon. View to N.E. Vergence indicates a syn-formal shape for the Duoldagon structure.

FIG. 13.25 Sketch map to illustrate folding of the Duoldagop Banded Group in stream section at locality with grid reference ; 511 513.



traced from sketch in field notebo...

FIG. 13.26 Sketch map to indicate estimated attitude of the axial planes of syn-schistosity folds in Duoldagop. As mentioned in the text, the Duoldagop Banded Group does not usually have a good schistosity, and the folds seen in the centre of Duoldagop are not well enough exposed to allow the axial planes to be readily determined. This map is therefore an estimate of the attitude of schistosity supposing that the rock had had a schistosity.

13.4 Styles of minor folds in the Rusty Psammite series.

Minor folds in this series are not easy to detect due to the rather uniform lithology. Slight colour differences and partings parallel to bedding indicate the folds, as in Fig. 13.15.

Folds are found in most parts of the Rusty Psammite outcrop and thus are useful in showing the variation in axial attitude over the area. The age of the folding is established from specimens 650, 642, 644, 679 and 640. Specimen 640 is very useful in correlation of the folds of the Rusty Psammite with the internal folds of the marbles, as is mentioned on the previous page.

Specimen 679, from the far north of Duoldagop (location marked on Map 2), contains ellipsoidal aggregates of small muscovites. As shown in Fig. 13.16 and Fig. 13.17, the aggregates are elongated parallel to the axis of the fold and parallel to the mineral lineation, and are flattened parallel to schistosity.

Other folds are illustrated in Figures 13.18 and 13.19. There is scope for more work on these folds since there are many more present than are represented on Map 2.

13.5 Styles of minor folds in the Duoldagop Banded Group.

Syn-schistosity folds of the Duoldagop Banded Group are seen in the east at 519 497, south of the higher Duoldagop lake, at the northern closure of the Duoldagop synform, and at several exposures on the north-east limb of that structure. Folds can be inferred in other places by the difference in attitude of bedding between exposures, the axis being constructed by a π diagram. Typical folds are illustrated in Figures 13.20 and 13.21. Figures 13.22, 23 and 24 are minor folds associated with the northern closure of the Duoldagop synform. Figure 13.25 is a sketch to show the fairly large scale folding at one locality.

The age of these folds is determined from specimens 603 and 677. In both these specimens the schistosity of the rock is only poorly developed, but is

Fig. 13.22 'M' type fold of Duoldagop Banded Group at the northern closure of the Duoldagop Synform. (Map 7).

Fig. 13.23 As above, but taken along axis of fold .

FIG. 13.30 Syn-schistosity folds in central Duoldagop.

Axes.

□ Duoldagop Banded Group.

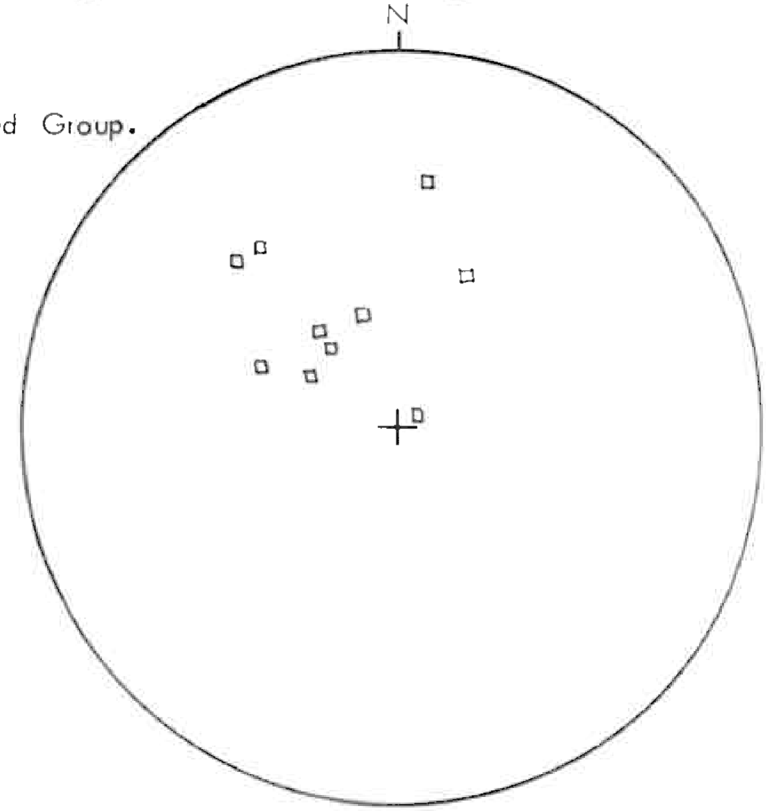


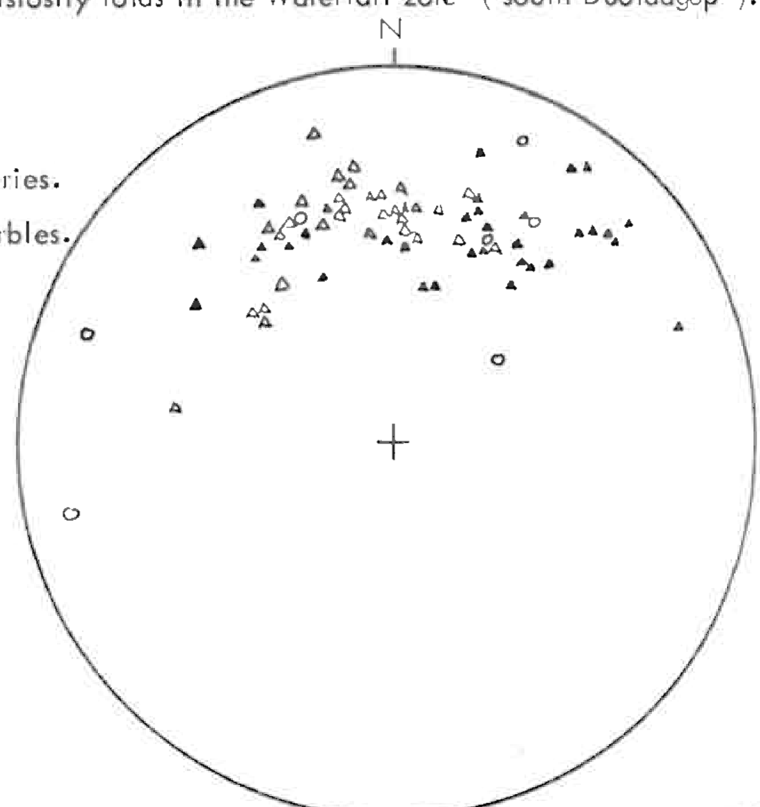
FIG. 13.31 Syn-schistosity folds in the Waterfall zone (south Duoldagop).

Axes.

○ Rusty Psammite.

▲ Marble-Psammite series.

△ Internal folds in marbles.



ldagop

plainly parallel to the axial plane of the fold, as in Fig. 13.27. Mason (1966 pg.53) has described the folds south of the higher Duoldagop lake as being folds of the regional schistosity, having a penetrative schistosity parallel to the axial plane. Since Mason refers to the regional schistosity as S2 (not, as in this account, S1), these folds are called by him F3, and the axial plane schistosity S3. Mason does not appear to make this interpretation on the evidence of thin sections, since none are mentioned, and it seems probable that Mason has confused the excellent banding in the rocks for schistosity.

It is assumed that the schistosity in the Duoldagop region if it were well developed would take the form of smoothly curving surfaces interpolated between the determined schistosity attitudes on the eastern and western margins, as in the sketch, Fig. 13.26.

13.6 The attitudes of the syn-schistosity folds.

A. The northern closure - Map 7.

The syn-schistosity minor folds in the northern closure fit the major structure. They have axes plunging almost vertically, as is represented in Fig. 13.28

B. The eastern closure.

The eastern closure of Duoldagop is clearly post - schistosity in age, as can be seen from the schistosity attitudes sketched in Fig. 13.26. The syn-schistosity folds south of the upper lake have near-horizontal axes, which lie nearly parallel to the strike of the schistosity. These folds are overturned to the south and therefore indicate that the early structure is a synform . The axes are plotted on Fig. 13. 29.

C. The southern closure of the Duoldagop synform.

This southern closure is not exposed, and consequently there is no exact evidence of location, and the attitudes of minor fold axes are unkown.

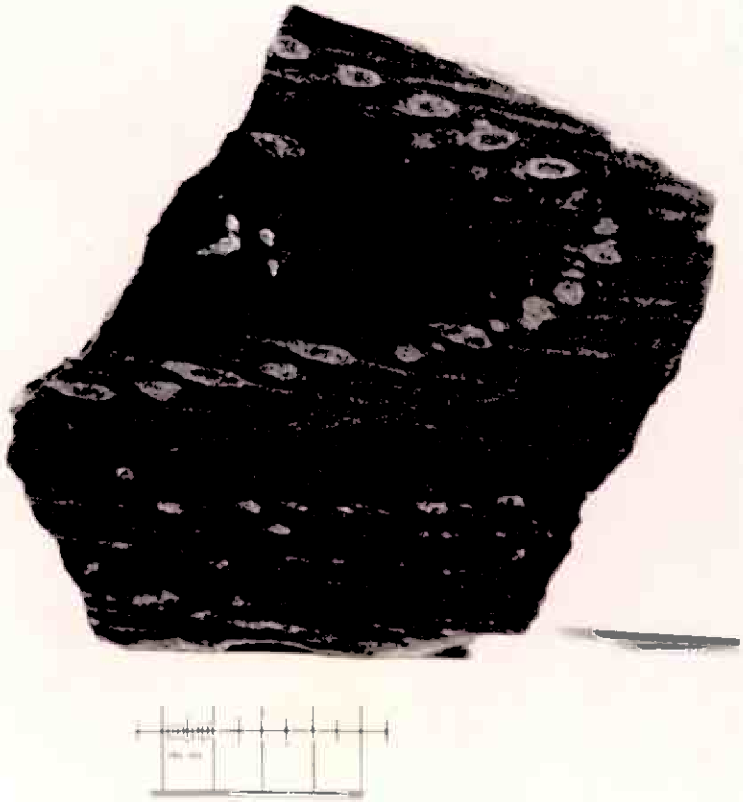


Fig. 13.24 Specimen taken from the closure of the Dholdogop Banded Group seen in Fig. 13.23 and 13.22. x½.

FIG. 13.28 Syn-schistosity fold axes from the northern closure of the Duoldagop synform, north Duoldagop.

Axes:-
□ Duoldagop Banded Group.
△ Rusty Psammite.
○ Marbles.
▲ Lapphelleren schist (diopsidic rock).

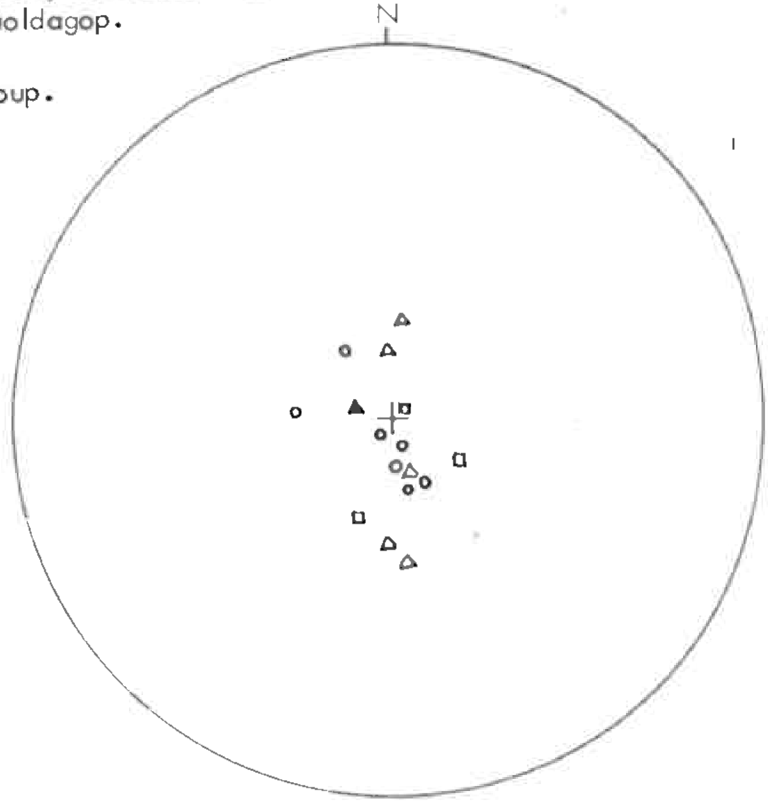
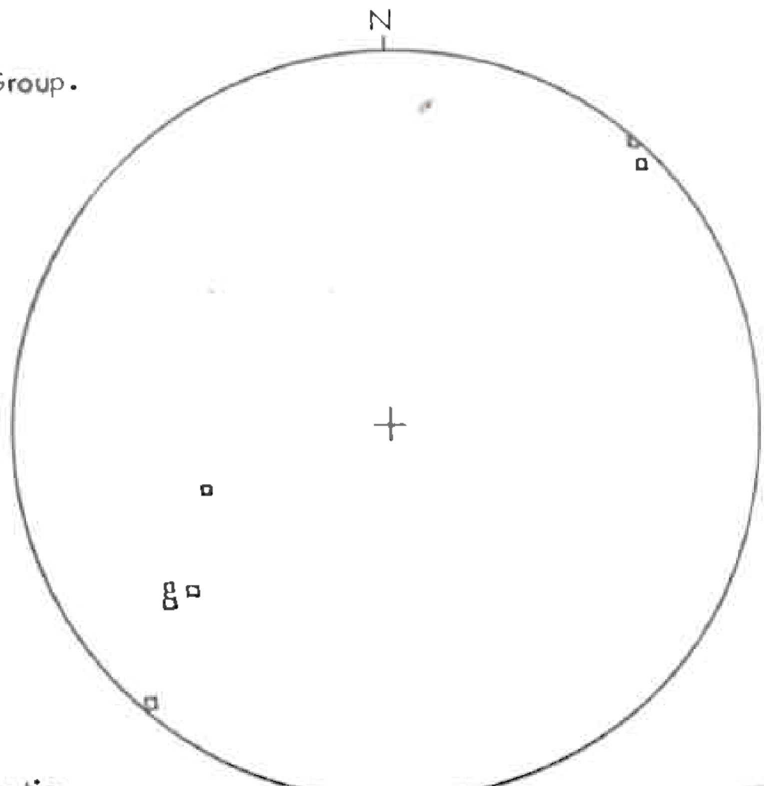


FIG. 13.29 Syn-schistosity folds from the eastern part of Duoldagop.

Axes :-
□ Duoldagop Banded Group.



... equal area projection

D. The central parts of Duoldagop.

In the centre of Duoldagop, north of the two lakes, there are a few syn-schistosity folds of the Duoldagop Banded Group. The axes of these folds, constructed by a π diagram, are plotted in Fig. 13.30, and can be seen to fall along a broad girdle across the stereogram.

E. The Waterfall zone - Map 4.

In the Waterfall zone there are syn-schistosity folds of the Rusty Psammite, the Marble-Psammite series and of the fine-grained psammite within the Rusty Psammite which was mentioned on page 109. A feature of the attitudes of the axes of these folds is that they are considerably dispersed. This is shown on Fig. 13.31. In Fig. 13.32 are shown the attitudes of the axes of folds of the Marble-Psammite series, the different symbols representing different exposures. It can be seen from this that even within one outcrop the fold axes are considerably dispersed. This is probably because the area contains several post-schistosity fold hinges, though these are not immediately apparent. Note that while the axes of the internal folds of calc-silicate layers are not so dispersed, the measurements were mainly taken from the limbs of the larger folds, and therefore are not as representative as the axes of folds of the Marble-Psammite series units.

F. North-east of Kobbertoppen.

North-east of Kobbertoppen there are folds seen at the southern closure of the Lapphelleren schist lying on the west of Duoldagop. Fold axes in the Rusty Psammite, and internal folds in the marbles plunge to the south-east (Fig. 13.33).

G. North and West of Kobbertoppen.

North and west of Kobbertoppen there are folds of Rusty Psammite and internal folds of marble, which have near-horizontal axes with east-west azimuth (Fig. 13.34).

G. South of Kobbertoppen .

South of Kobbertoppen there are some folds in the Lapphelleren schist with east-west axes, near horizontal . They are overturned to the north, opposite in sense to folds of the Duoldagop Banded Group in east Duoldagop , (Fig. 13.35).

FIG. 13.32 Syn-schistosity folds of Marble-Psammite series in the Waterfall zone, south Duoldagop.

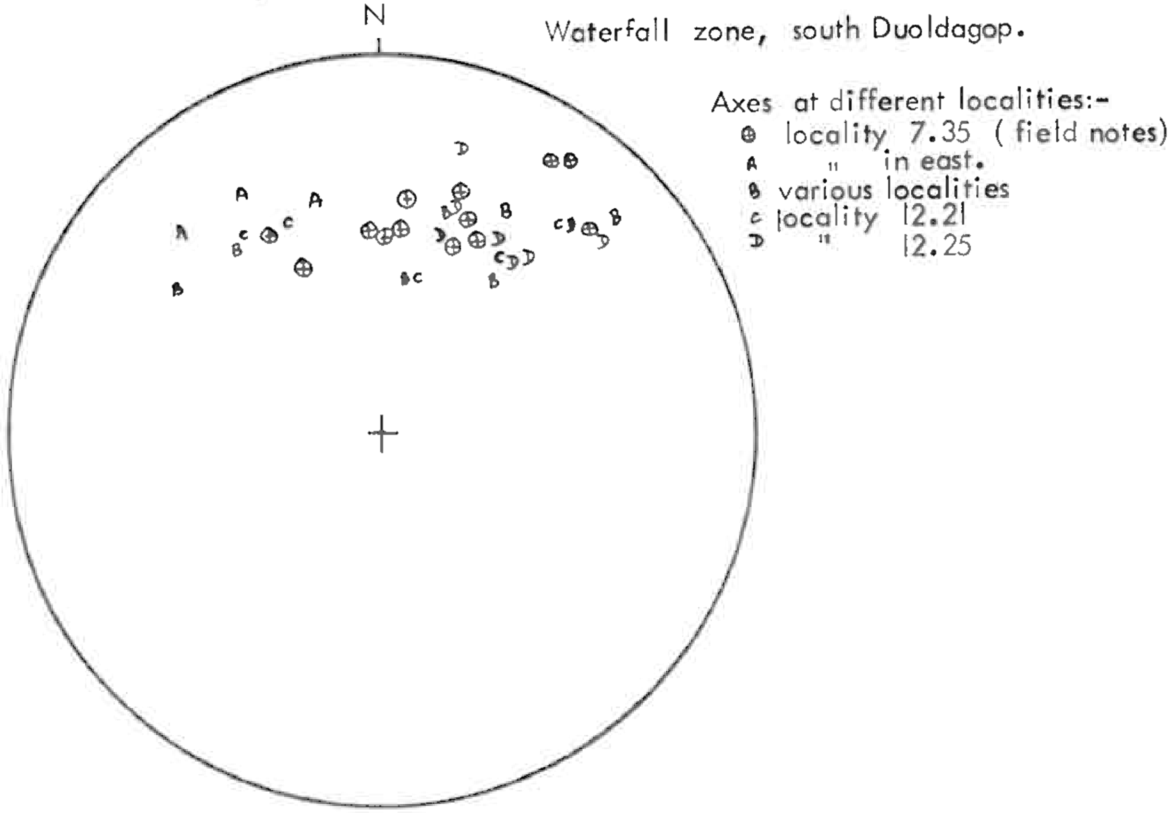
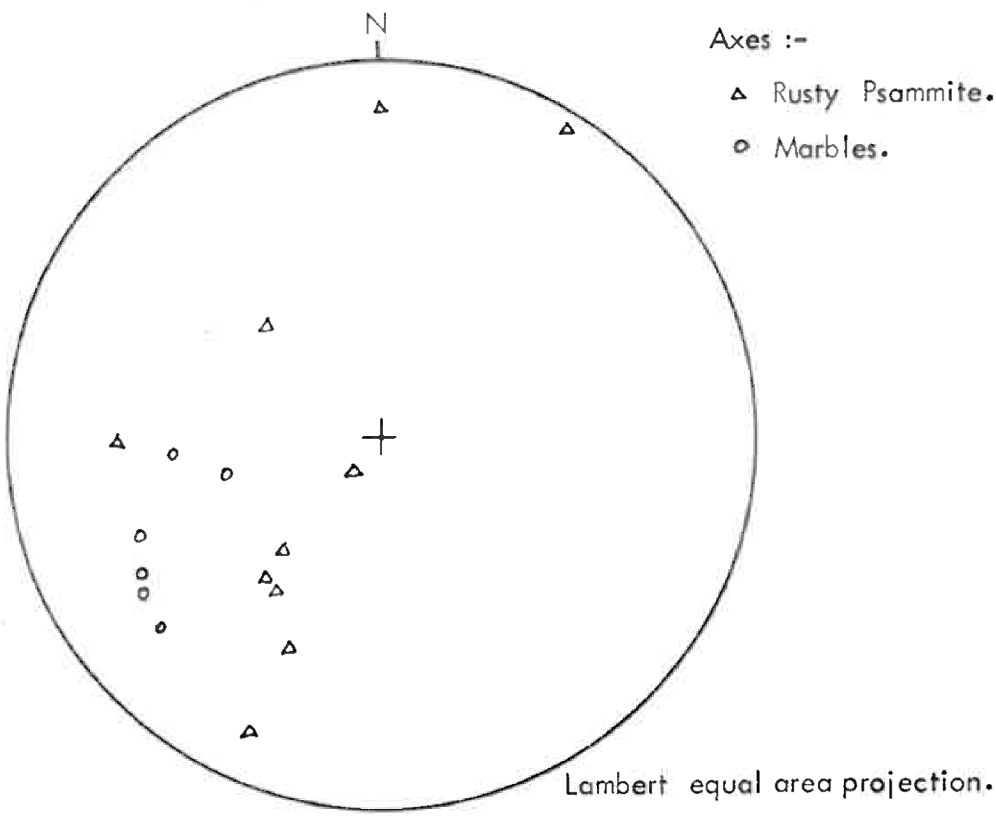


FIG. 13.33 Syn-schistosity folds north-east of Kobbertoppen.



Lambert equal area projection.

FIG. 13.34 Syn-schistosity folds from north and west of Kobbertoppen.

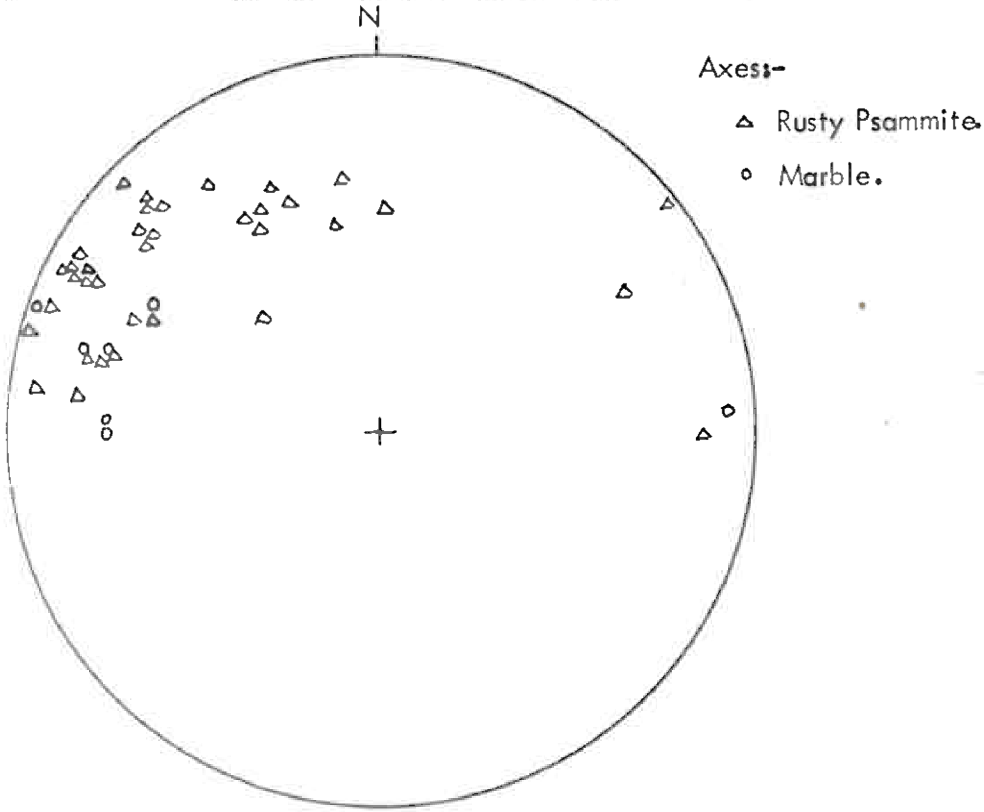
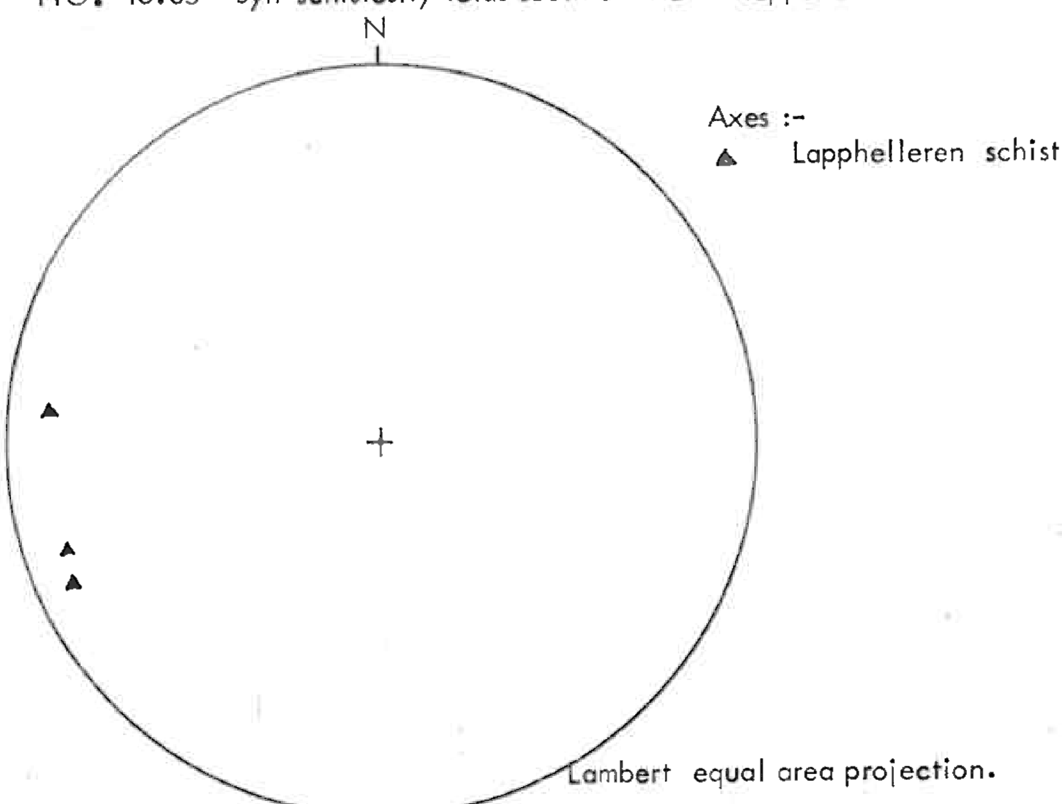


FIG. 13.35 Syn-schistosity folds south of Kobbertoppen.

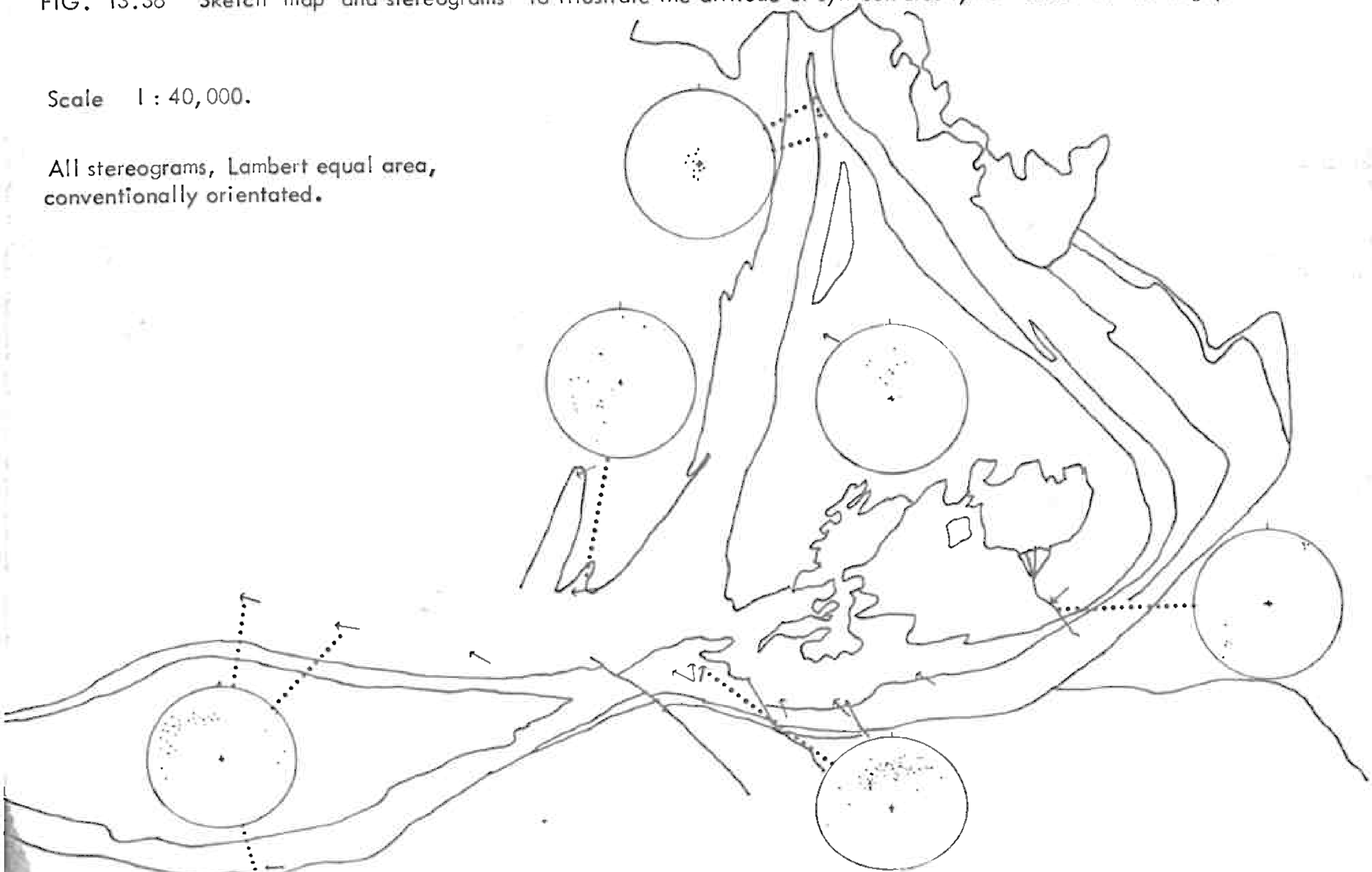


Lambert equal area projection.

FIG. 13.36 Sketch map and stereograms to illustrate the attitude of syn-schistosity fold axes in Duoldagop.

Scale 1 : 40,000.

All stereograms, Lambert equal area, conventionally orientated.



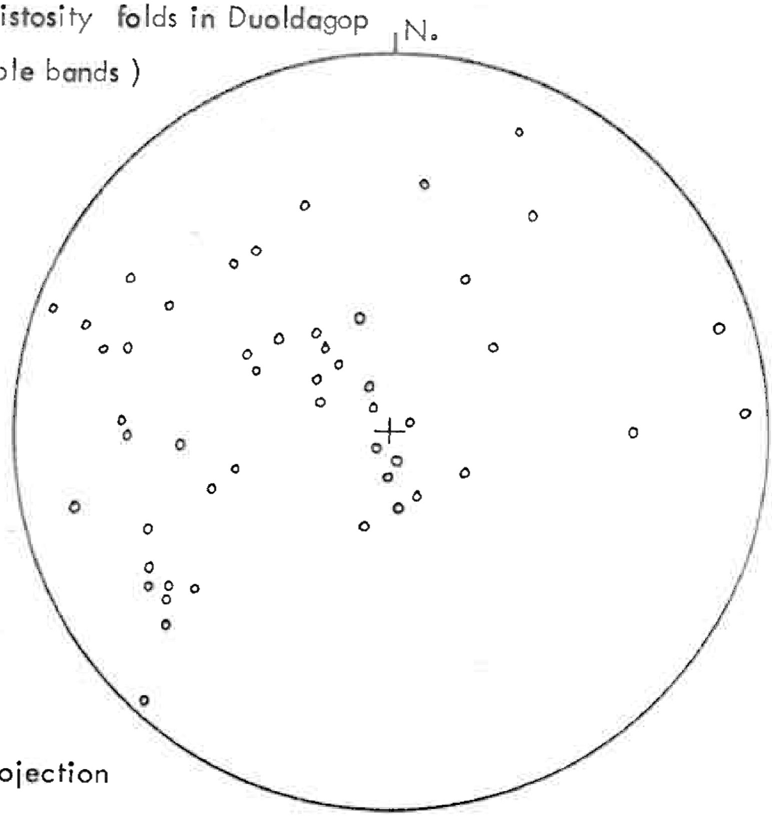
13.7 Synthesis .

Fig. 13.36 is a sketch map showing the attitudes of axes in the different parts of Duoldagop. Fig. 13.37 is a plot of all syn-schistosity fold axes , except those in the marbles (which were unevenly distributed), in the area east of Kobbertoppen. The axes fall on a broad girdle and demonstrate the dispersing effect of the post-schistosity deformation. At first sight this suggests folding around an axis trending about 340° and plunging very gently, but an allowance must be made for the inhomogeneous strain against the Sulitjelma gabbro.

The dispersal of fold axes in the Waterfall area suggests that this is the hinge zone of a post-schistosity set of folds.

FIG. 13.37 Syn-schistosity folds in Duoldagop
(except those of marble bands)

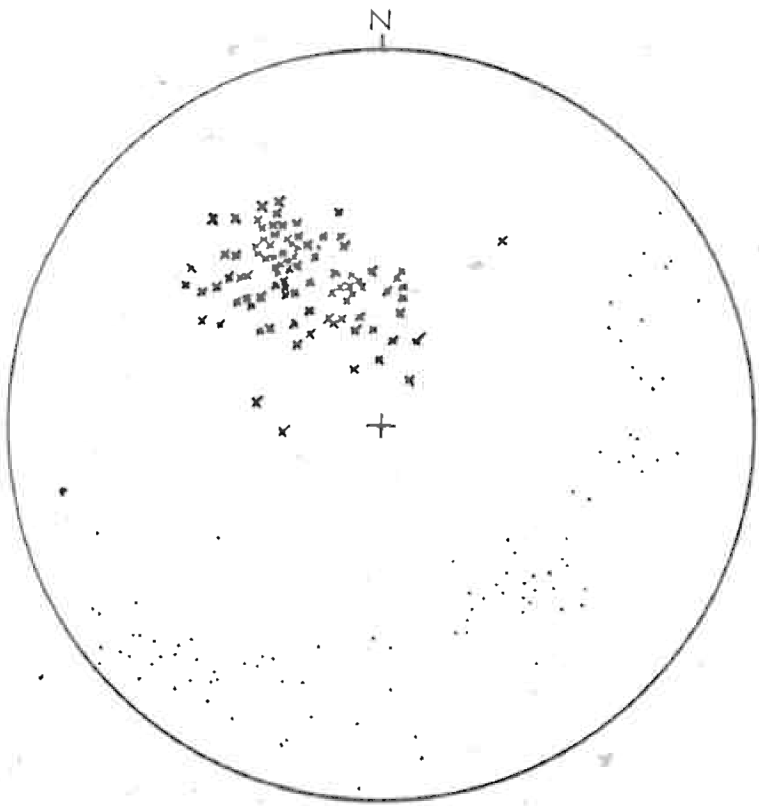
Axes ;- o



Lambert equal area projection

FIG. 14.1 Post-schistosity folding of the eastern body of the Furulund granite.

Schistosity and lineation attitudes round the closure in Duoldagop.



Poles to schistosity :- •

Mineral lineation :- ×

CHAPTER 14

POST - SCHISTOSITY FOLDS OF THE SULITJELMA SCHIST SEQUENCE

14.1 Introduction.

The schistosity of the Sulitjelma Schist Sequence is folded on both major and minor scales. Map I indicates the schistosity attitudes in Duoldagop and illustrates the effects of a major fold whose axis plunges to the north-west. This fold has buckled the Sulitjelma gabbro and the eastern body of the Furulund granite and has refolded the early Duoldagop synform to give an eyed fold. The tightness of the major fold becomes less to the west of Duoldagop, the schistosity on the western margin of the thesis area being only gently folded, as is shown on Map I, especially in the stereogram of poles to schistosity on the western side of Duoldagop. This variation in intensity of folding suggests that the folding of the meta-sediments is the result of the buckling of the relatively competent gabbro, the metasediments elsewhere having deformed without folding.

The axis of the folding of the foliation of the eastern body of the Furulund granite is determined from the π diagram Fig. 14.I. This, and the axial plane determined from the axial trace is marked on Map 3.

An additional fold which is probably of post-schistosity age is the major fold in the Waterfall zone, the evidence for which is presented in Chapter 10.2 on page 102. The close association of this fold with post-schistosity minor folds is the main reason for suggesting that it is of post-schistosity age. The fold is tight and it is only possible to specify the axis attitude as probably being near to the horizontal, with an east-west azimuth. As discussed on page 104, the fold is most probably a "Z" type fold, overturned to the south with part of the lower limb having been cut out along a slide.

Minor post-schistosity folds of the Sulitjelma Schist Sequence fall into three groups. Firstly there are those developed outside the Duoldagop region,

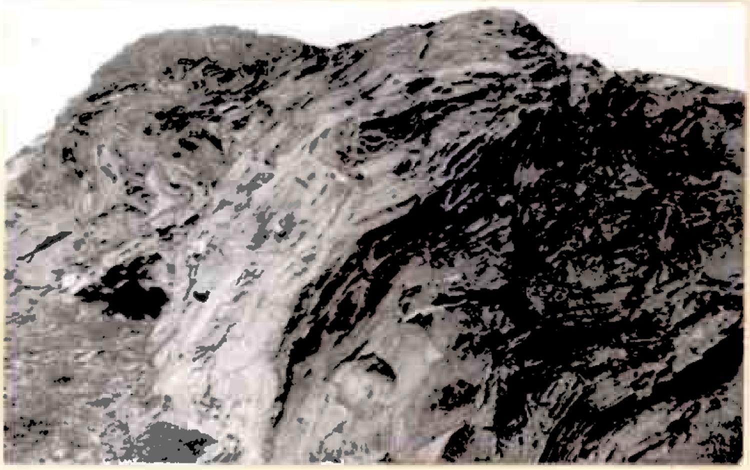


Fig. 14.2 Post-schistosity minor folds west of Kobbertoppen. Note varieties of lithologies involved.

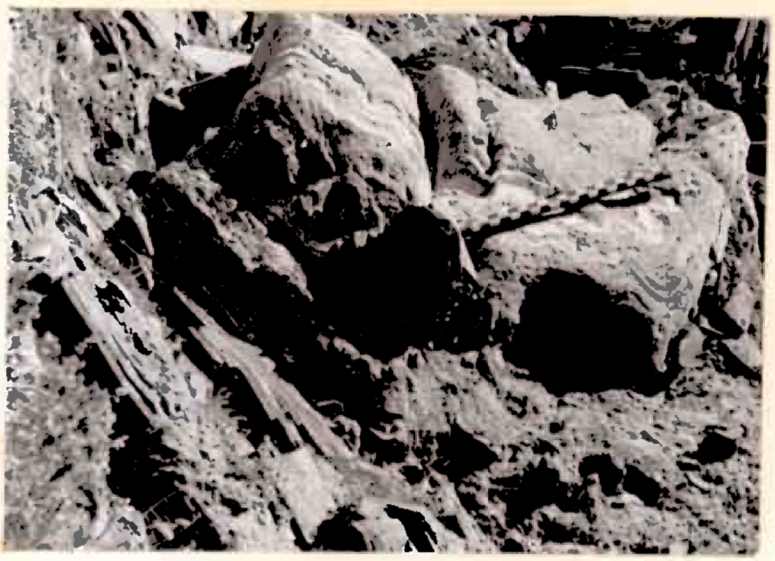


Fig. 14.3 as above.

Fig. 14.4 Post-schistosity minor folds west of Kobbertoppen.

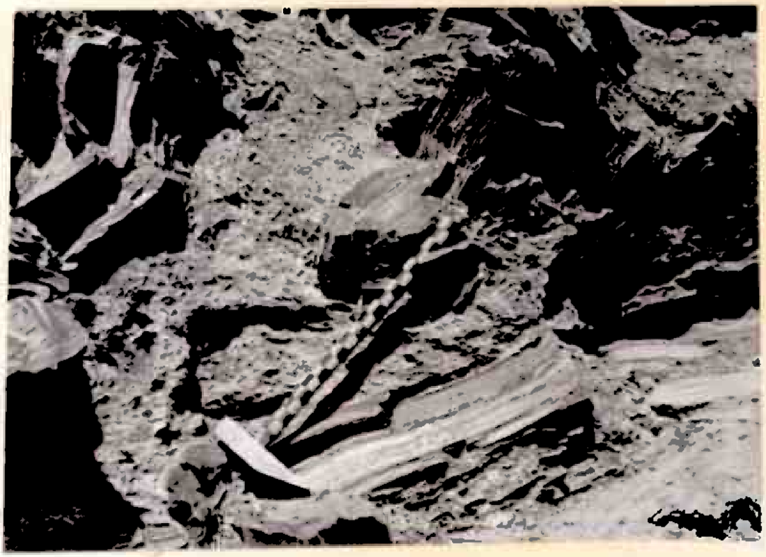


Fig. 14.5 Post-schistosity minor folds west of Kobbertoppen. Note the disharmonic nature of the folds, the variation in axial direction and the disruption in the bedding.

FIG. 14.6 Post-schistosity minor folds in the Sulitjelma Schist Sequence in area west of Kobbertoppen.

Axes :- o

Poles to axial plane :- ⊙

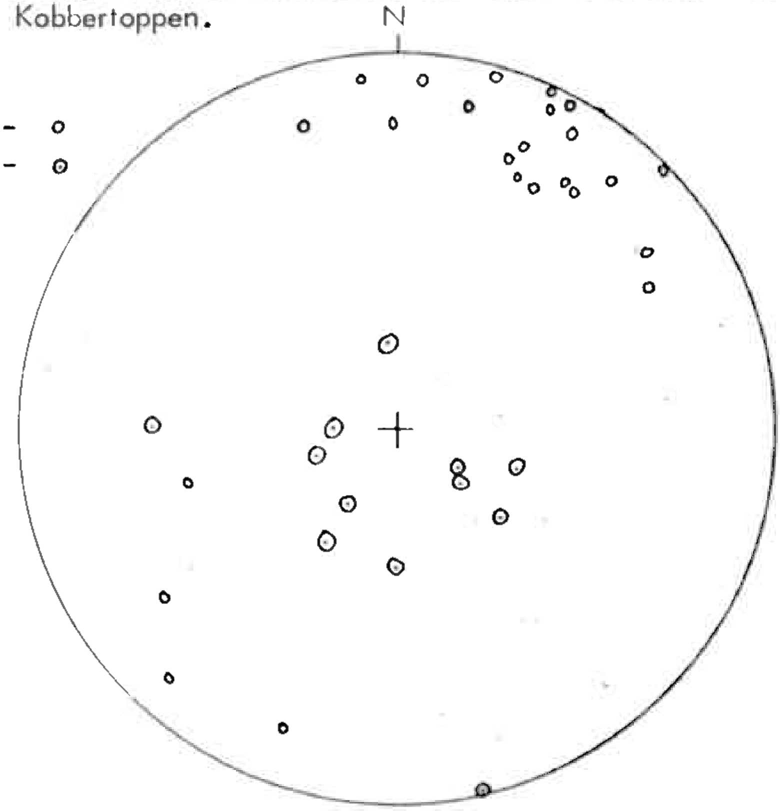
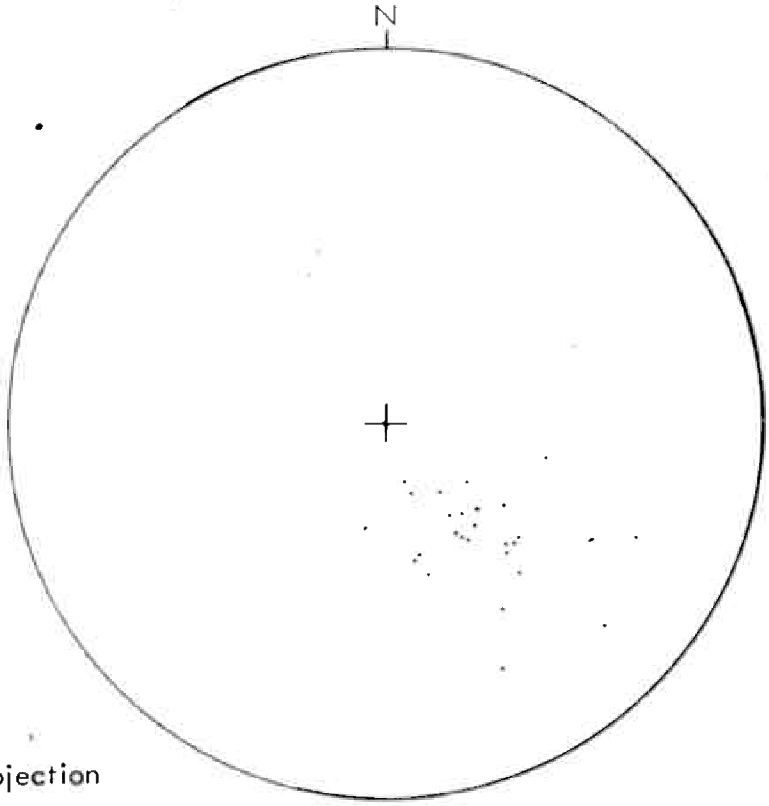


FIG. 14.7 Attitude of schistosity in area of minor folding west of Kobbertoppen.

Poles to schistosity :- •



Lambert equal area projection

on the north-west side of the western Furulund granite. Secondly there are those minor folds which are readily related to the major fold in Duoldagop, and thirdly there is a development of very tight folds in the Waterfall zone which it is suggested is related to the major fold there. The possible relations of these three groups will be discussed when they have been described in detail.

14.2 Minor folds in the west of the thesis area.

In Chapter 10.7 on page 111 it was mentioned that above the Rusty Psammite west of Kobbertoppen there is a series of rocks not found in Duoldagop. Above a series of grey flaggy schists, and a series of coarse-grained massive schists there is a series of marbles, quartzites and schists, which are all intensely folded on a minor scale as is shown in Figures 14.2 and 14.3. The folding continues beyond the area mapped. The limbs of the folds are short, usually less than a metre, so that closures are very common. In bands with contrasting lithologies there are disharmonic folds showing considerable variation in axial attitude as is shown in Figures 14.4 and 14.5. In the uniform lithologies the folding is of chevron type, with planar limbs and very angular hinges.

Fig. 14.6 shows that the fold axes are spread between 350° and 050°, with plunge varying between horizontal and 30°. The axial planes are mostly within 30° of horizontal, but are well spread out in attitude. The folds are overturned to the west and since the ground surface is dipping to the north-west apparently parallel to the enveloping surface, the same lithological horizon is exposed down the hillside.

Figure 14.7 is a stereogram of poles to schistosity in this area and indicates that there is no major folding within the area. On Fig. 14.8 is marked the constructed axis of folding of the granite and Lapphelleren schists at Bursi, and the axes of folding of the Furulund schist at Bursi, referred to in Chapter 6. The parallelism of axes of folds of Furulund schist, granite and the rocks described above suggests that this folding may have been a common event.

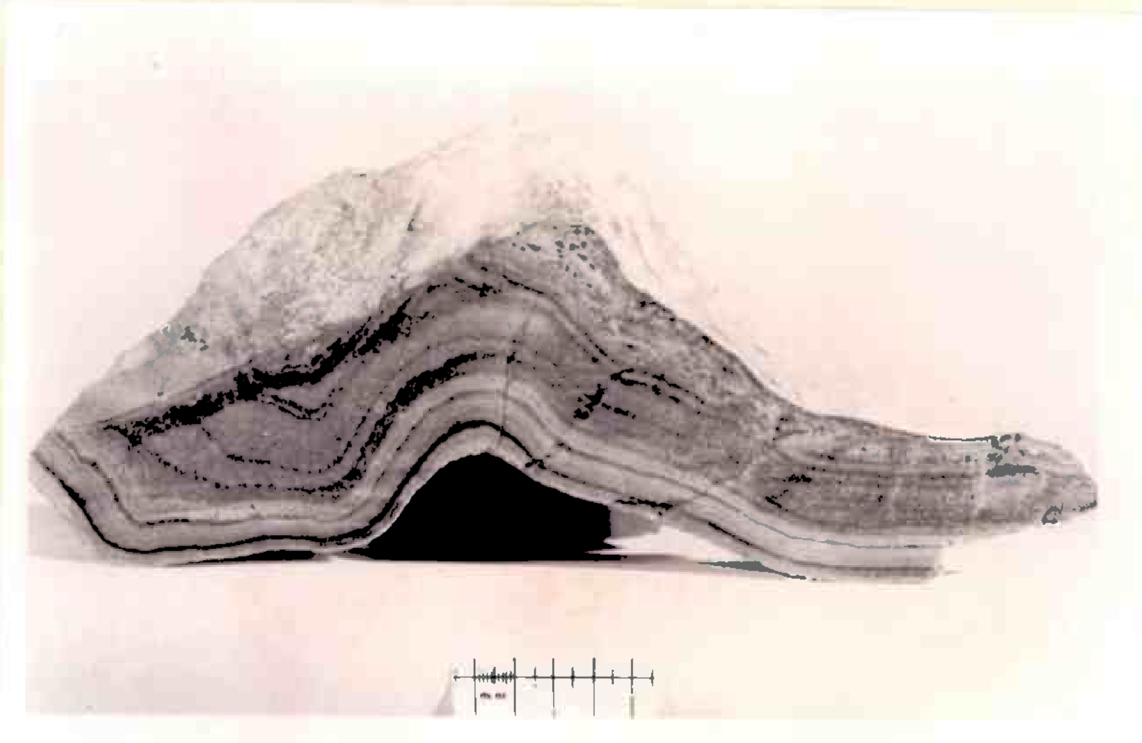


FIG. 14.10 Specimen 705. Marble from locality in Fig. 14.2. Example of a post-schistosity fold in the area west of Kobbertoppen. Photograph taken along axis of folding.

FIG. 14.8 Folds at Bursi - Furlund schist, Lapphelleren schist and granite.

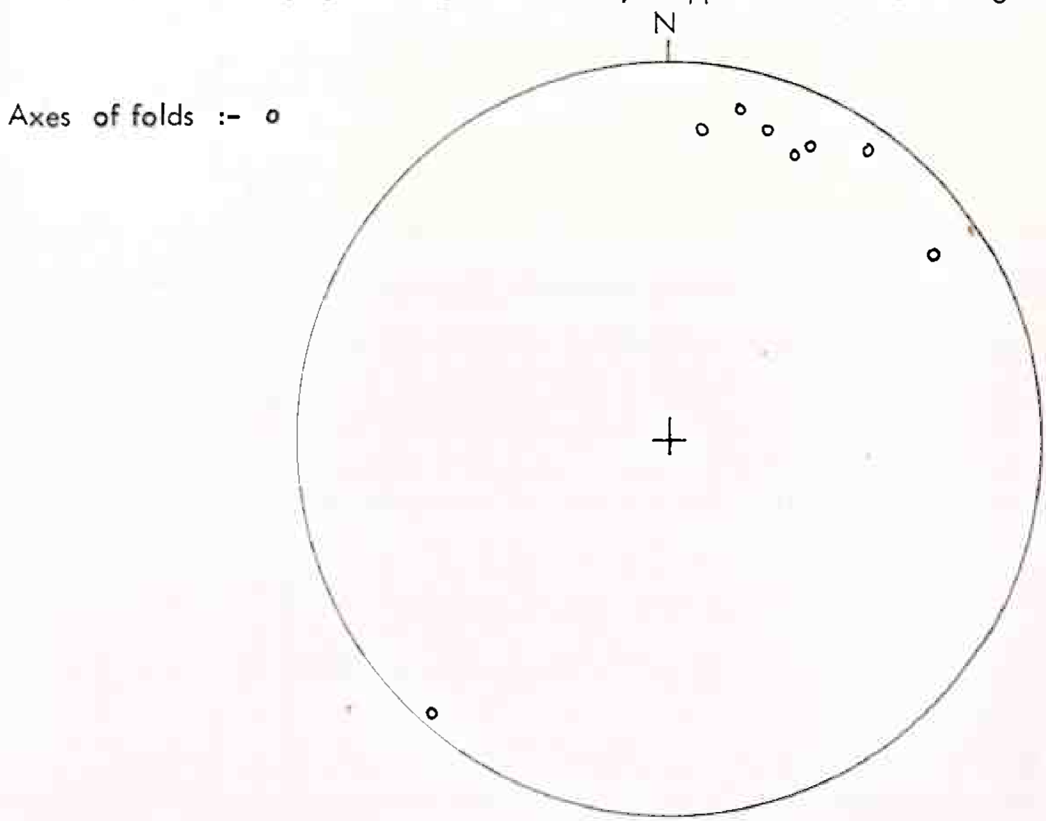


FIG. 14.9 Folding of early lineations by minor post-schistosity folds west of Kobbertoppen, at locality in Fig.14.2.

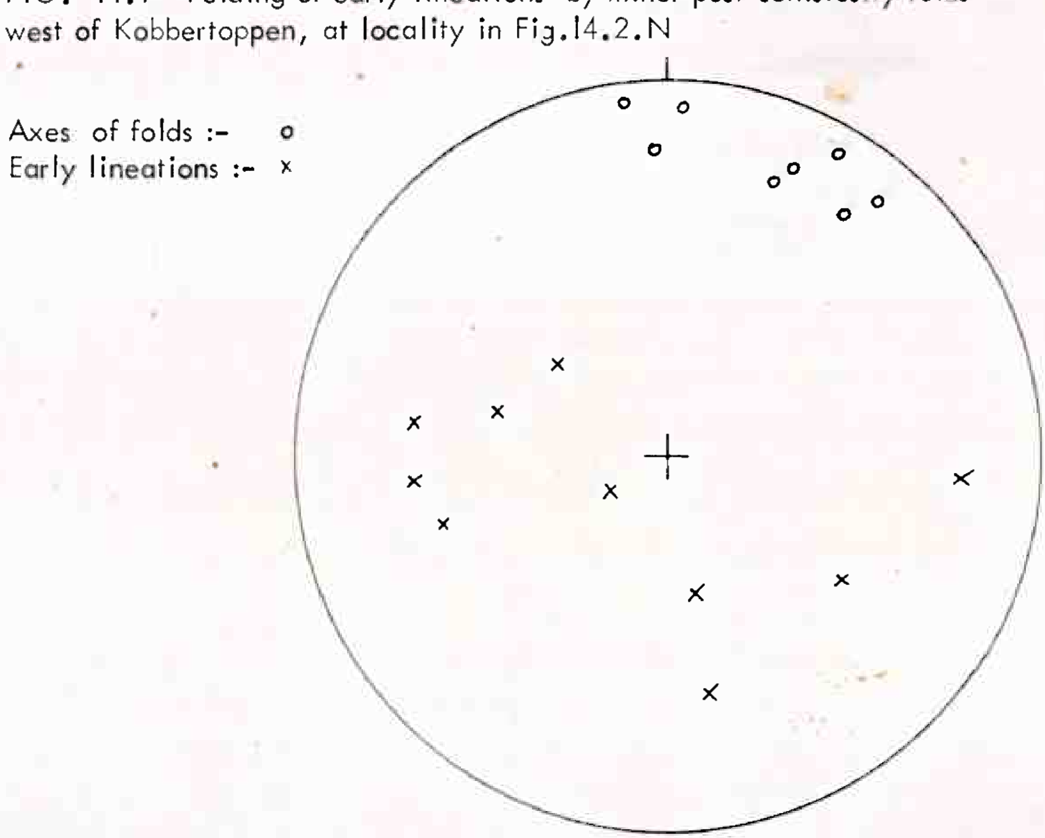
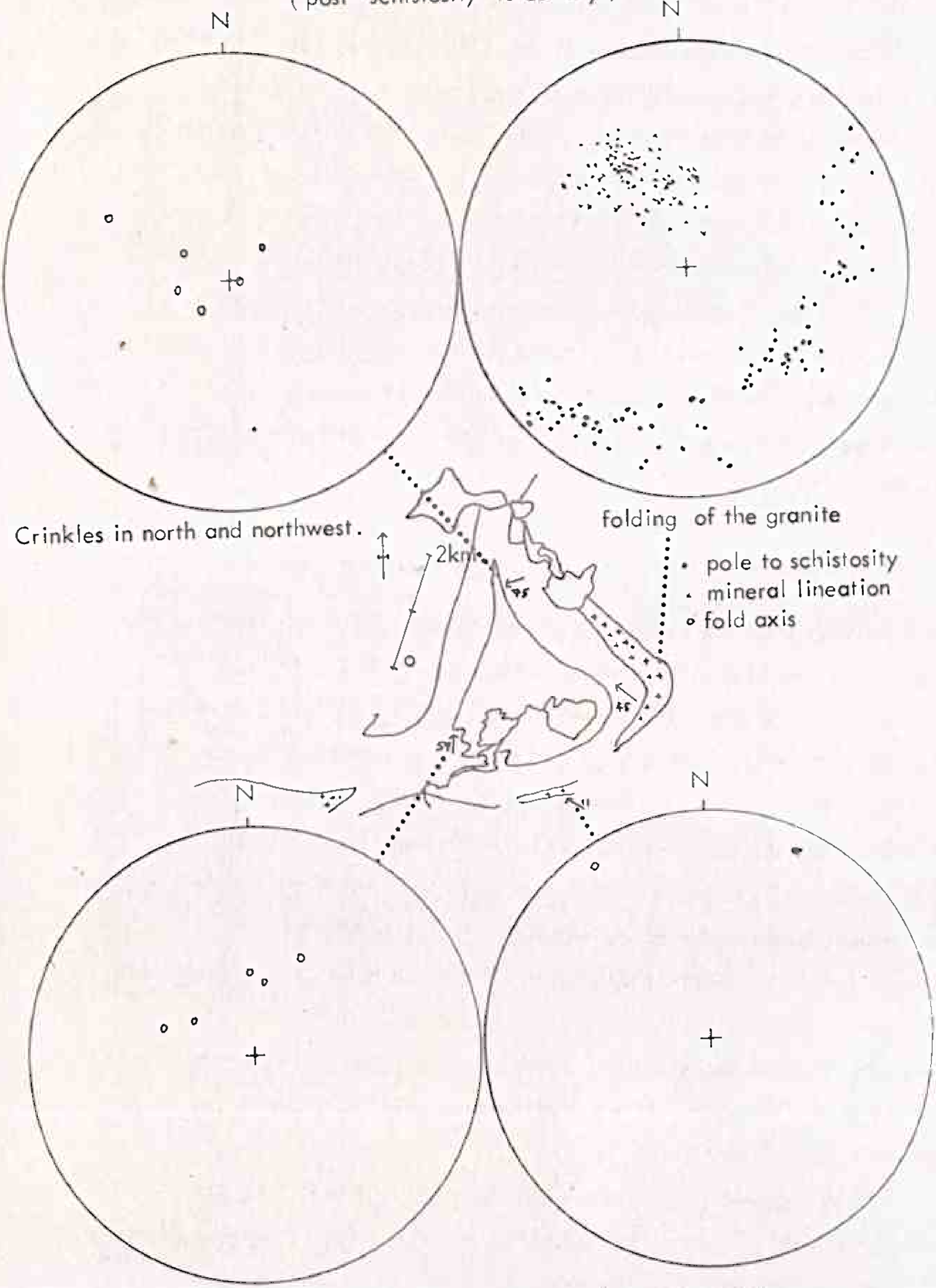


FIG. 14.11 Minor folds in Duoldagop outside the Waterfall zone.

(post- schistosity folds only)



Folds in Rusty Psammite in south-west

Folds in south-east.

The locality whose photograph forms Fig. 14.2 is at position 443 390 and the general position is indicated on the panorama Fig. 6.33. Early intersection lineations were seen here, folded round the post-schistosity fold closures. It was impracticable to measure their attitude round any one closure, and no closures with lineations could be removed. Fig. 14.9 is a plot of lineation attitudes taken from different hinges. The various axes are also marked. The lineations fall approximately onto a great circle whose pole is near to the average position of the fold axes, but the variation in axis attitude precludes a proper study of the geometry of the fold deformation. Fig. 14.10 is a photograph of specimen 705 from this locality, the specimen having been cut normal to the fold axis.

14.3 Minor folds in Duoldagop outside the Waterfall zone.

Outside the Waterfall zone minor folds are not very common. In the northern part of Duoldagop the Lapphelleren schists are frequently folded into crinkles with wavelengths up to 10cm. and amplitude 2-3cm. These did not usually show any sense of overturn. In the far north these crinkles, exemplified by specimen 645, have axes which are nearly vertical and axial planes which strike approximately east-west as shown on Fig. 14.11. Similar crinkles are seen on the north-east side of Duoldagop and have axes parallel to the constructed axis of the major fold of the Furulund granite.

In the south-east of Duoldagop at 518 490 there occurs between the Furulund granite and the Flaser Gabbro a patch of highly folded green and white rock. It is mainly made up of hornblende, quartz and plagioclase, with mica rich bands. The folds, whose axes plunge gently to the north-west, are illustrated in Fig. 14.12.

In the south-west of Duoldagop there are post-schistosity folds in the Rusty Psammite, and in the strip of grey schists within the Rusty Psammite. The axes at position 497 500 plunge north at between 50° and 70°.

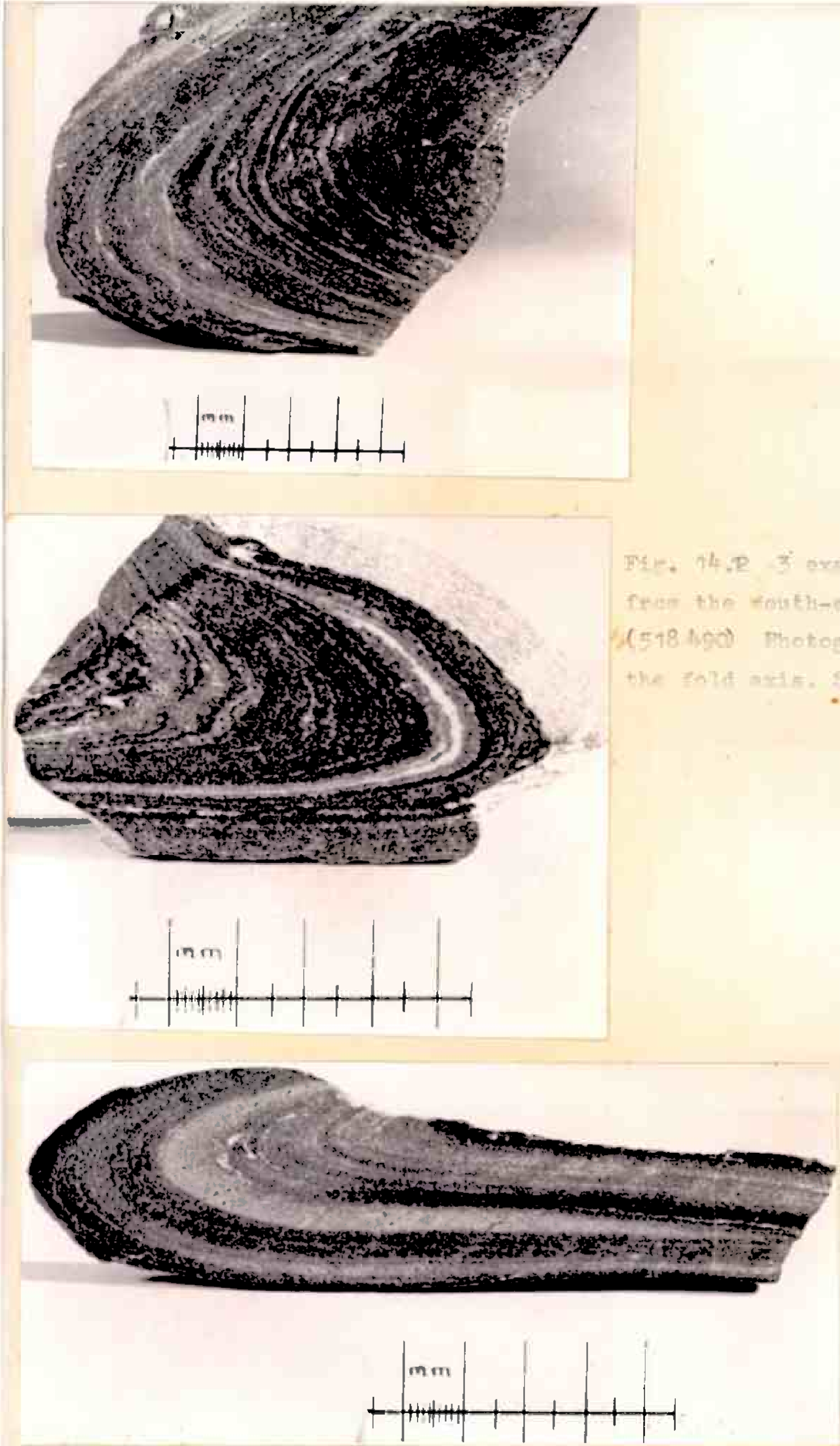


Fig. 14.P. 3 examples of folds from the south-east of Dubldogop. (518 490) Photographs taken along the fold axis. See page 134.

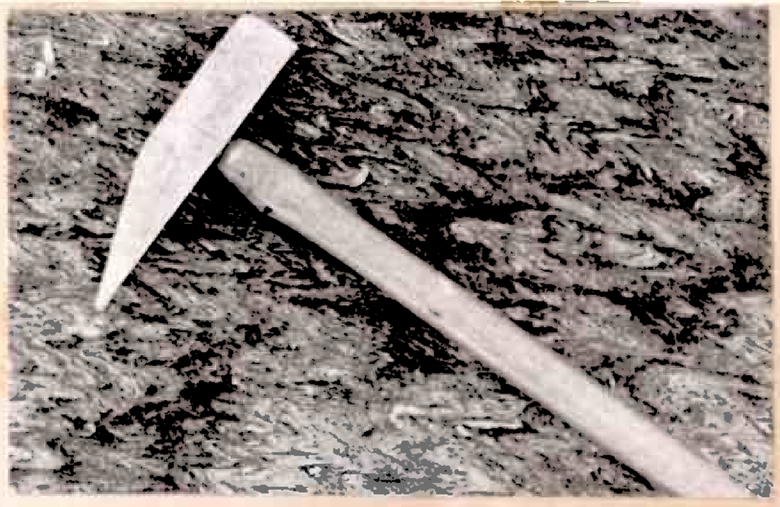


Fig. 14.13 Very tight post-schistosity folds in the Lapphelleren Schist of the Waterfall zone. White pseudomorphs of quartz and muscovite after kyanite can be seen folded.

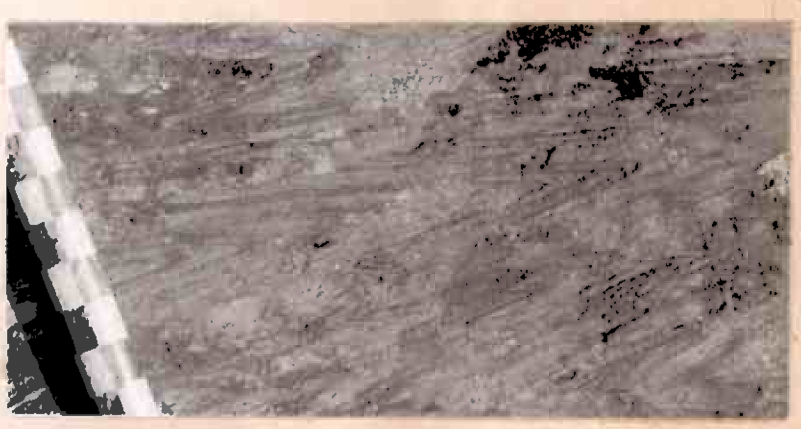


Fig. 14.14 As above.

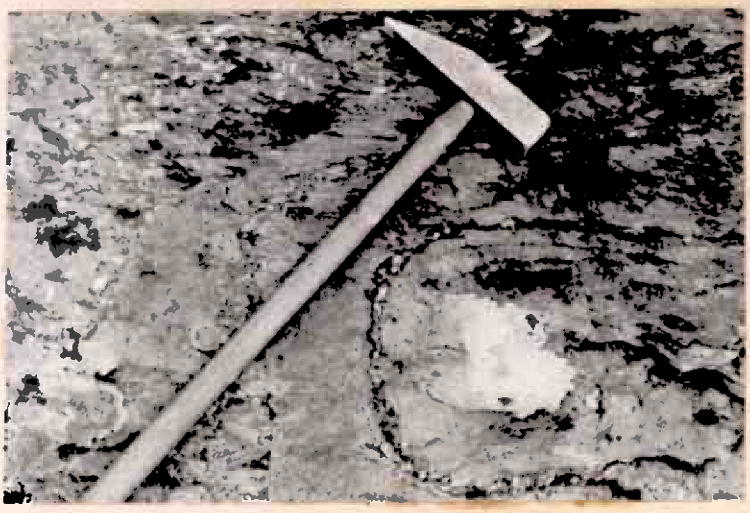
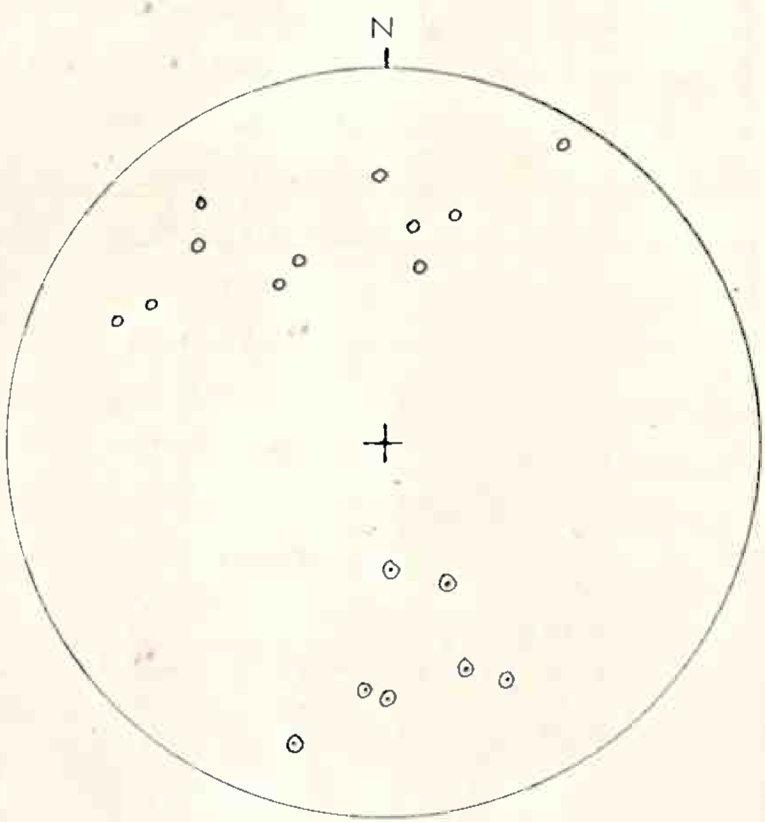


Fig. 14.15 and 14.16. Very tight folds of Lapphelleren Schist in Waterfall zone.

FIG. 14.17 Post-schistosity minor folds of the Lapphelleren schist in the Waterfall zone.



Axes of folds :- o

Poles to axial planes :- ⊙

14.4 Post-schistosity minor folds in the Waterfall zone

As indicated on Map 3 virtually the whole outcrop of Lapphelleren schists between the eastings 490 and 500 is intensely folded. The style and intensity of folding is shown in Figures 14.13 to 14.16. Fig. 14.17 is a plot of the fold axes and poles to axial planes. There is a considerable spread in axial attitudes and this is attributed to further deformation following the initial folding of the schistosity.

The age of the folding relative to porphyroblast growth can be determined from specimens 359 and 724. The [illegible] large pseudomorphs of kyanite which are tightly folded [illegible] 13. Specimen 359 has sillimanite orientated parallel to the axial [illegible] is shown in Fig. 11.11 and in specimens 359 and 724 [illegible] have grown over tight folds of schistosity, as shown in Fig [illegible]. The folds are therefore later than the growth of mica [illegible] same age as the growth of sillimanite and earlier than the [illegible] thin section the folds are sometimes quite difficult to [illegible] the closures lie at very low angles to the axial pl[illegible] This is also an indication of continuing deformation after [illegible]

The relat[illegible] major folds in the Waterfall zone is not so apparent [illegible] that the minor folds are related to some of the fold[illegible] but the relation to the major fold of the Lapphelleren [illegible] fortunately the evidence of [illegible]ergence was not easy to se[illegible] could be done here. The behaviour of beds [illegible] that the axis would trend east-west, perhaps plunging gently to the west. This does not fit with the post-schistosity minor folds. However the intensity of the minor folding in this region suggests some connection. Conversely if this minor folding is not connected to the major folding then some reason must be given to account for its intensity.

14.5 Synthesis for post-schistosity folds.

The relationship between the three groups of folds is not apparent. There is no interference between folds of different groups and only the minor folds in the Waterfall zone can be related to porphyroblast growth. It is suggested that the major fold in the Waterfall zone is earlier than the major fold in Duoldagop. This hypothesis is based on the following three observations. Firstly the Waterfall zone fold, and the minor folds which probably are associated with it are dissimilar to the folds in the rest of Duoldagop, being much tighter in style. Secondly, the dispersion of minor fold axes in the Waterfall zone suggests deformation following folding. Thirdly, considerations of the time relations of igneous intrusion and deformation suggests that there was a deformation of considerable extent following the establishment of the pre-gabbro and granite early Duoldagop synform but before the folding of the granite and gabbro. This intermediate deformation was responsible for the development of an L-S tectonite fabric in the granite and in the margins of the gabbro prior to the late fold episode. The minor folding in the Waterfall zone is therefore correlated with this event.

It is most probable that the minor folding in the west of the region may be correlated with the major fold in Duoldagop. While the axes of folding are different in the two areas (compare Figures 14.6 and 14.7) this could be the effect of the unusually high degree of strain around the gabbro.

CHAPTER 15

DEFORMATION OF THE SULITJELMA SCHIST SEQUENCE - SYNTHESIS

15.1. Summary of facts available. (Figures in brackets refer to chapters).

Major folding :-

Syn-schistosity Duoldagop synform, (Chapter 13.1).

Post-schistosity folding of the gabbro and of the Duoldagop synform to give eyed structure, (14.1).

Fold in Waterfall zone with slide or thrust at base, (10.4).

Minor folding :-

Syn-schistosity folds in north with near-vertical axes and vergence to fit Duoldagop synform, (13.5).

Syn-schistosity fold axes in Duoldagop dispersed around a girdle, In Waterfall zone syn-schistosity fold axes highly dispersed, (15.3).

Post-schistosity folds which fit the major post-schistosity fold in Duoldagop, (13.3).

Post-schistosity folds in Waterfall zone. Location suggests a relationship to the major fold in the Waterfall zone. Axes dispersed, garnets grow over the minor closures, (13.4).

Post-schistosity folds west of Kobbertoppen, (13.2)

Gabbro intrusion:-

According to Mason, later than earliest phase of folding, but earlier than the post-schistosity folding, (12.8).

Furulund granite intrusion :-

Both bodies of granite show L-S tectonite fabric which has, in the east, been folded, (12.5).

15.2 Uncertainties.

Age of intrusion of the Furulund granite:-

The only good evidence that the granite is not pre-tectonic is that veins of granite cut the gabbro. It is possible that this is back-veining (12.7).

The fold in the Waterfall zone :-

As discussed in Chapter 10.2, the form of this fold is not certain, the fold being either a "Z" type fold, with one of the limbs being a short limb, or a "M" type fold, having two long limbs. If it is an "M" type then major thrusting is necessary, since the succession of lithologies on each limb do not match. An "M" type fold is of neccessity earlier than the intrusion of the western body of the Furulund granite, which lies along what would be its axial plane. The scale of such an "M" type fold would suggest an analogy with the the large-scale Duoldagop synform, which is of syn-schistosity age. A post-schistosity age is suggested, however, by the relationship between the major fold and minor folds in the Waterfall zone which are of post-schistosity age. As is discussed in Chapter 12.7, a post-schistosity fold episode before granite intrusion means that there were two phases of deformation before granite intrusion and two after, whereas alternatives suggest a total of three phases of deformation. Evidence from further afield, (Nicholson, pers. comm.) does not favour an important "M" type fold at this level, and so the preferred interpretation is that this is a "Z" type fold with a relatively minor slide cutting out much of the lower long limb.

Age relations of the schistosity and the gabbro.

The interpretation by Mason(1966) of the relationship between schistosity, major folding and gabbro intrusion is partly based on the interpretation by Henley of the deformation of the Sulitjelma Schist Sequence, (the "Upper unit " of Henley). According to the interpretation of Henley, based mainly on work south of Langvann, the main schistosity-

FIG. 15.1 ALTERNATIVE SEQUENCES OF EVENTS SULITJELMA SCHIST SEQUENCE

	A	B	C	D	E	F
Form of Waterfall zone fold :-	M	M	Z	Z	Z	
Age of Waterfall zone fold :-	syn-schistosity	post-schistosity	syn-schistosity	post-schistosity	post-schistosity	Mason (1966) (adapted)
D1 event	Major syn-schistosity folds-Duoldagop synform and Waterfall zone THRUST	Major fold of Duoldagop synform	Syn-schistosity	GRANITE folding with slide in Waterfall S-L fabric in granite		Structures preserved only in xenoliths
D2 event	GABBRO GRANITE Major fold in Duoldagop Minor folds in Waterfall zone. GARNETS	Post-schistosity Waterfall zone fold THRUST GABBRO GRANITE GARNETS	GABBRO GRANITE minor post-schistosity folds W'fall z. GARNETS	GABBRO & back-veining. major fold of granite and gb. W'fall zone slide. GARNETS	GABBRO GRANITE W'fall zone fold plus formation of schistosity in granite and gb. GARNETS	GABBRO GRANITE Syn-schist. folding, + schistosity in granite and gb.
D 3 event.	v.slight compr.	event to give granite its sch.	Major fold of granite & gb.		post-schistosity major refold	post-schistosity major refold
D4 event		Major refolding.				

lineation fabric is the product of a second major deformation phase, and is therefore termed S2. Mason therefore regards the syn-schistosity Duoldagop synform as an F2 fold. He suggests that there is no trace at all of the D1 deformation except for some F1 folds in rafts of country rock within the gabbro. During the D1 event kyanite and staurolite grew. During the second event the base of the gabbro was strongly deformed together with the underlying amphibolitic rocks to give the "flaser gabbro". unit. During a third deformation the whole of the gabbro was folded, together with the adjacent schists.

The main argument against Mason's interpretation is that there is no trace in the country rocks of any event earlier than the formation of the main schistosity, and it is suggested that it is most unlikely that there should be no trace at all. This matter is discussed in Chapter 5.2 with reference to the Furulund schist.

An important advantage of Mason's interpretation over that suggested in Chapter 10.1, page 102, is that it explains the presence of gabbro and granite on the western side of the Duoldagop synform, as shown in the index map accompanying Map 1. An alternative suggestion to Mason's view that they were folded into this position is that they were intruded in such a position.

15.3 Alternative sequences of events.

In the accompanying table, Fig. 15.1, the various possibilities are taken into account to give several alternative sequences of events. In the second table, Fig. 15.2, the preferred sequence (alternative 'E' of Fig. 15.1) is related to the mineral growth as discussed in Chapter 11, and to the deformation and mineral growth in the Furulund schist as discussed in Chapter 16.3.

An important disadvantage with alternatives A, C, D and F of Fig. 15.1 is that they place garnet growth as the very last event. Evidence discussed in Chapter 7.17 and 11.6 shows that in both the Furulund schist and the Sulitjelma Schist Sequence the schistosity is compressed around the garnets. In the Furulund schist there is definite evidence of folding after garnet growth.

The correlation of the preferred sequence "E" (Fig. 15.1) with the sequence of events in Furulund schist is discussed in the next chapter, and is illustrated in Fig. 15.2 below.

FIG. 15.2 STRUCTURAL AND METAMORPHIC HISTORY - SYNTHESIS.

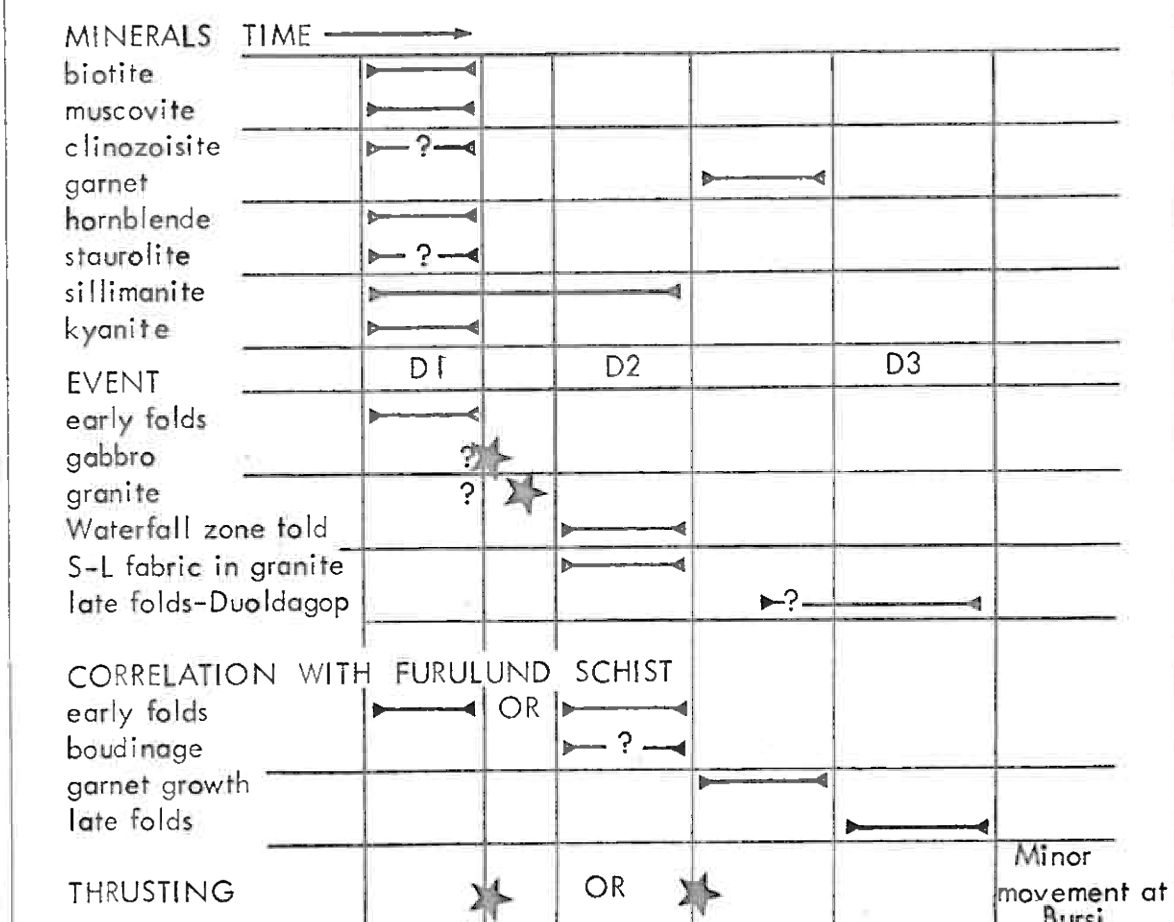


FIG. 16.1 . STRUCTURAL CORRELATIONS ACROSS THE THESIS AREA

Event	Preferred sequence of events for the Sulitjelma Schist Sequence.	Alternative correlations with Furulund schist A "No thrust" hypothesis	B "Early thrust" hypothesis	C (Best) "Late thrust" hypothesis
		Does not explain inversion of isograds	Does not explain inversion of isograds	Explains inversion of isograds
D1	Syn-schistosity folds and growth of kyanite	Syn-schistosity minor folds		
	GABBRO GRANITE		(THRUST)	
D2	S-L fabric in the granite and in the margins of the gabbro. Major fold in Waterfall zone with slide on lower limb.	Further growth of schistosity but no new folds generated.	Syn-schistosity minor folds.	Syn-schistosity folds developed elsewhere.
				(THRUST)
	GARNET growth follow minor folding.	GARNET growth with local simple shear strain.	GARNET growth with local simple shear strain.	GARNET growth
D3	Folding of the gabbro, strong lineation adjacent to the gabbro emphasised.	Post-schistosity Folds		

PART FIVE

CHAPTER 16

ON THE METHODS OF IDENTIFICATION OF THRUST ZONES AND THE APPLICATION OF THESE METHODS TO THE THESIS AREA

16.1 Stratigraphy.

Rocks at higher levels in a structural succession may be older than , or exact stratigraphic equivalents of rocks at lower levels. This is the method which was first developed in the Alps, and is most useful in fossiliferous areas. The method has been used extensively in Norway and Sweden, and Kautsky applied it to the area between Sulitjelma and Akkajaure. Kautsky suggested that the lithologies of the " Gasak nappe" are so similar to those of the "Pieske nappe " that they can be stratigraphically correlated. In the thesis area there is no support for this correlation.

16.2 Discordances of lithological units.

Discordances of lithology which cannot be explained by facies changes or unconformities are commonly described from thrust zones. Such discordances are of course conspicuous in the Moine thrust belt in Scotland, as for example at Assynt. Along the eastern edge of the Caledonides in Sweden such discordances are well displayed. Kulling (1955, Fig 81, pg. 154, and 1960, Fig. 4, pg. 158) illustrates sections across the eastern marginal zone showing the discordance between the overlying Seve-koli nappe and the lower nappes , and the discordances between the individual lower nappes.

Rutland and Nicholson (1965) describe nappes which disrupt the stratigraphy as " disjunctive " in contrast to "conjunctive" nappes whose boundary thrusts lie parallel to major stratigraphic boundaries. The Swedish nappes are generally conjunctive away from the thrust front. The method by which Scandinavian geologists have traced thrust zones away from the thrust front in Sweden into Norway has generally been by establishing that there is a thrust between two units and following these units westwards. But how far west do thrusts extend? In theory two adjacent rock units undergoing the same deformation may through differences of lithological character be strained differently, one unit perhaps flattening at a greater rate than the other and thereby generating a discordance between them which does not extend the whole length of the stratigraphic boundary. A possible example of this is in the thesis area where there is proof that the "Pieske" and "Vasten nappes" of Kautsky together form one stratigraphic unit (see page 20) Further east if the "Vasten " rocks were flattend to a greater extent than the underlying "Pieske" rocks there could be overthrusting at this level.

Kautsky clearly shows discordances below the "Vasten nappe" east of Sorjusjaure. Preliminary investigations by Dr Nicholson and the writer in 1966 suggested that Kautsky's map was incorrect in this area, there being no evidence of discordance. Another major discordance according to Kautsky is the absence in the Sulitjelma area of rocks of the "Salo nappe" , which further north is found between the "Gasak " and "Vasten nappe ".

In the thesis area there is some evidence of discordance. In the Waterfall area (in the east of the thesis area) a large fold has been identified in the Sulitjelma Schist Sequence, as described in Chapter 10.2 and mapped on Map 4. Although inner members of the lithological sequence can be correlated across the axial trace, much of the upper limb development is missing below, suggesting loss of one limb by extreme thinning and eventual dislocation. Unfortunately, because of later faulting it is not certain from evidence in this area that the fold is an "M"type(Elliot , 1968, page 172) involving a considerable part of the Sulitjelma Schist Sequence rather than a "Z" type fold with a definite short limb. In the latter case a local slide (Bailey ,1910, pg.593, Fleuty,1964,) is necessary but not a major thrust dislocation. Evidence from beyond the area is not in favour of a marked fold at this level. The discordance does ,however, lie at the base of the series of rocks which Kautsky designated as the "Gasak nappe".

Mason (1967) suggested that there are discordances of lithology against the Tectonic breccias (Mason's Flaser gabbro), using this evidence to support his view that the Flaser gabbro unit represents a thrust zone. The discordances which Mason records from above the unit (1967, pg.241) are interpreted here as being caused in part at least, by the the movements on the postulated local slide at this level (see previous page). The discordance below is very likely to be an original discordance, since it involves the thinning out of metamorphosed volcanic rocks (the meta-porphyritic amphibolites, Mason 1967, pg 243). Such a series would not be expected to maintain constant thickness, and indeed Mason's map (Fig.2 , 1967) shows that lower parts of the same series of meta-volcanics thin out completely. Therefore the discordances reported by Mason are not considered evidence of large-scale translation of one unit against the other.

16.3 Differences of metamorphic and structural history.

The adjacent parts of two nappes will probably have been deformed and metamorphosed in different environments before thrusting and it may well be that there is sufficient difference in the early history of mineral growth and deformation between the adjacent parts of two supposed nappes to prove that thrusting has occurred and to indicate when it occured.

The extreme examples of this are seen from the eastern and western margins of the N.European Caledonian belt, where deformed metamorphic rocks overly unmetamorphosed sediments with fossils; the original "Mountain Problem " of Törnebohm. Within a metamorphic belt it is more difficult to identify thrusts with certainty by this method, though suitable metamorphic differences are reported. As discussed in Chapter 2.2, in Kulling's description of Västerbotten and Norrbotten the structurally higher units are usually of higher metamorphic grade. An exception is the upper part of the Seve-köli complex(the Köli - schists) which is of lower grade than the lower part,(the Seve - schists). Lakeman (1952) described an area in North Västerbotten containing junctions which Kulling later (1955) described as tectonic contacts between the Rödingstjåll Nappe and the Seve-köli complex,(see Chapter 2.2). Lakeman notes that the structurally higher rocks are of higher metamorphic grade but interprets this as the result of post-metamorphic folding, the whole sequence being inverted. He makes some rather unreliable stratigraphic correlations which suggest inversion.

Gustavson (1966) describes the northern Ofoten and southern Troms regions and finds a close correlation between changes of metamorphic facies and thrusting. "The boundaries between different facies are partly coincident with the thrust planes, thus indicating that thrusting post-dates the main regional metamorphism. Where the thrust-plane is also a metamorphic boundary higher grade rocks are everywhere overlying those of lower grade." (pg. 8). The thrusts marked by Gustavson are usually parallel to the stratigraphic boundaries , and in this paper Gustavson does not justify their description as thrusts. A later paper on the structure is planned.

Kautsky describes the "Gasak nappe" (equivalent to the Sulitjelma Schist Sequence) as being of high grade, while the "Pieske nappe" (equivalent to the Furulund schist and lower rocks) is of low grade. In the thesis area the metamorphic zones do not lie parallel to the lithological units which are supposed to be nappes. The Furulund schists vary from low grade to high grade, the isograds being apparently developed so that the high grade rocks overly lower grade, as was originally described by Vogt (1927, pg. 483.)Vogt suggests that there may be a connection between the higher grade of metamorphism and the frequent granite intrusions in the higher structural unit. The revision of Vogt's work on the metamorphism by Henley has confirmed the 'inversion' of the isograds, although Henley replaces Vogt's garnet isograd by a garnet-hornblende isograd and abandons Vogt's oligoclase isograd. Henley, and Nicholson(1966 Fig. 3) show that the garnet isograd continues within the Furulund schist at least as far east as the eastern end of Lomivann. In other words, garnets in biotite-schist are found in the uppermost part of the Furulund schist as far east as the frontier with Sweden. Mason(1967) describes a gradual increase in grade up through the amphibolites overlying the Furulund schist. A possible explanation of the apparent inversion of the metamorphic zones put forward by Nicholson and Rutland (in press) is that the Furulund schists are overlain by rocks which were thrust into place while sufficiently hot to provide a heat source for the garnet-grade metamorphism. This, as pointed out by Nicholson and Rutland, is analogous to the situation in part of Gaaseland, East Greenland, (Wenk, 1961) where an inversion of metamorphic zones is linked to the introduction of heat from an overlying series of thrust rocks, (Haller and Kulp, 1962, pg 23). If this is the case in Sulitjelma then the postulated thrust would have taken place at the beginning of garnet growth in the Furulund schist (Chapters 4.5, and 7). The event would come between the establishment of schistosity and the folding of schistosity at Bursi and in the east of the thesis area.

In order to determine which structural and metamorphic events are common to those rock units on each side of Kautsky's supposed "Gasak-Vasten" thrust the detailed history of these units has been investigated. The Sulitjelma amphibolites are poor in minor structures relative to the Furulund schist and the Sulitjelma Schist Sequence, and therefore comparison was mostly restricted to the two schist series.

In the Furulund schists three main phases of deformation are recognised . These are discussed in Chapter 4.5, and are tabulated in Fig. 4.10. In the first phase the main schistose fabric of the rocks was generated along with isoclinal minor folds of bedding. The second phase was not so powerful and caused modification to the schistosity . It can be identified because it was coeval with garnet growth. It is quite possible that in places this deformation was a continuation of the earlier deformation. This deformation is not uniform over the entire mapped region. Following the growth of garnet and hornblende were several phases of minor folding which developed in different parts of the region and whose relations to porphyroblast growth show slight differences suggesting not quite contemporary development. In addition to these main phases, there was widespread boudinage, which probably took place prior to the post-schistosity minor folding, and in addition, late kinking.

In considering the structural history of the Sulitjelma Schist Sequence it is found that porphyroblast growth is not quite as useful in these rocks as in the Furulund schist, but the age relations of the intrusions of the Furulund granite and the Sulitjelma gabbro are of considerable importance. Major folding is well developed. As described in Chapter 15.2 there are several uncertainties about the timing of events and consequently in Chapter 15.3 several alternative histories are considered. The most reasonable is case 'E' on Fig. 15.1.. In the first event the development of schistosity was accompanied by major folding and growth of kyanite. This event was followed by the intrusion of the Sulitjelma gabbro and then the Furulund granite. A second deformation event resulted in the formation of the biotite fabric of the granite and the fabric of the margins of the gabbro. In the Waterfall zone (Map 4) major folding took place with minor folding which can be seen to be later than kyanite growth, earlier than garnet growth. There was movement along a slide genetically connected with the major fold which cut out part of the lower limb of the major fold. In a third deformation event the gabbro itself folded, folds in the adjacent schists interferring with the syn-schistosity Duoldagop synform to generate a large eyed fold.

In fitting these two sequences of events together a vital piece of evidence is that garnet growth in the Sulitjelma Schist Sequence in the Waterfall zone is later than folding of schistosity. It is likely though not certain that garnet growth in both units was approximately coeval, so this is an indication that there are more phases of pre-garnet deformation evident in the Sulitjelma Schist Sequence than in the Furulund Schist. After garnet growth both units suffered one phase of deformation.

In order to judge whether or not the above evidence proves that thrusting has taken place it is necessary to discuss the evidence and implications carefully. Firstly, the evidence that garnet growth is later than post-schistosity folding ,(reviewed in Chapter II.6) is not abundant, being only present in two garnets from two rocks, the garnets overgrowing the microfolds of biotite (Fig. II.8 and Fig. II.9). Secondly it must be considered that all the garnets in the Sulitjelma Schist Sequence may not have grown at the same time. Evidence in Chapter II.6 does suggest that the garnets are of coeval growth, but this correlation of events in the Sulitjelma Schist Sequence and the Furulund Schist depends on approximately coeval garnet growth throughout the region. A third consideration is that if there were two periods of pre-garnet folding in Sulitjelma Schist Sequence and only one period in the Furulund Schist then either the earlier of the two Sulitjelma Schist Sequence fold phases developed when that part of the unit was elsewhere, or the deformation that caused one of the fold phases in the Sulitjelma Schist Sequence also deformed the Furulund schist but its effects cannot be detected. In the above sequence of events it is assumed that the second deformation of the Sulitjelma Schist Sequence which generated the folds in the Waterfall zone was also responsible for the development of the L-S tectonite fabrics of the granite and of the margin of the gabbro. If this deformation had a simple flattening effect on the granite it may well have had the same effect on the Furulund schist and since the garnet and hornblende porphyroblasts grew later there would be no means of identifiying its effects. Perhaps this event could be correlated with the boudinage of competent bands within the Furulund schist which is probably earlier than the post-schistosity minor folding of the Furulund schist.

If it is assumed that the two units under consideration are separated by a thrust then the movement could have taken place either before or after the first phase of deformation of the Furulund schist, or as part of that deformation. Evidence in favour of a 'late' interpretation is the apparent inversion of metamorphic zones which suggests thrusting during garnet growth in the Furulund schist, while evidence in favour of an 'early' interpretation concerns the lineation. Since the mineral orientation lineation in the Sulitjelma Schist Sequence is parallel to that in the Furulund schist and Sulitjelma amphibolite across the boundaries of these units, it is reasonable to suppose that the lineation was generated in a common event, unless the attitude of the lineation is constant over a considerable area. However, as is discussed in Chapter 7.17, the mica fabric of the Furulund schist has been modified twice since its original generation and therefore this particular evidence gives no indication of the date of the possible thrusting. Fig. 16.1, (opposite) summarises possible correlations between the two units.

16.4 Special fabrics and lithologies associated with thrusting.

The movement of one mass of rock against another is likely to be accompanied by special deformation of the rock at and near the movement zone. Faults are frequently accompanied by slickensides and fault-breccias. Accounts of thrusting often mention their connection with mineral lineations and the development of mylonites (Flinn 1965a pg.39, Flinn 1961, Kvale 1953). The type of structure that is seen at a thrust is probably dependant on the width of the zone over which thrust movements take place and this width is probably related to the temperature at which the rocks are at the time, as well as other factors such as fluid pressures.

The connection between mylonites and thrusting has been discussed with reference to the western margin of the Scottish Caledonides by Johnson, Christie, Barber and others, who have recently analysed the structural history of the thrust zone, (Johnson 1957, 1960a, 1960b, 1961, 1963, 1967, Barber 1965, Christie 1963). Early workers had assumed a connection between the brittle late thrusts and the zones of mylonites along the Caledonian thrust belt. Johnson (particularly 1961) demonstrates that the mylonites which are zones of intense strain and flattening with constriction (1967), were produced in a very early stage in the deformation history and that there were several phases of movement, resulting in the formation of early mylonites followed by shearing to form blastomylonites (in which there was recrystallisation) and finally late brittle thrusting accompanied by local cataclasis. It is probable that if similar modern structural methods were applied to the eastern boundary of the Caledonides in Sweden, just as complex a history of movements might emerge. Accounts of the eastern marginal zone mention cataclastic rock types (eg. Marklund 1949).

It has been suggested by Kautsky(1953) that the tectonic breccias in the Sulitjelma area are the result of thrust movements, and Vogt was prepared to admit when questioned by Kautsky in 1949 that the brecciation was probably related to minor thrusting. As discussed in Chapter 9B.7 , most of the breccias are interpreted as the result of flattening, causing boudinage and "pinch and swell" structures to develop. As stated on page 100 there is no evidence that the breccias were generated by thrusting. It is possible, though, as Vogt stated in 1949, that there may have been some very slight late movements, which can be correlated here with chloritisation of the breccia margins, and the disharmonic fold at Bursi (which is later than the main brecciation).

Mylonites have not been identified, unless a streaky banded fine-grained quartz-plagioclase rock found in thin sheets at the top of the

Tectonic breccia (page 94) represents acid igneous rock which has been mylonitised and recrystallised. Since these sheets are now boudined in the Tectonic breccia, any mylonitisation took place before brecciation.

The change from a schistose fabric (S tectonite) to a linear fabric (L tectonite) is said to be characteristic of thrust zones (Flinn, 1965a,p. 39). Many papers (e.g. Kvale 1953) have discussed the relationship of lineation to thrust movements in both the Norwegian and Scottish Caledonides. The specific regions where the relationship between rock fabric and thrust movements has been investigated in recent years are the Shetlands (Flinn), the Jotunheim district of Norway (Hossack) and the Moine thrust zone (Johnson, Barber and Christie).

Both the Upper Jotun nappe(Jotunheim) and the thrust rocks of the Shetlands lie on top of comglomerates which have been deformed. In neither case, however, do the deformed conglomerates show strains which can be directly related to the thrust movements. Flinn (1958) describes the deformation of the Funzie conglomerate in Unst (Shetland).

"The deformation of the conglomerate culminates at the thrust at Staves Geo. It is clear that the thrust is somehow genetically related to the deformation, yet the monoclinic movement on the thrust is confined to the thrust plane. A foot or so below the thrust the penetrative movements had a radial symmetry (flattening). Several hundred feet lower where elongation of pebbles took place the movement had an orthorhombic symmetry. Therefore the movement on the thrust plane did not directly give rise to the tectonic fabric of the conglomerate...... The monoclinic simple shear movement of the thrusting was confined to very thin layers of rock." (page 132).

Hossack (1968) described the deformation of the Bygdin conglomerate below the Upper Jotun nappe.

"The amount of finite distortional strain in the pebbles is generally highest at the basal thrust plane of the Upper Jotun nappe and decreases downward, . . ." (pg.325). "Throughout the whole of the area the dominant strain was one of flattening . ." (page 327). "the symmetry of the pebble deformation cannot be directly related to the symmetry of the thrusting ." (page 330).

Hossack expected that there would be a strong component of simple shear in the deformation, but he found a strong component of flattening present as well, which probably post-dates the nappe emplacement.

"The pebble deformation was dominantly one of flattening and seems to have taken place after the nappe had stopped moving because of the apparent absence of rotational deformational fabrics in the conglomerate. . . . . (the simple shear) fabric may have been effaced by the flattening deformation "(pg334). "generally the thrust plane does not seem to have been a strain discontinuity during the pebble deformation because the same fabrics are found above and below the thrust plane." (page335).

This latter point is important , that later deformation can efface any special fabrics which have formed during a thrust event.

In considering these points in relation to the postulated thrusting at Sulitjelma one must see if there are any levels at which there are unusual fabrics, and examine the thrusting hypothesis to see if later deformation could have effaced any special fabrics.

Fabrics in the Sulitjelma area .

The deformed rocks show L-S tectonite fabrics varying considerably in the degree of intensity of the lineation element. The rocks immediately adjacent to the Sulitjelma gabbro, including the edges of the gabbro itself show a very strong lineation. The meta-basic rocks on the south side of the gabbro showing this lineation have been termed "flaser gabbro" by Mason(1967) and he interpreted the intense strain as the result of thrusting. This interpretation is rejected because the intense development of lineation does not continue along the supposed thrust level to the west, and because a similar strong lineation characterises the western margin of the gabbro, a zone which Mason (or Kautsky) does not consider to be a thrust level. Around all parts of the southern and western margins of the gabbro which have been visited in this investigation (see map 1) the intensity of lineation development dies out away from the gabbro, as does the tightness of the post - schistosity fold. Since the gabbro represents a relatively undeformed mass, (primary igneous bedding can be seen, original igneous textures are preserved), it is here suggested that the intense lineation develop ment is due to abnormal strain around the gabbro prior to, and during the folding of the gabbro.

Within the Furulund schist there are considerable variations in the intensity of lineation development , as discussed in Chapter 7.1 , but the complete range of variation can be seen within one hand specimen.

Kautsky supposed the thrusting to be later than the metamorphism in the east where the "Gasak nappe" rocks contain staurolite. In the northern part of his area Kautsky traced the rock units into the west towards and into Norway and found that they became folded on a large scale, the folding clearly being later than the thrusting. Analogous folding has been described from west of Sulitjelma (Nicholson and Rutland , in press) and any recrystallisation accompanying this folding would tend to obscure special fabrics of thrusting. It seems most probable that the folding to the west of Sulitjelma which is on approximately north-south trending axes can be correlated with the Baldaoive Synform (described by Henley), which it is suggested in Chapter 6.1 and 6.12, either correlates with the minor folding in the Bursi area, or is later than that folding. In either case the major folding will be later than garnet growth, and modification to fabric following garnet growth is thought to be only of slight effect, (see Chapter 7.17). Therefore any special thrust fabrics should still be present. Johnson (1961) is able to identify fabrics related to several movement phases in the Moine thrust zone despite recrystallisation.

16.5 Summary of evidence for thrusting in the Sulitjelma area.

A. Kautsky's supposed stratigraphic equivalence of the "Gasak nappe" rocks with the "Pieske nappe" rocks. This is not proved. It is based on a doubtful lithological correlation, not on palaeontological evidence.

B. Discordances of lithology:- Kautsky claimed discordances of lithology outside the thesis area, but some of his examples are now doubted (Nicholson and Rutland, in press). In the thesis area there is some evidence of dislocation, but it is probably the result of a slide whose regional significance is not great.

C. Differences of metamorphism:- The supposed thrusts are not sharp metamorphic boundaries; the garnet - hornblende isograd lies within the Furulund Schist (Henley).

D. Inverted metamorphic zones:- The apparent inversion of metamorphic zones argues in favour of an overthrust of hot rock immediately before the growth of garnets in the Furulund schist.

E. Dissimilarities of structural history:- Since the Sulitjelma Schist Sequence has evidence of two phases of folding before garnet growth while the Furulund schist has evidence of only one phase before garnet growth, this argues in favour of a thrust, although there are alternative explanations.

F. Special fabrics, structures and lithologies near the supposed thrust zone:-

i. There is no special development of L tectonites.

ii. There is no convincing evidence of mylonite development.

iii. Tectonic breccias developed adjacent to the supposed "Gasak-Vasten" nappe boundary show no evidence of having been generated in response to thrust movements, but generally appear to have developed in response to flattening normal to the banding. There may have been slight movements at a late date at the margins to the breccia, probably coeval with disharmonic post-schistosity folds at Bursi.

iv. Disharmonic folding at Bursi (Chapter 6.6) can be explained as the result of simple shear strain on a large scale at the Sulitjelma amphibolite-

Sulitjelma Schist Sequence junction, caused by the eastward movement of the Sulitjelma Schist Sequence. But this disharmonic folding is later than garnet growth and is probably coeval with the large-scale folding of the supposed thrust horizon further to the west.

v. During growth of garnets and hornblendes the Furulund schist; was deformed by inhomogenous simple shear , with the shear plane parallel to the schistosity, (Chapter 7.14 , 7.15). In such a small area as studied it is impossible to tell if this simple shear deformation is found throughout the Furulund schists, but the evidence presented in Chapter 7 suggests that it is important at least at the top of the Furulund schist. This shear could be generated by the movement of an overlying nappe.

16.6 Conclusions.

A. The junction between Kautsky's supposed Pieske and Vasten nappes.

There is no tectonic break between the units which Kautsky correlated with the Pieske and Vasten nappes in Sweden. As described in Chapter3.4 and in Mason (1967), the two units together form a sequence of meta-sedimentary rocks passing upwards into meta-volcanic rocks with associated meta-sediments. At Ny Sulitjelma (Map 5) and, as described by Mason (1967 Fig.2,) from further east, there is interdigitation of meta-sediments and meta-volcanics.

B. The junction between Kautsky's supposed Vasten and Gasak nappes.

Within the thesis area there is no conclusive evidence in favour of a thrust hypothesis, though some features are very conveniently explained if it can be assumed that there was thrusting of the Sulitjelma Schist Sequence over the Furulund schist immediately prior to and possibly during the growth of garnets in the Furulund schist. An obvious priority for further work is the detailed mapping of ground further east, to examine Kautsky's nappe hypothesis on his own ground by modern methods. Kautsky mapped a large area (some 80km. by 30km.) in about six months, and while his work has been of great value, the accuracy must not be taken for granted.

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GEOLOGICAL MAP OF THE AREA NORTHEAST OF LANGVANN · SULITJELMA · NORWAY
Scale 1:10,000
Map 1
0 1 Km
Prepared from aeriel photographs supplied
by Widerøes Flyveselskap A/S Oslo
Ground control from A.M.S. 1:50,000 map
based on Norwegian topographic survey
Grid : 1,000 m. Universal Transverse Mercator
M.R. WILSON Ph.D. F.G.S. Department of Geology & Mineralogy, Oxford
INDEX MAP
Scale 1:40,000
SULITJELMA SCHIST SEQUENCE
DUOLDAGOP BANDED GROUP
RUSTY PSAMMITE
MARBLE BANDS
PSAMMITE BANDS
CALC-SILICATE BANDS
LAPPHELLEREN SCHISTS
FURULUND GRANITE
GRANITE VEINS
GABBRO
SULITJELMA AMPHIBOLITES
SCHISTOSE AMPHIBOLITE
META-PORPHYRITIC AMPHIBOLITE
BANDS OF MICA SCHIST
CONGLOMERATES
COPPER ORE
FURULUND SCHIST
FURULUND SCHIST (RUSTY PHYLLITIC VARIETY)
COLOUR INDICATES LOCALITIES VISITED
ATTITUDE OF SCHISTOSITY
ATTITUDE OF LINEATION (PENETRATIVE MINERAL ORIENTATION)
ATTITUDE OF BEDDING (DUOLDAGOP BANDED GROUP ONLY)
ANGLES IN DEGREES
TYPICAL FOLD AXES EARLY LATE
FAULTS
STEREOGRAMS – LAMBERT EQUAL AREA PROJECTION
Pole to schistosity · Mineral lineation ×
TECTONIC BRECCIA
LENSES OF COARSE MATERIAL
SMALL-SCALE BRECCIATION
LAPPHELLEREN SCHISTS ON WEST SIDE OF DUOLDGOP
NORTH DUOLDAGOP
FURULUND GRANITE
WATERFALL ZONE
NY SULITJELMA
MAIN PART OF FURULUND SCHIST BETWEEN BURSI AND THE CHURCH
SMÅSORJUS
DUOLDAGOP
GABBRO
Axis of major fold
LANGVANN
141m.
MINE OFFICE
CHURCH
SCHOOL
SMELTER
LOMI ELV
GIKEN ELV
BURSI ELV
GRONLID
BURSI
GLASTUNES
LAPPHELLEREN
OTERVANN
958m.
960m.
806m.
804m.
961m.
1012m.

MAP 6 BURSI

LAPPHELLEREN SCHISTS AND SULITJELMA SCHIST SEQUENCE

FURULUND GRANITE

TECTONIC BRECCIA - COARSE BANDS

TECTONIC BRECCIA - SMALL FRAGMENTS

FURULUND SCHIST

COPPER ORE

SCALE APPROXIMATELY 1:5,000 0 100 m 200 m

REFERENCE GRID - AS USED BY SULITJELMA MINE COMPANY - RELATION TO UNIVERSAL TRANSVERSE MERCATOR GRID IS SHOWN ON THE MARGIN

ATTITUDE OF SCHISTOSITY

ATTITUDE OF MINERAL LINEATION

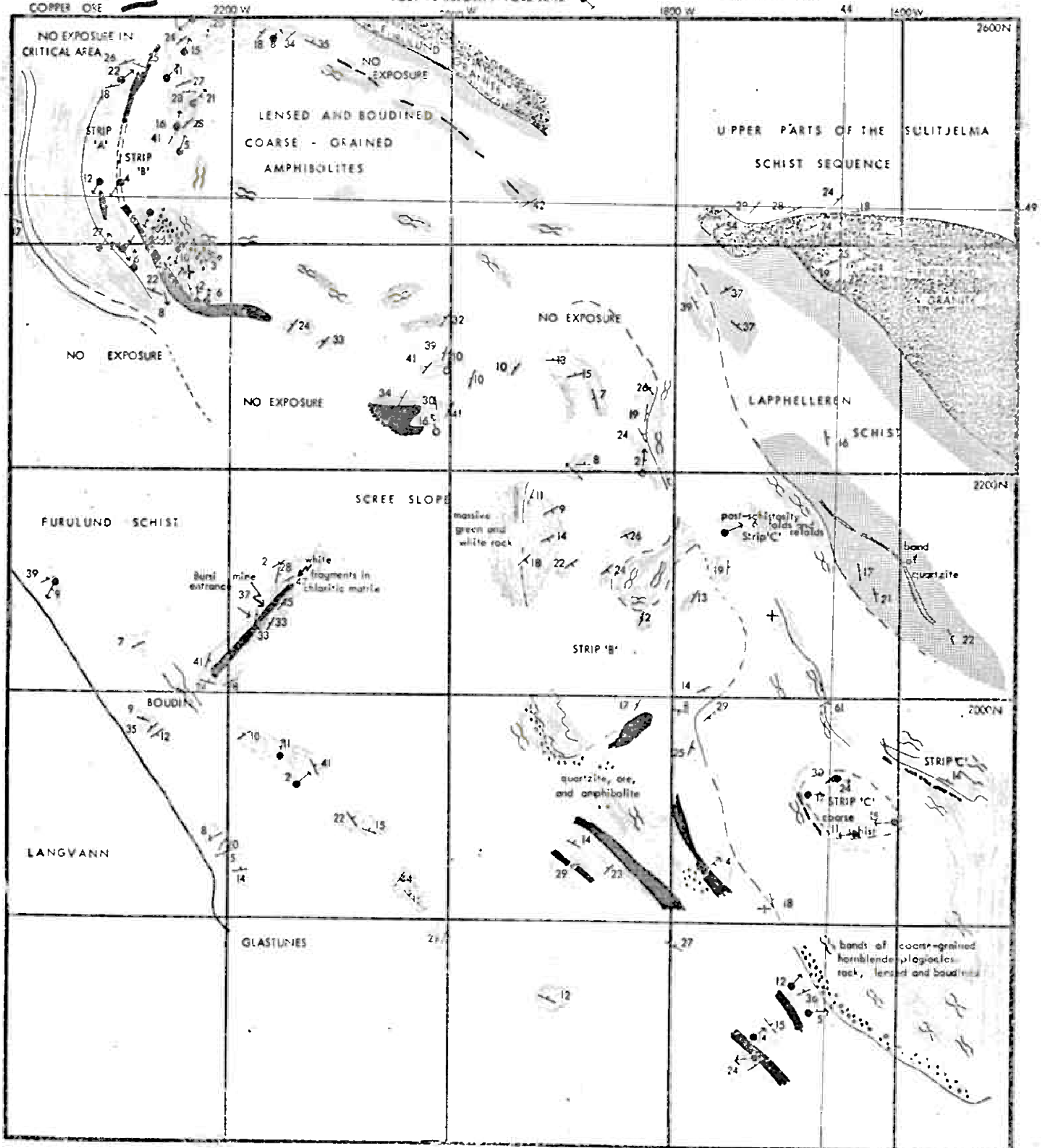
SYN-SCHISTOSITY FOLD AXIS

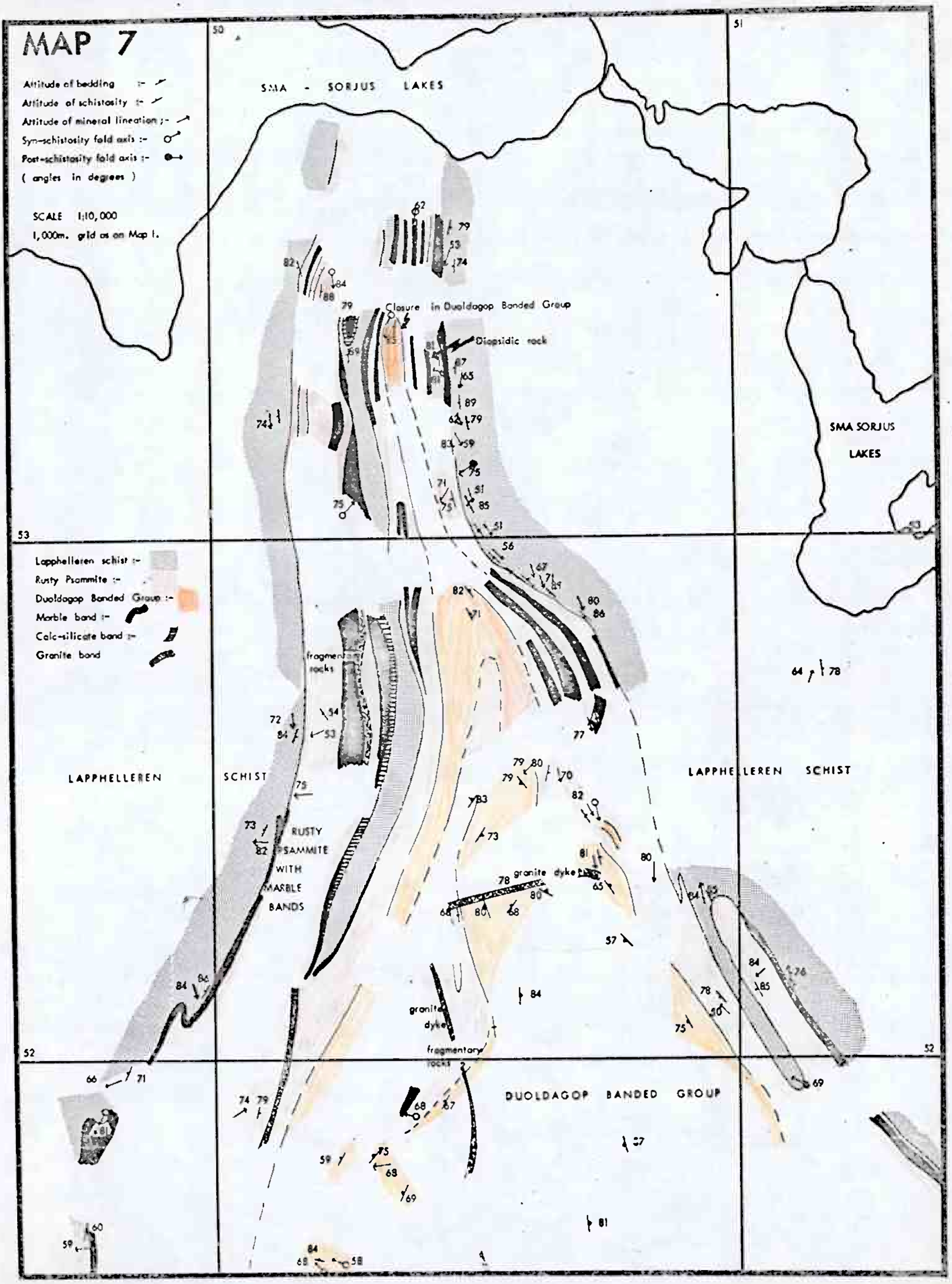
POST-SCHISTOSITY FOLD AXIS

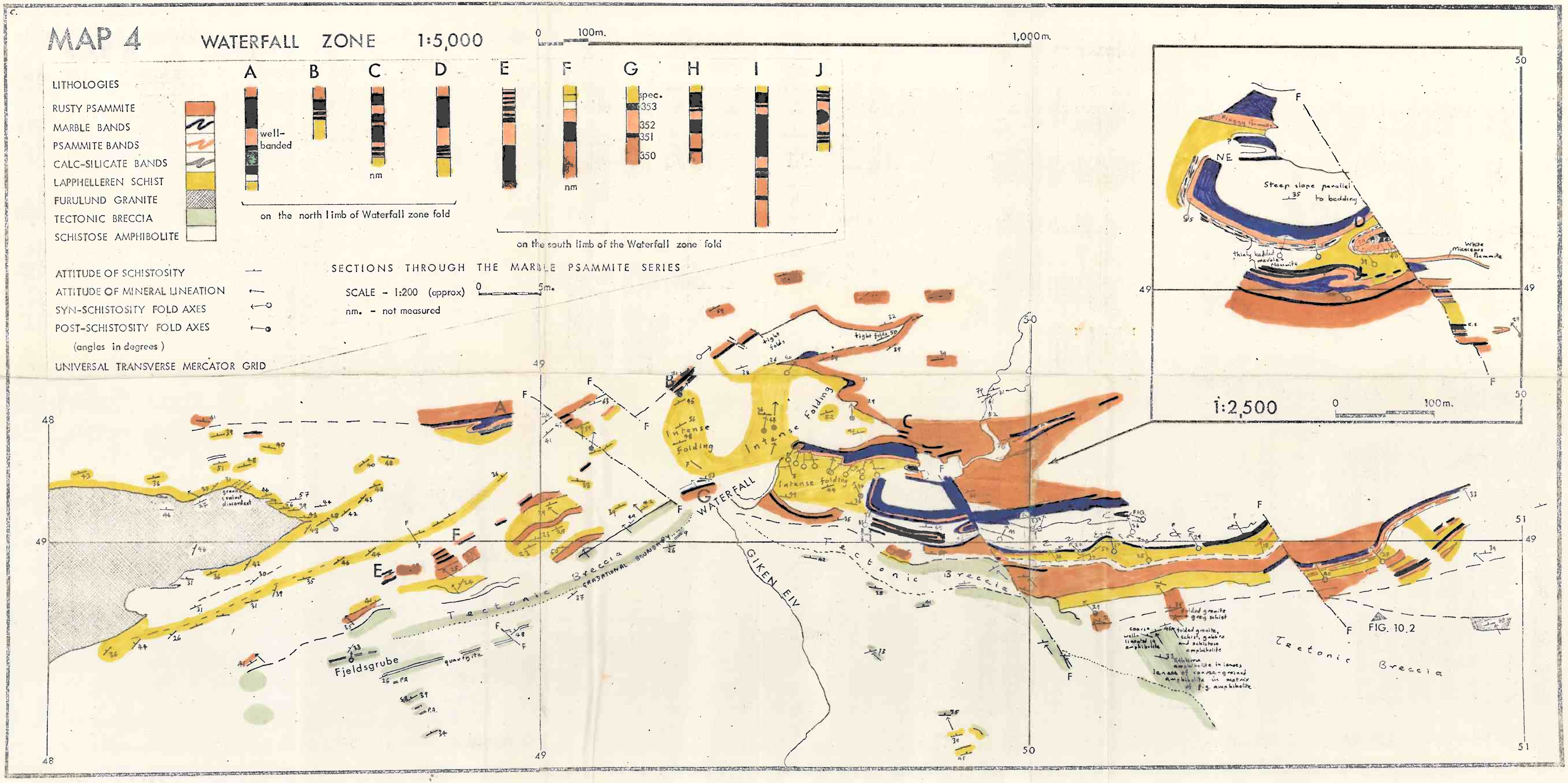
ATTITUDE OF AXIAL PLANES TO POST-SCHISTOSITY FOLDS

CONGLOMERATE

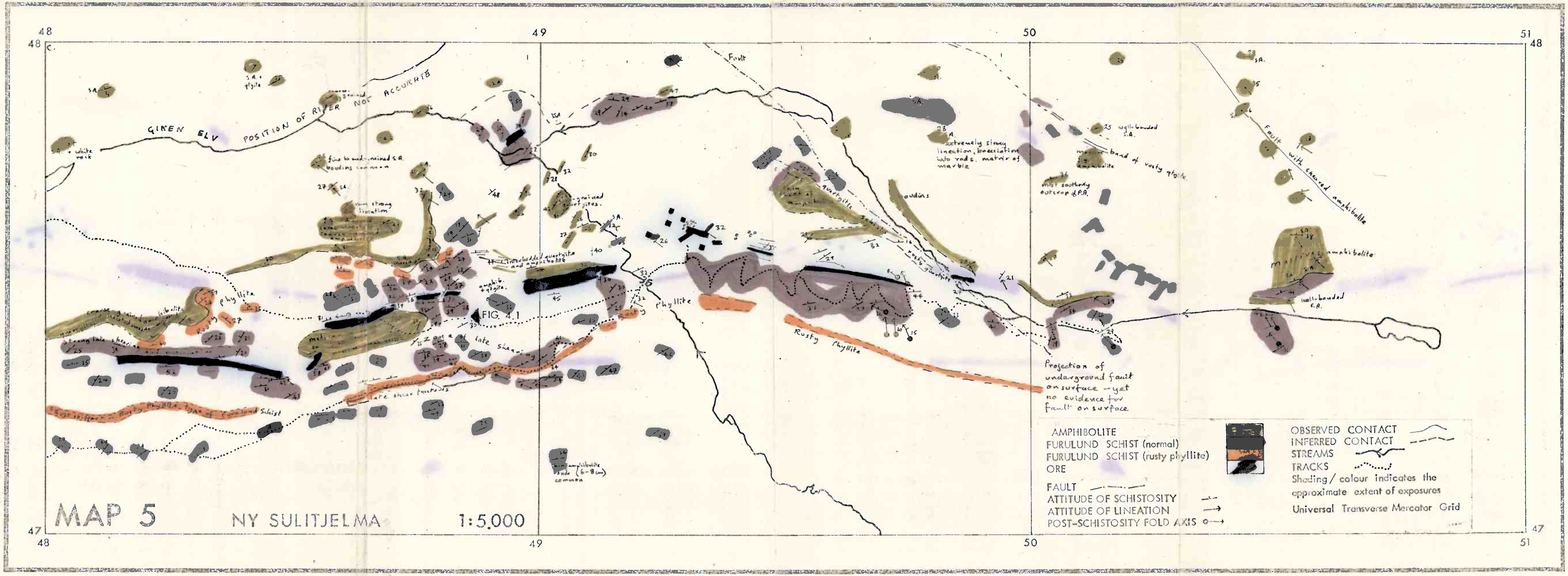
(angles in degrees)




MAP 7
Attitude of bedding :-
Attitude of schistosity :-
Attitude of mineral lineation :-
Syn-schistosity fold axis :-
Post-schistosity fold axis :-
(angles in degrees)
SCALE 1:10,000
1,000m. grid as on Map 1.
SMA - SORJUS LAKES
SMA SORJUS LAKES
Closure in Duoldagop Banded Group
Diopsidic rock
Lapphelleren schist :-
Rusty Psammite :-
Duoldagop Banded Group :-
Marble band :-
Calc-silicate band :-
Granite band
fragmentary rocks
LAPPHELLEREN SCHIST
LAPPHELLEREN SCHIST
RUSTY PSAMMITE WITH MARBLE BANDS
granite dyke
granite dyke
fragmentary rocks
DUOLDAGOP BANDED GROUP


MAP 4
WATERFALL ZONE 1:5,000
0 100m. 1,000m.
LITHOLOGIES
RUSTY PSAMMITE
MARBLE BANDS
PSAMMITE BANDS
CALC-SILICATE BANDS
LAPPHELLEREN SCHIST
FURULUND GRANITE
TECTONIC BRECCIA
SCHISTOSE AMPHIBOLITE
A B C D E F G H I J
well-banded
nm
spec. 353
352
351
350
on the north limb of Waterfall zone fold
on the south limb of the Waterfall zone fold
SECTIONS THROUGH THE MARBLE PSAMMITE SERIES
SCALE - 1:200 (approx) 0 5m.
nm. - not measured
ATTITUDE OF SCHISTOSITY
ATTITUDE OF MINERAL LINEATION
SYN-SCHISTOSITY FOLD AXES
POST-SCHISTOSITY FOLD AXES
(angles in degrees)
UNIVERSAL TRANSVERSE MERCATOR GRID
Steep slope parallel to bedding
NE
White micaceous psammite
1:2,500
0 100m.
Intense folding
Intense folding
Intense folding
tight folds
WATERFALL
GIKEN ELV
Tectonic Breccia
GRADATIONAL BOUNDARY
Tectonic Breccia
Tectonic Breccia
Fjeldsgrube
quartzite
FIG. 10.2
granite contact discordant
folded granite grey schist
lenses of coarse-grained amphibolite in matrix of f.g. amphibolite
48
49
50
51

MAP 8 Garnets in the Furulund schist


MAP 5
NY SULITJELMA
1:5,000
GIKEN ELV
POSITION OF RIVER NOT ACCURATE
Fault
FIG. 4.1
Phyllite
Rusty Phyllite
boudins
zone of late shear
late shear fractures
Projection of underground fault on surface – yet no evidence for fault on surface
Fault with sheared amphibolite
massive amphibolite
well-banded S.A.
extremely strong lineation, brecciation into rods, matrix of marble
band of rusty qtzite
AMPHIBOLITE
FURULUND SCHIST (normal)
FURULUND SCHIST (rusty phyllite)
ORE
FAULT
ATTITUDE OF SCHISTOSITY
ATTITUDE OF LINEATION
POST-SCHISTOSITY FOLD AXIS
OBSERVED CONTACT
INFERRED CONTACT
STREAMS
TRACKS
Shading / colour indicates the approximate extent of exposures
Universal Transverse Mercator Grid
48
49
50
51
47

MAP 9 Amphibolites and Tectonic breccias

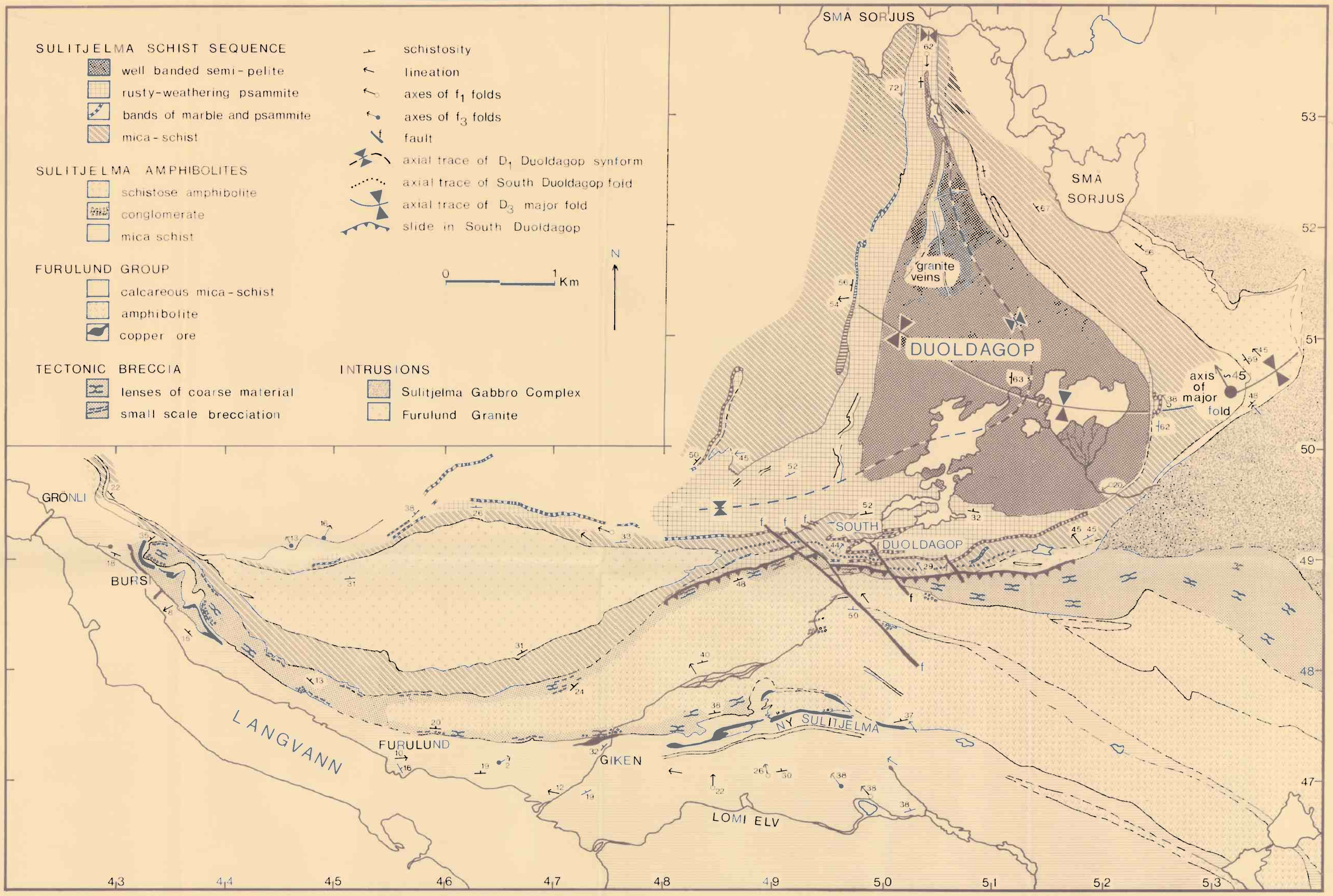
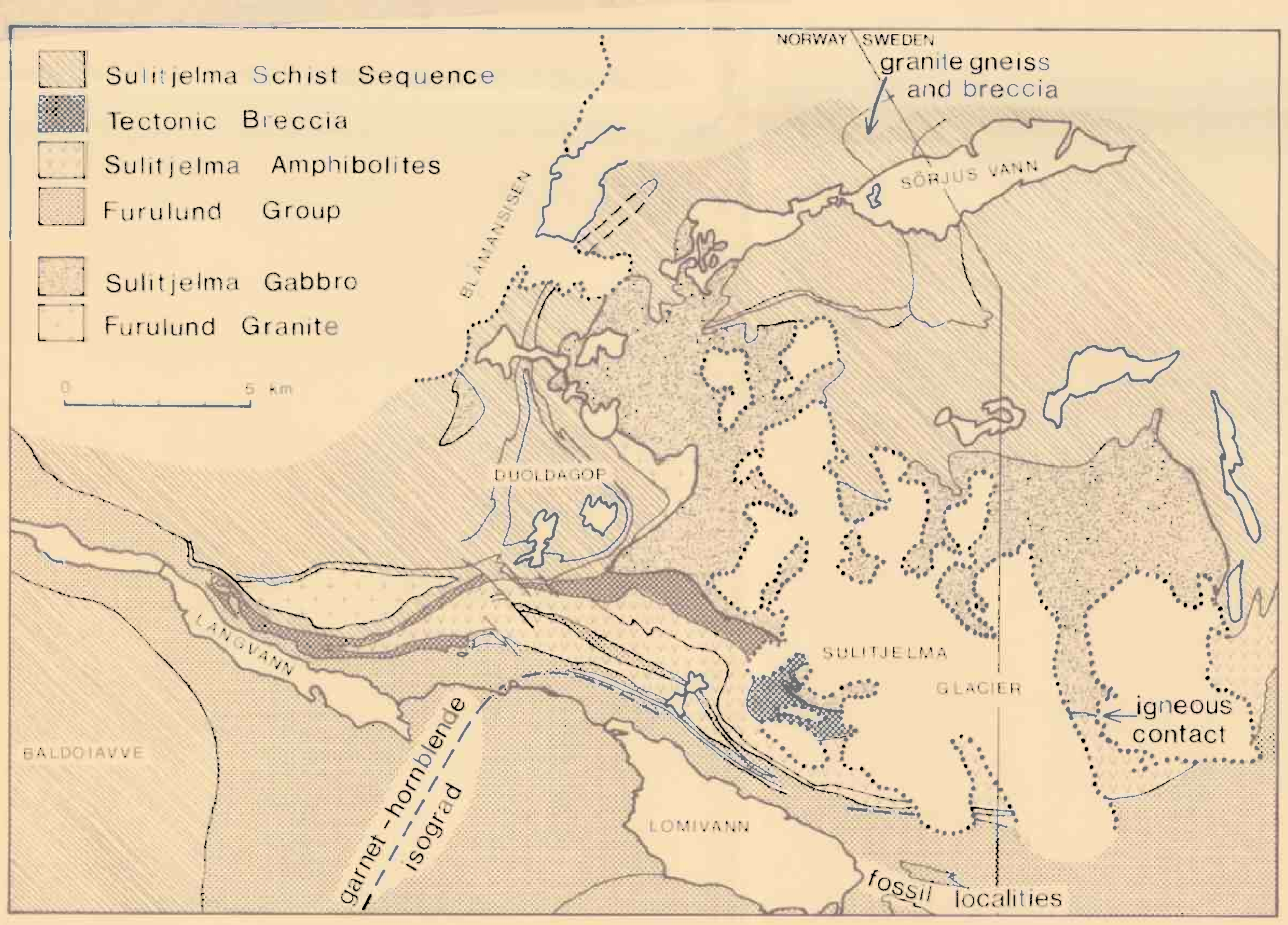
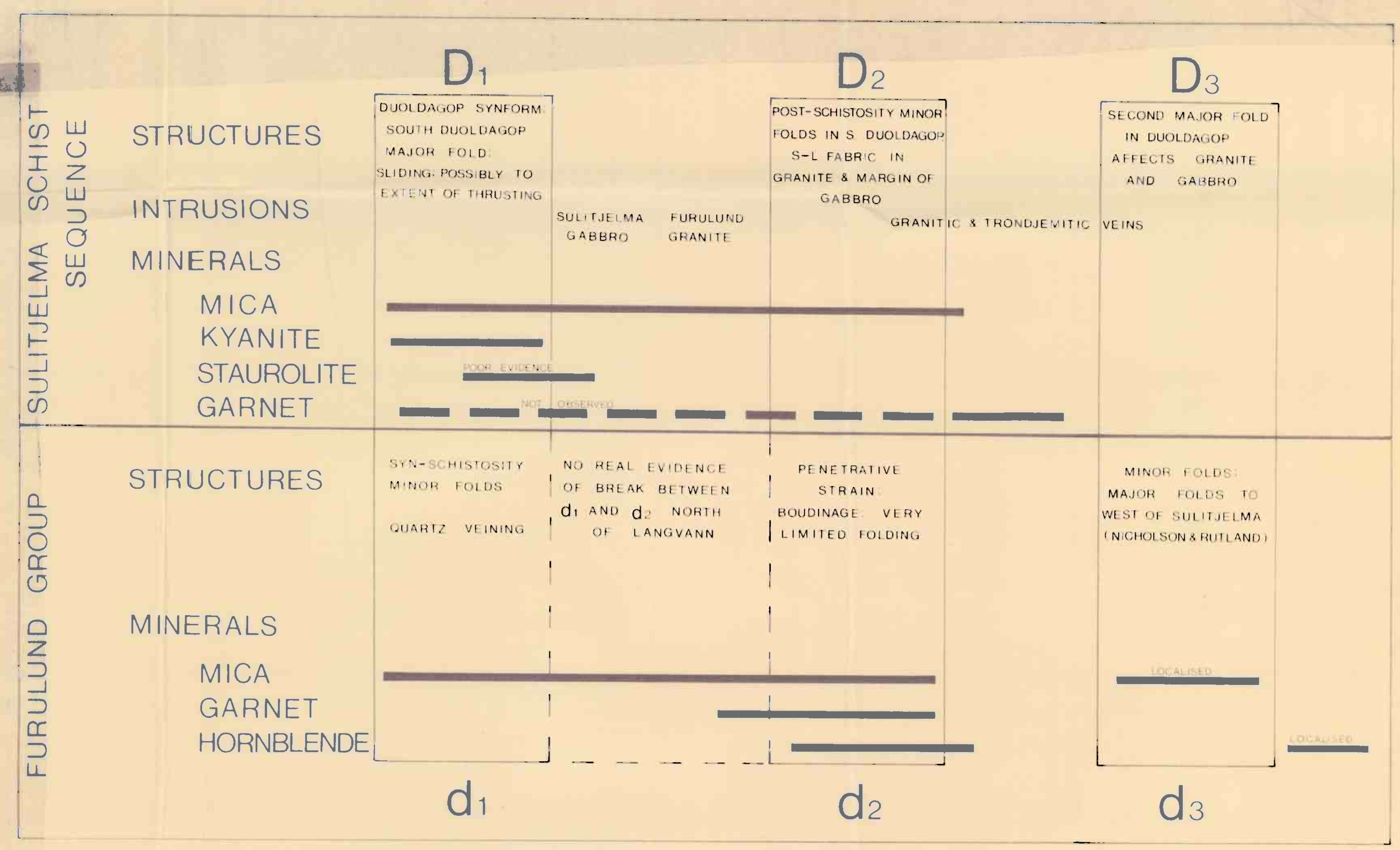


FIG. 2. M.R WILSON : STRUCTURAL INVESTIGATION OF SUPPOSED THRUSTS, SULITJELMA, NORWAY



Reduce to ½ (linearly) FIGURE 1 M.R.WILSON : STRUCTURAL INVESTIGATION OF SUPPOSED THRUSTS, SULITJELMA, NORWAY



Reduce to approx. ½ (linearly) FIGURE 3 M.R. WILSON : STRUCTURAL INVESTIGATION OF SUPPOSED THRUSTS, SULITJELMA, NORWAY