View to the northeast of the mountains above Vaksdal. with Veafjord stretching into

Basement/Cover Relationships of the Bergsdalen Area, Central South West Norway

by

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ABSTRACT

The Bergsdalen area of central southwest Norway comprises late Archaean and early Proterozoic gneisses that are intruded by amphibolites and Sveconorwegian granites and gabbros; the gneisses were tectonically stacked, forming four structural units:

1. Autochthonous and parautochthonous acid and intermediate late Archaean orthogneisses.
2. Parautochthonous Mixed Gneisses that contain lithologies of both the basement and the succeeding allochthon.
3. Allochthonous Eggjane Nappe, derived in the main from a Proterozoic quartz diorite pluton.
4. Allochthonous Lower Bergsdalen Nappe comprising Proterozoic calc-alkaline and tholeiitic metavolcanics and metasediments.

The Basal orthogneisses were deformed at amphibolite facies during both the Svecofennian and Sveconorwegian orogenic cycles; Caledonian effects are minimal.

The allochthonous gneisses have a pervasive amphibolite facies mylonitic foliation, thought to be of Sveconorwegian origin, instead of Caledonian, as previously suggested.

The allochthonous gneisses were uplifted, and reworked during a phase of nappe emplacement along mylonitic and phyllonitic thrust

zones, during late Sveconorwegian times. This contrasts with the traditional view of the Lower Bergsdalen Nappe being Caledonian in age.

Superimposed Greenschist facies Caledonian folding and thrusting was restricted to higher structural levels, culminating in a cross fold to form the Bergen Arcs.

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Section 1 INTRODUCTION

1.1 Location of Research Area

The area under investigation is situated within central south-west Norway, 40 kilometres to the east-north-east of Bergen, centred on the towns of Dale and Vaksdal (fig 1). The area occupies portions of sheets 1216 I, III and 1215 I, IV of the AMS M711 series 1:50000 topographical maps of Norway (from which all grid references quoted are taken), and is contained within the Vaksdal Kommune.

1.2 Aim of the Project and Methodology

The research was undertaken as part of a NERC financed research project based at Bedford College, London University, to investigate the nappes and the underlying basement gneisses at the margins of the Bergen Arc. During the early investigations by other members of the group (Eastoe pers. comm. 1977, Hopper 1980) it was realised that the Lower Bergsdalen Nappe was closely involved in the development of the Bergen Arcs; consequently the aim of this project was 3 fold:

a. to investigate the nature of the relationship between basement gneisses and the Lower Bergsdalen Nappe.

b. to deduce the internal history of the Lower Bergsdalen Nappe.

c. to study the reworking of the Lower Bergsdalen Nappe at the eastern margin of the Bergen Arcs.

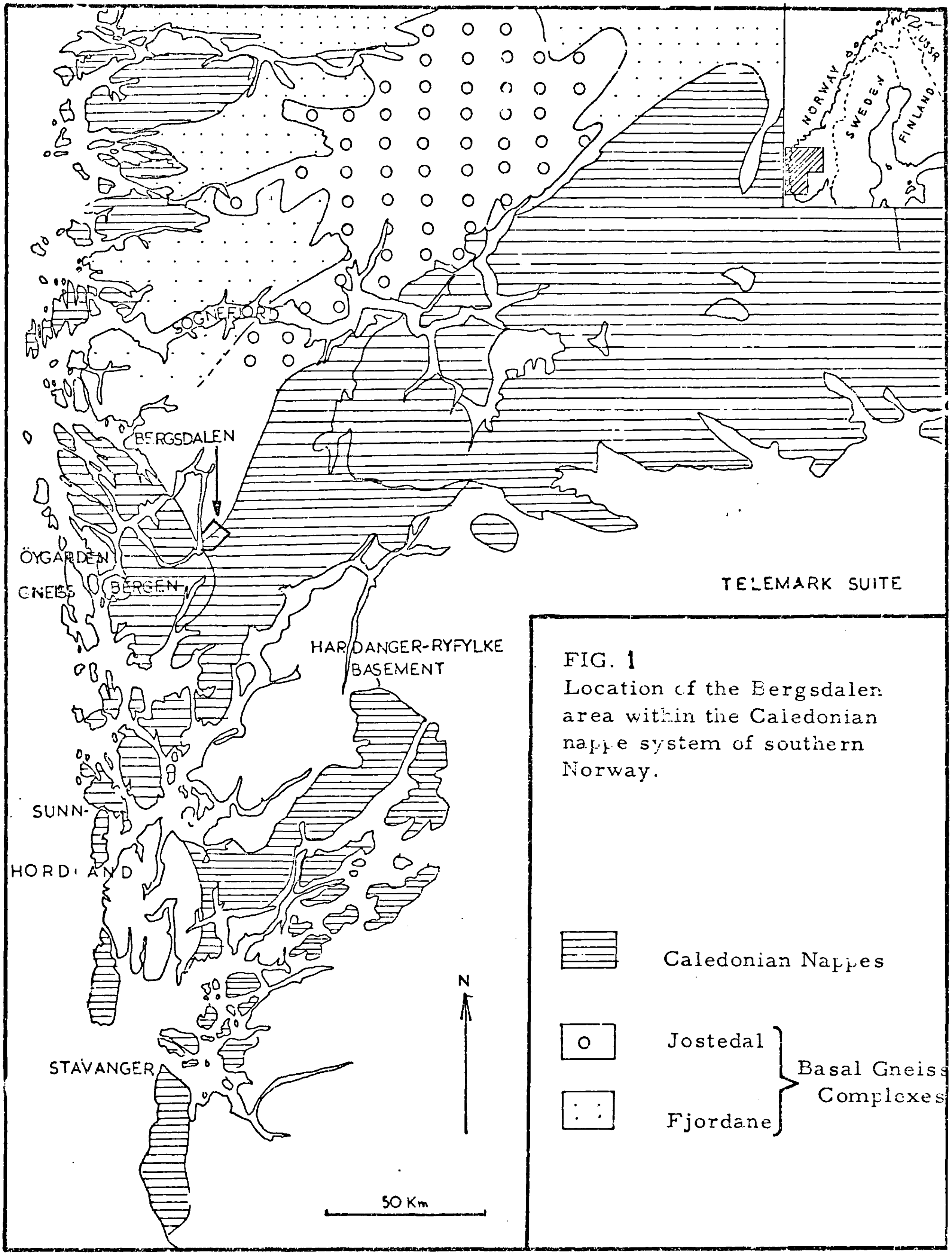


FIG. 1
Location of the Bergsdalen area within the Caledonian nappe system of southern Norway.

Field based research was started in 1976, and lasted 3 field seasons (11 months total), laboratory work was based on field observations and sample collections.

Field mapping was recorded on aerial photographs, which provided almost complete cover at scales of approximately 1:15000 and 1:35000. (The photographs were obtained from Nor-Fly A/S, Honefoss. Photograph numbers are 1:15000 R64 256 203-214, 308-316, 407-417, 513-523, 614-623, 714-721, 820-824. 1:3500 R64 266 301-306, 401-407).

Where aerial photographic cover was unavailable, either the 1:5000 land use maps (Økonomisk Kvarteverk - available from kommune centres: these have cover restricted to road and to areas of low relief) or enlarged 1:50000 maps were utilised. The latter were enlarged by hand to a scale of 1:12500, using grid square processes.

1.3 Topography, vegetation and climate

The area comprises a flat plateau region (750-850m), with rounded mountains up to 1000m, terminated along the western margin by the steeply incised north-south trending Veafjord. Steep sided valleys controlled by the dominant north-easterly structural trend are also cut into the plateau, especially around Vaksdal. Of these valleys, the most impressive is that followed by the communication routes from Stanghelle to Dale, which in places has sheer 700m sides.

The Bergsdalen forms the third major topographic feature cutting into the plateau. From Dale to Storfossen this east-south-easterly trending valley is a very steep sided gorge (400-700m deep) floored by the Dale river. From Storfossen eastwards, the valley has a more rounded section.
Joint controlled northwest trending gullies are an additional feature on the plateau.

Valley sides are heavily wooded below the tree line (about 600m), whilst above this the plateau has excellent exposure of rock, with very little vegetation cover. Snow covers the plateau region from mid or late September until early June.

1.4 Regional Geology

The Lower Bergsdalen Nappe forms part of the southern Norwegian Caledonides (Strand and Kulling 1972) which are dominated by a series of thrust nappe complexes that contain both Precambrian and Cambro-Silurian rocks. The nappes are preserved in a north-easterly trending downwarp (the "Faltungsgraben") between the major autochthonous basement complexes on either side; however, in the Hardanger-Ryfylke area, the nappes are considered to rest on autochthonous Cambrian pelites.

The Caledonide nappe system overlies 3 distinct Basement complexes within southern Norway (fig 1):

1. the Basal Gneiss complex of north west southern Norway.

2. the Hardangervidda-Telemark Basement.

3. the Øygarden Gneisses (underlying the Bergen Arcs).

1.5 The Basal Gneiss complex of north-west southern Norway.

The Basal Gneiss complex underlies the Bergen Nappe along its north eastern margin, and the Bergsdalen and Jotun Nappes along their western margins. The Basal Gneisses cover an extensive area of some 20000km, and have only recently received much geological attention. The geology of parts of the area remain unknown or only poorly understood. Essentially, the Basal Gneisses contain acid and intermediate gneisses, with areas of metasediments (especially quartzites) included.

Carswell (1973) has reviewed the literature on the Basal Gneiss complex, and has shown that interpretations of its age have, in the past, been contradictory. The initial interpretation was that the gneisses formed a Precambrian basement to the Cambro-Silurian metasediments that overlie them, in particular to the east (Reusch 1881, Kolderup 1923). Subsequent workers recognised strong Caledonian influences, and considered the gneisses to be either totally, or at least in part, derived from "Caledonian" (Eocambrian or Cambro-Silurian) metasediments (Holtedahl 1936, 1938, 1944,Gjelsvik 1953, Kolderup 1952, 1960; Hernes 1965, 1967).

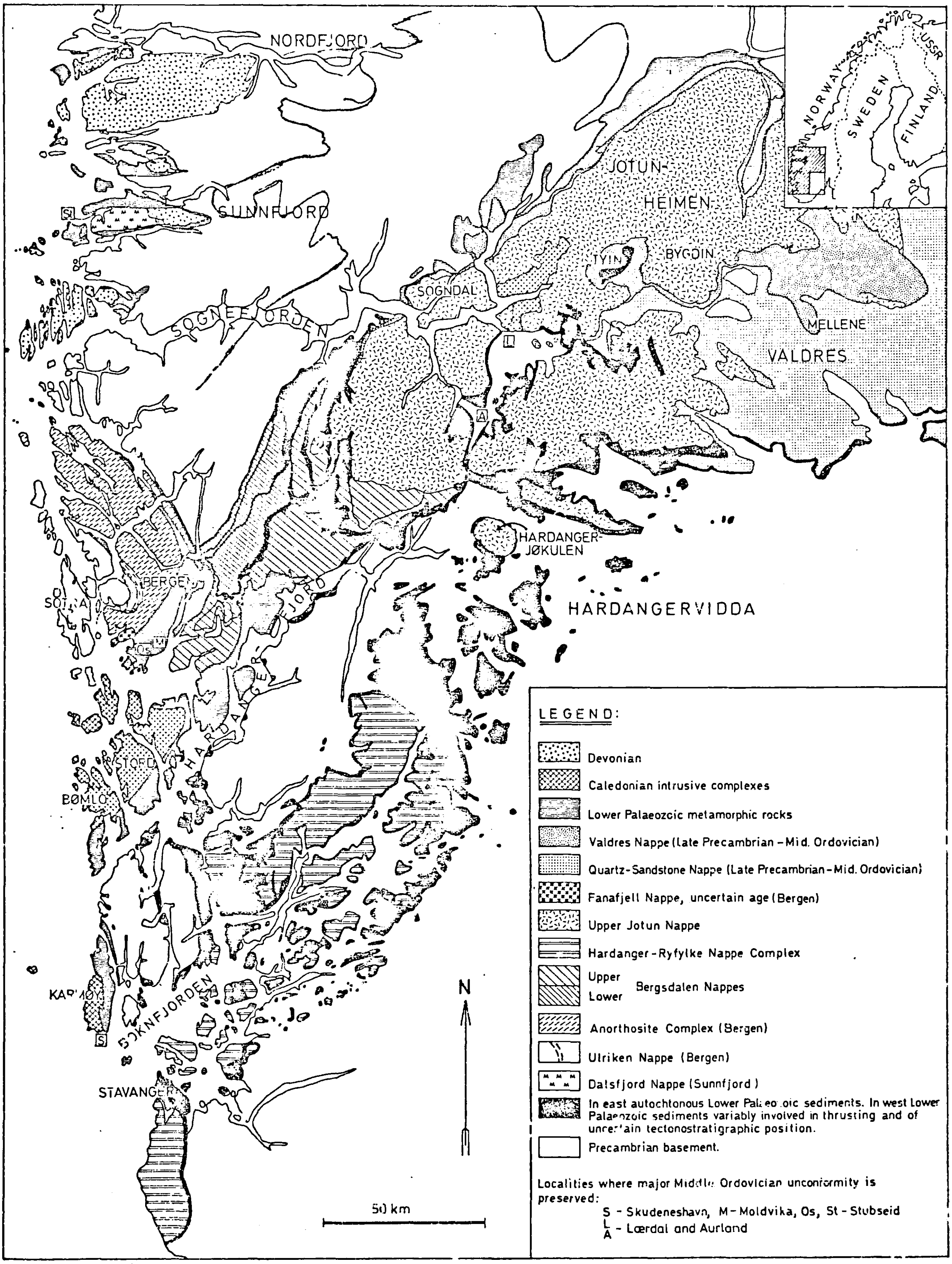


Figure 2. Principal tectono-stratigraphic units of the southern Norwegian Caledonides.

(from Sturt & Thon 1978)

Strand (1960) concluded that there was evidence for the formation of some of the gneisses of the Basal Gneiss region from sediments of Sparagmitian or Cambro-Silurian age, which were subsequently infolded with areas of Caledonised Basement gneiss of Precambrian age.

More recent investigation on the age of the gneisses led Brhyni (1966) to differentiate between assumed Eocambrian-Silurian metasediments and transformed pre-Eocambrian basement, which he termed the Fjordane and Jostedal complexes respectively (fig 1). However, recent isotopic dating has led to a different interpretation of the gneiss and metasedimentary units.

The Jostedal complex contains relatively homogeneous granitic gneisses and migmatites that have been dated by both Rb/Sr whole rock, and $^{40}Ar/^{39}Ar$ mineral methods as between 960-1200 ma. (Brueckner et.al. 1968, Brueckner 1972, 1979, Priem et.al. 1973). The Fjordane complex structurally overlies the Jostedal complex and consists of heterogeneous rocks that have locally been placed into tentative stratigraphic groupings (Hernes 1965, Råheim 1972). Essentially, the Fjordane complex contains schists, gneisses, quartzite, marble, eclogite, amphibolite, peridotite and anorthosites. It is considered (Brhyni 1977) as representing a sequence of clay, sand, arkosic and carbonate sediments, together with extensive dacitic/rhyodacitic and basaltic vulcanism.

The Fjordane complex was originally considered to contain rocks of both Cambro-Silurian age and older elements corresponding to those within the Jotun thrust masses. This age was deduced by correlation of quartzites in the Basal gneiss complex with the Eocambrian sparagmite complex in the east, and also peridotites with similar rocks in Cambro-Silurian metasediments, also in the east. Subsequently, however, Brhyni and Grimstad (1970) have suggested a Precambrian age for the Fjordane complex, based partly on the presence of anorthosites. They have also suggested a tentative correlation, on lithological grounds; of the supracrustals with the Precambrian rocks of Telemark and Bergsdalen.

A Precambrian age for the Fjordane supracrustals has recently been confirmed by isotopic dating; the Fjordane complex yields Svecofennian ages between 1550-1900 ma (Abdel-Monem and Brhyni 1979, Brueckner 1979, Lappin et.al 1979), whilst Sveconorwegian ages (Brueckner 1979) determined from the complex are considered to be re-equilibration ages, subsequent to the Svecofennian cycle.

Thus, the Fjordane complex (Svecofennian) appears to be older than the Jostedal complex (Sveconorwegian), contrasting strongly with the earlier views.

More specifically, the Basal Gneisses which underlie the western margin of the Bergsdalen Nappe and were briefly described by Kvale (1946) as granodioritic gneisses and migmatites (i.e. of Jostedal complex type), are shown by recent investigations on Osterøy (Hopper 1980) and Eksingdalen (Gray 1978) to contain minor metasedimentary units intercalated with gneisses, thus providing a tentative correlation with the Fjordane complex. Gray (op. cit) obtained a whole rock Rb/Sr metamorphic age of 1855±242 ma from the Basal Gneisses of granodiorite appearance, collected about 10km north of Dale.

1.6 The Hardangervidda and Telemark Basements (fig 1)

The Hardangervidda Basement underlies the southern margin of the Bergsdalen and Jotun nappe complexes, and is itself structurally overlain by the Hardangervidda-Ryfylke nappes, which are an additional part of the Caledonian nappe system (fig 2).

The basement consists of Precambrian granitic gneisses, migmatites and supracrustal rocks, i.e. pelites, semi-pelites, acid and basic volcanics and some meta-agglomerates; gabbroic and granitic bodies are intrusive into this basement complex. (Solli 1978, Sturt and Thon 1978). In addition, a complex of Precambrian gneisses, quartzites and granites that have been ascribed to the Telemark suite, and are considered to be very similar to the rocks of the Bergsdalen Nappes, form part of the Basement supracrustal complex at Sørfjord, immediately beneath the Bergsdalen Nappe. (Strand & Kulling 1972 p.44).

The Hardangervidda basement extends in both an easterly and south easterly direction into the Precambrian supracrustal Telemark series, which in its most northerly portion, underlies part of the Jotun nappe complex.

A correlation between the supracrustals in the Hardanger basement and the Telemark series has been made by Sturt and Thon (1978). The Telemark series is divided into 3 groups which, in order of age are: the Rjukan Group, the Seljord Group and the Bandak Group. (fig 3).

The Rjukan Group is further divided into the stratigraphically underlying Tuddal Formation, consisting of acidic lavas, tuffs and ignimbrites that lie unconformably on Svecofennian (~1800 ma) granitoid basement, and the higher Vermark Formation, comprising greywackes, andesitic volcanics and arkoses. (Dons 1960, Martins 1968).

Ploquin (1977) concluded on whole rock Rb/Sr isotopic evidence, that the Rjukan Group was deposited, deformed, and suffered metamorphism, migmatisation and granite intrusion between 1750-1400 ma: this supports Priem et.al. (1973) who obtained an age of deposition around 1570 ma.

FIG 3

The Telemark Suite

post tectonic granites (970-850 ma.)

Bandak Group (~1200 ma.)

------------ unconformity

Seljòrd Group (~1400 ma.)

------------ unconformity

Rjukan Group

- Vermark Formation
- Tuddal Formation

Svecofennian Basement (~1800 ma.)

The Seljord Group, composed almost entirely of quartzites and minor pelites, with abundant basic sills (Dons 1960, Singh 1969) lies unconformably upon the Rjukan Group and is considered by Ploquin (1977) to have been deposited between 1400-1200 ma.

The Bandak Group is also unconformable, overlying the Seljord Group; it is composed of both acidic and basic volcanics, with interbanded quartzites, semi-pelites and conglomerates (Hasan 1971) and is considered to have been deposited about 1200 ma (Ploquin 1977).

The Telemark series has undergone both deformation and metamorphism at about 1000 ma (Michot & Pasteels 1972, Priem et.al. 1973), and has been intruded by post tectonic granites between 850-970 ma.

1.7 Øygarden's Gneiss Complex (fig 1)

Øygarden's Gneiss complex lies immediately to the west of Bergen, with an outcrop of some 800km^2, beneath the western margin of the Bergen Nappe complex. (Sturt and Thon 1978). This basement complex has received little attention since first being described by Kolderup and Kolderup (1940). Their initial study, and subsequent more detailed work by Johns (pers com 1979) has shown that the gneisses are predominantly of homogeneous acid and intermediate character, with frequent migmatite complexes. In addition, there are several large amphibolite bodies which may contain some supracrustal elements.

The gneisses have undergone a complex tectono-metamorphic history, with evidence for an early, high grade metamorphic event at 1750$\pm$60 ma (Sturt et.al. 1975) followed by a probable Sveconorwegian reworking at about 1000 ma, and subsequent polyphasal Caledonian deformation.

1.8 The Nappe Complexes

The southern Norwegian Nappe system can be divided into four major nappe complexes; the Bergsdalen Nappe complex; the Jotun Nappe complex; the Bergen Nappe complex and the Hardangervidda-Ryfylke Nappe complex. (fig 4). The nappe system has a continuous outcrop from the west coast around Bergen, on towards Jotunheimen, 270 km towards the north-east. From there, the system takes on a more northerly trend, becoming involved with the Central Norwegian nappe system. (In all, the southern Norwegian nappe system has a total outcrop of some 24000 km^2).

The Bergsdalen-Jotun nappes lie in a trough in the basement (Strand and Kulling 1972 p.30) that was termed "Faltungsgraben" by Goldschmidt (1912). The nappes are preserved within this synclinal downwarp, apart from the eastern margin of the Jotun nappe complex and the Hardangervidda-Ryfylke nappe complex, which form an outlier to the south of the main nappe system (fig 4).

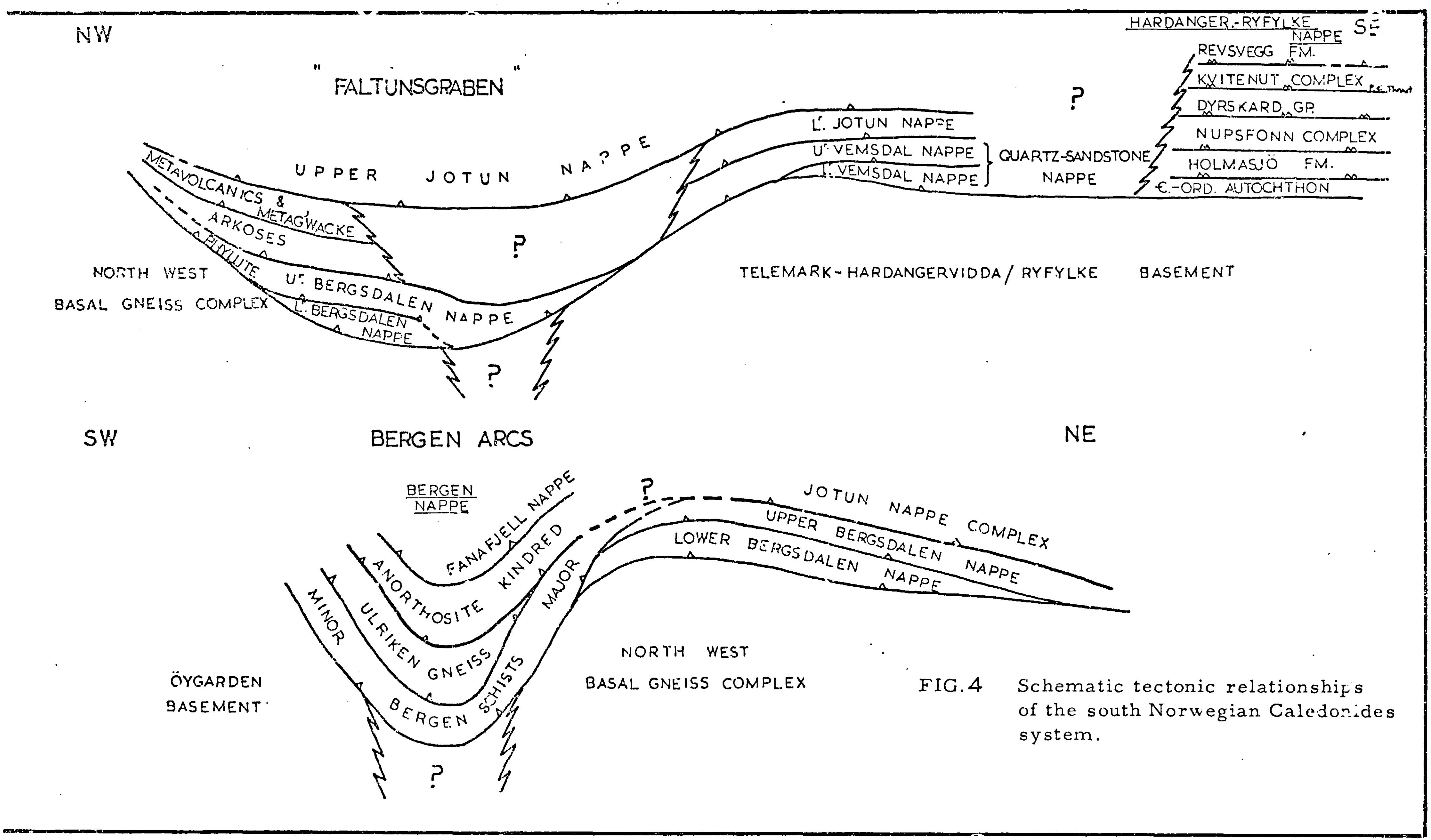


FIG.4 Schematic tectonic relationships of the south Norwegian Caledonides system.

The tectonic succession for the four Nappe complexes is not completely known. That the Bergsdalen Nappe complex is overlain by both the Jotun and Bergen Nappe complexes is well documented. (Kvale 1960, Sturt & Thon 1978). However, the Bergen, Jotun and Hardangervidda-Ryfylke Nappe complexes are of uncertain positions relative to each other (fig 4).

All of the Nappe complexes of the southern Norwegian Caledonides have dark phyllites and schists associated with them, most commonly at their bases or along thrust planes. A lower Palaeozoic age, based on fossil evidence, can be proved for the autochthonous pelitic succession that is unconformable on the Precambrian Hardangervidda basement in the Finse area (Kvale 1960), and can be followed north towards Sogn:

	middle:		Phyllite
Ordovician			Limestone
	lower	(	Dark quartzite
	--------	(	
	upper	(	Phyllite/Alum shale + dictyonema
Cambrian			Quartz schist (often missing)
	lower		Basal conglomerate + torellella, laerigata, strennella
			---------- unconformity -------
			Precambrian gneisses

1.9 The Bergsdalen Nappe Complex

The Bergsdalen Nappe complex has been divided into lower and upper units (fig 4) (Kvale 1946, 1960) that are separated by a thick development of schists and phyllites, of presumed Lower Palaeozoic age. Internally, the Lower and Upper units are themselves subdivided into lower, middle and upper sheets. (Kvale op.cit.)

The Bergsdalen Nappe dips moderately (30^0- 40^o) towards the east on its western margin, whilst its eastern margin is low lying, with a gentle westerly dip.

The Lower Bergsdalen Nappe has nearly identical trends to the Basement Gneisses and overlies them along a thin zone of mica schist that can be traced towards the north east into a zone of phyllites and schists around Norddalen; here, the Lower Bergsdalen Nappe wedges out, being overstepped by the Upper Bergsdalen Nappe (fig 2). The lower unit is also overstepped by the upper unit in the south-east, so that the Upper Bergsdalen Nappe rests directly on basement along the eastern margin of the nappe complex.

To the south-west, the Bergsdalen Nappes are overlain by the Bergen Nappe, although the contact is complicated by folding (fig 4).

The Lower Bergsdalen Nappe contains an assemblage of Precambrian gneisses and supracrustals (Kvale 1946, 1960; Sturt & Thon 1978; Gray 1978) that are considered to represent a series of metabasalts, metadacites, metarhyolites and quartzites that have been correlated with the Telemark series (Kvale 1960). Certain of the metavolcanics have been re-interpreted by Sturt & Thon (op. cit) to be retrograded and variably mylonitic gneisses. This assemblage is intruded by gabbroic, quartz dioritic and granitic bodies; the latter have been dated as Precambrian by whole rock Rb/Sr methods, with ages of intrusion at 1274 ± 84 ma - Hernes granite (Pringle et. al 1975), 948 ± 56 ma - Bukkefjell & Fosse granite in Bergsdalen (Pringle, in Gray 1978) and 971 ± 71 ma - Fosse granite in Eksingdalen (Gray 1978).

The assemblages within the Lower Bergsdalen Nappe were deformed by north easterly trending folds during amphibolite facies metamorphism prior to thrusting (Kvale 1946, 1960, Gray 1978). Large scale, post thrust folding on a north easterly axis has occurred within the lower nappe, and has involved the basement/ nappe contact around Eksingdalen (Gray 1978).

The Upper Bergsdalen Nappe is separated from the Lower Bergsdalen Nappe by a thick sequence of low grade pelites of uncertain Lower Palaeozoic or Precambrian age. The assemblages within the Upper Nappe include those typical of the Lower Nappe (metavolcanics, quartzites, granites, gabbros, quartz diorites) with additionally, a sheet of acidic basement style gneisses. Also, in the southern part of the Nappe, there are localised developments of rocks of the Anorthosite kindred, (Kvale 1960), of uncertain tectono-stratigraphic position. In contrast to the

Lower Bergsdalen Nappe, the Upper Nappe is at a lower metamorphic grade - Upper Greenschist/Epidote-amphibolite facies (Kvale 1960).

The metamorphism of the Bergsdalen Nappe complex was considered to be Caledonian in age (Kvale 1960) and ranged high up into the amphibolite facies. However, Sturt and Thon (1978) believe that a constraint is put on the extent of the Caledonian metamorphism by the maximum grade attained in the Lower Palaeozoic sediments. The latter never exceeded the Greenschist facies, thus implying that the higher grade metamorphism is of Pre-Caledonian development.

To the north of the Bergsdalen complex, the pelites (phyllites) that are an intimate part of the Bergsdalen Nappes, continue beneath the Jotun Nappe complex, although recognisable Bergsdalen lithologies are lost, being overstepped by the lower units of the Jotun Nappe complex. (fig 2)

1.10 The Jotun Nappe complex

The Jotun Nappe complex has contrasting successions at its north-western and south-eastern margins. (fig 4).

(a) South-eastern margin

The Telemark series of supracrustals forms the basement to the south-eastern margin of the Jotun Nappe. The basement is unconformably overlain by a thin (~ 100m) Lower Palaeozoic, low grade (Greenschist), pelitic succession that is a lateral extension of the Finse autochthonous cover. (Section 1.8) Hiem 1977).

The lowest nappe within the flat lying allochthon (fig 4) is the Quartz-sandstone Nappe (Vemdal Nappe) that contains quartzites and phyllites which, on fossil evidence, are of late Precambrian to Middle Ordovician age. (Sturt and Thon 1978). The middle nappe unit is the Lower Jotun Nappe (sometimes called the Valdres Nappe) which has gneissic rocks that resemble the Precambrian crystallines of the Upper Jotun Nappe, at its base (Hossack 1968, 1978). This crystalline base is in part succeeded by a preserved stratigraphic unconformity, overlain by a thick sequence of Eocambrian sparagmites (the Valdres sparagmites), which are in turn overlain by a Cambro-Ordovician sequence, dated by Middle Ordovician graptolite-shelly fauna.

The Lower Jotun Nappe is overlain by the Upper Jotun Nappe (fig 4) which comprises high grade gneisses, granulite facies dominates in the interior part, with anorthosites, mangerites, jotunites and pyroxene granulites (Griffin 1971, Battey & McRitchie 1973, 1975), whilst the marginal areas are at amphibolite facies, and contain essentially gabbroic and granitic rocks. The close similarity between the high grade rocks of the Upper Jotun Nappe and the Bergen Arcs has led to them being termed "the Bergen-Jotun Kindred" (Goldschmidt 1912)

All of the nappes of this south-eastern margin contain extensive internal folding that predates thrusting (Hossack 1968, Battey & McRitchie 1973, Nickelsen 1974). However, the Lower Palaeozoic sediments nowhere exceed Greenschist metamorphism. Thus the higher grade metamorphism is of Pre-Cambrian age, with k-Ar mineral dates in the range from 426-1280 ma. (Battey & McRitchie 1975).

(b) The North-Western Margin (fig 4)

This margin dips moderately (30^{o}-40^{o}) towards the south-east, and is underlain by the Basal Gneiss complex with an east-west trending foliation, that is modified by rotation and flattening immediately beneath the lowermost thrust unit (Banham 1968), creating a nappe-parallel (north-easterly trending) unit of flaggy muscovite gneiss.

The basement is locally overlain along a preserved primary stratigraphic unconformity by conglomerates, quartzites, sparagmites and mica schists that have been correlated with the Eocambrian-Silurian succession (Strand 1951) of the Lower Jotun Nappe (Valdres sparagmite) on the south-eastern margin.

The basement is tectonically overlain by a succession of pelitic rocks (Skjerlie 1957) that are considered to be Caledonian supracrustals, and closely resemble the older schists from the Major Bergen Arc in terms of lithology and metamorphic grade; they are considered by Sturt & Thon (1978) to represent a klippe of the Bergen Nappe.

Tectonically overlying the schists (fig 4) is a unit of micaceous meta-arkoses (sparagmites) with associated schists, equivalent to the autochthonous sparagmite. Structurally above, and separated from the sparagmites by thrusting is a succession of metagreywackes and metavolcanics (Elliott & Cowan 1966, Banham et.al. 1979).

Together, these units may represent parautochthonous cover that is overlain by the Bergen-Jotun kindred rocks of the allochthonous, Upper Jotun Nappe.

As with the south-eastern margin, the tectonic slabs all contain intensive deformational features, generated prior to thrusting. (Roberts 1976, Banham et.al. 1979). Information on metamorphism is sparse, although much of the parautochthon is within the Greenschist facies (Banham pers. com. 1980).

1.11 The Hardangervidda-Ryfylke Nappes (fig 2)

The Hardangervidda-Ryfylke Nappe complex sits on autochthonous basement gneisses that contain elements of the supracrustal Telemark suite, along with a thin autochthonous Greenschist facies Cambro-

Ordovician cover sequence (Section 1.8) that shows a primary stratigraphic unconformity to the gneisses. This autochthonous cover sequence has, in the past, been considered to be extensively developed (Sturt & Thon 1978). However, Solli et. al. (1978) have shown that in the Outer Hardanger fjord area, the large tract of pelitic rocks previously ascribed entirely to the autochthonous Cambro-Ordovician, does have elements of allochthonous Precambrian schists imbricated within it. These schists contain bands of gneiss identical to the meta-andesites of Suldal, that have been dated at 1145±98 ma. (Sigmond & Andresen 1976).

The allochthonous nappe pile is divided into five tectono-stratigraphic units, (fig 4) of which the lowermost, the Holmasjø Formation, comprising quartz schists and minor quartzites was considered (Andresen 1974) to be Cambro-Ordovician, although a Precambrian age may also be suspected.

Above the schists lies a nappe (the Nupsfonn complex) of uncertain status, containing variably migmatitic gneisses, similar to the structurally higher Kvitenut complex.

The middle units of the nappe pile are the Dyrskard and Kvitenut complexes. These overlie the Nupsfonn complex along a Caledonian thrust. However, the thrust plane between the two units (Dyrskard and Kvitenut) is of Precambrian age, on the basis of isotopic evidence (Gabrielsen 1979), and as such should be considered together as one Caledonian tectonic unit. The Dyrskard Group contains supracrustal rocks - banded quartzofeldspathic gneisses, meta-rhyodacites, and variable quartzites. Preliminary work on the meta-rhyodacites suggests an age of 1550 ma for metamorphism, and/or deposition. (Gabrielsen op. cit). The Kvitenut complex comprises gneisses and migmatites, which have yielded dates between 1643-1534 ma. (Sturt & Thon 1978). The two complexes were thrust together and syntectonically metamorphosed at 1537$\pm$41 ma; folding, tentativelycorrelated with the thrusting had a strike to the east-north-east, and axial surfaces dipping to the north-north-west. (Gabrielsen op. cit).

It is considered, because of lithological similarities (Sturt & Thon 1978), that these two units may represent the allochthonous equivalents of the two major units in the autochthonous basement i.e. the Telemark suite and the pre-Telemark gneiss complex.

1.12 The Bergen Nappe (figs 2, 4)

The Bergen Nappe is preserved within an arcuate synform, the shape of which has given rise to the term, the "Bergen Arcs". (Kolderup & Kolderup 1940). Both eastern and western boundaries tectonically overlie basement gneiss complexes, (Sturt & Thon 1978, Hopper 1980) - the Øygarden Gneiss complex in the west and the

Basal Gneiss complex to the east. In addition, the nappes overstep the Bergsdalen Nappe complex in the south-east. (fig 2).

The lowermost unit of the Bergen Nappes consists of the "Bergen Schists", that outcrop along the outer (major) and inner (minor) portions of the arc (fig 4). The schists are subdivided into the pre-Ashgillian, the Samnanger complex, comprising mica schists, quartzites, amphibolites and submarine basic metavolcanics that were metamorphosed at amphibolite facies, prior to the deposition of the Holdhus group (phyllites, schists, greywackes, limestones and quartzites). This lies above a primary stratigraphic unconformity represented by the Moberg conglomerate, (Faerseth et. al. 1977) and contains Ashgillian and Llandoverian faunas.

The Samnanger complex is of unknown age, but is assumed (Faerseth et. al. 1977) to be Lower Cambrian-Ordovician, on the basis of regional correlations. However, Hopper (1980) has suggested it may be Precambrian, because of the presence of quartzite inclusions within a granite body isotopically dated at about 900 ma. An age of deposition older than 700 ma is also considered by Bryhni & Brastad (1980), from Rb/Sr dates derived from intrusive granite veins.

The Holdhus and Samnanger complexes were together involved in Caledonian polyphase deformation and metamorphism, ranging from low to high Greenschist facies, together with internal thrusting and imbrication.

The schist unit is overlain by the Ulrikens Gneiss Nappe (fig 4), (Sturt & Thon 1975) which is a complex unit comprising a series of thin (several hundred metres) thrust sheets of gneiss, each capped by a cover sequence of presumed Lower Palaeozoic metasediments at greenschist facies, with locally preserved primary stratigraphic unconformities. The gneisses have undergone several phases of migmatisation, the latest of which was dated at 1440$\pm$100 ma (Sturt & Thon 1975).

The Ulrikens Gneiss complex is overlain tectonically by the Anorthosite complex (fig 4), which is a range of para and orthogneisses, together with plutonic rocks of anorthosite - mangerite kindred, that have been metamorphosed to granulite facies; regression lines gave an age representing the granulite facies metamorphism at about 1775 ma. (Sturt et. al. 1975). The highest tectonic unit within the Bergen Nappe complex is the Fanafjell nappe, (fig 4) comprising ortho- and paragneisses, granites, mica schists and quartzites, of probable Precambrian age. (Sturt & Thon 1978).

All of the thrust contacts within the Nappe pile have been folded.

To the south of the Bergen region, in Sunn-Hordland, (fig1) a succession of Lower Palaeozoic rocks lie in an allochthonous position. However, their exact relation to the Bergen Nappes and the Hardanger-Ryfylke Nappes is not clear. The probable correlative of the major unconformity (Moberg conglomerate) recognised in the Bergen Arcs is seen on Karmøy, where a (fig 2) development of conglomerates and calcareous sandstones rests with a profound stratigraphic unconformity on a polyphasely deformed complex that includes mica schists, greenstones, metagabbros and serpentinites, considered to represent an ophiolite complex (Sturt et. al 1979) that has been tectonically emplaced onto basement gneisses.

Nearby, on Stord, an assemblage of Upper Ordovician and Lower Silurian sediments has been identified (Lippard 1976), along with extensive volcanic rocks that have been dated at $455^{+}_{-}5$ ma. (Priem and Torske 1973).

1.13 Plate Tectonics in Southern Norway

The southern Norwegian Caledonides contain elements that have undergone several orogenic episodes. Within both the underlying basement and in the nappes, there is radiometric evidence for extensive phases of recrystallisation during the Svecofennian (~1800 ma) and the Sveconorwegian (~1000 ma) events. Krogh (1977), based on P-T evidence for eclogites, has suggested that a plate tectonic regime was active during the Svecofennian, resulting in a continent-continent collision, sited approximately along the coastline of the north-west Basal Gneiss complex (fig 5).

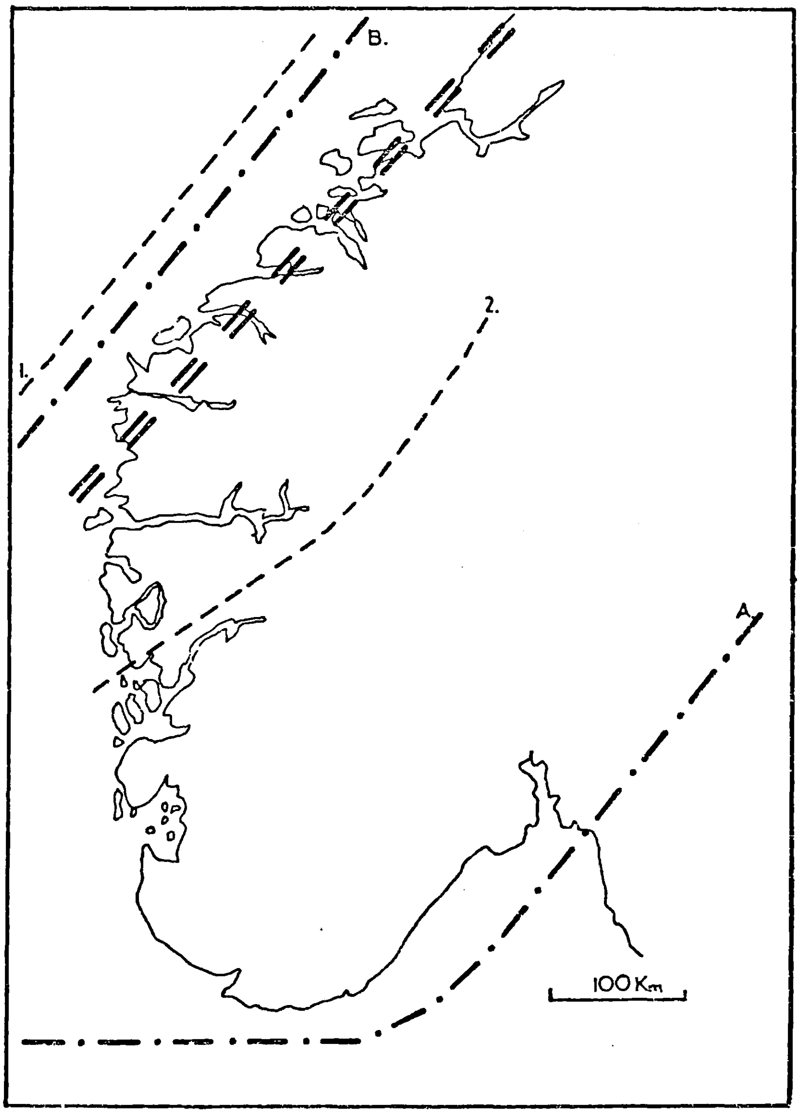
The Svecofennian complexes suffered reworking during the Sveconorwegian event, which was most strongly developed along the southern coast of Norway, but had extensive effects throughout most of Norway. On the basis of Rb/Sr ages, the Sveconorwegian orogenic belt is traditionally projected to pass immediately to the south of Norway, swinging onto a north-north-easterly trend in south-east Norway and south-west Sweden. (Wright 1976, Torske 1977). From evidence relating to the Telemark supracrustals, Torske (op. cit) has suggested that the Sveconorwegian event was of the Cordilleran type. (fig 5).

From the presence of Sveconorwegian Rb/Sr ages in the North-West Basal Gneisses, the Southern Norwegian Nappe complexes, Lofoten Islands and west Finnmark, Sturt et. al. (1975) suggest that a major arm of the Sveconorwegian orogenic zone may also have extended in a north-easterly direction between Greenland and Scandinavia; Hopper (1980) postulates the zone passing through the Jotun area. (fig 5).

Because Silurian rocks are involved (Strand & Kulling 1972), the Southern Norwegian Nappe complex was emplaced in its present position during the Caledonian orogenic cycle.

Plate tectonic reconstructions of the Norwegian Caledonides favour siting an easterly dipping Caledonian subduction zone off the west

FIG. 5 Proposed orogenic sutures through south west Norway.



Legend:
- Svecofennian (Krogh 1977)
- A. Sveconorwegian (Torske 1977)
- B. Sveconorwegian (Sturt et, al. 1977)
- 1. Caledonian (e.g. Furnes et al. 1975)
- 2. Caledonian (Wilson 1966, Dewey 1969, Banham et. al. 1979)

coast of Norway (for further references, see: Gale & Roberts 1972, Gee 1975, Furnes et.al. 1976). Furnes et.al. (op.cit) propose that the subduction of an oceanic plate beneath the Baltic shield gave rise to Island Arc volcanism during early to middle Ordovician times (fig 6). Back arc spreading occurred in association with initial thrusting of the eugeosynclinal pile. Volcanism ceased, and erosion of the inactive arc occurred during Upper Ordovician-Lower Silurian times, followed by continental collision in the Middle Silurian, between the American and Baltic plates; this resulted in the main phase of nappe translation, and the emplacement of the Bergsdalen-Jotun-Bergen-Hardanger/Ryfylke complexes from the north-west orogenic zone. The uppermost nappes are considered to have travelled distances up to 1000km (Gee 1975), although a more detailed analysis by Hossack (1978), based on balanced cross sections, indicates distances of at least 290km for the Jotun Nappe, and between 100-270km for the lower nappes in the Jotun region. (fig 6).

However, alternative models for the origin of the nappes have been proposed. Early work (Goldschmidt 1912, Oftedahl 1961) suggested a local root zone in the Jotunheim for the crystalline Jotun Nappe. Additionally, in the early plate tectonic reconstructions of the proto-Atlantic, both Wilson (1966) and Dewey (1969) placed a Caledonian suture through central southern Norway. Geophysical data reveals the presence of strong gravity anomalies beneath the

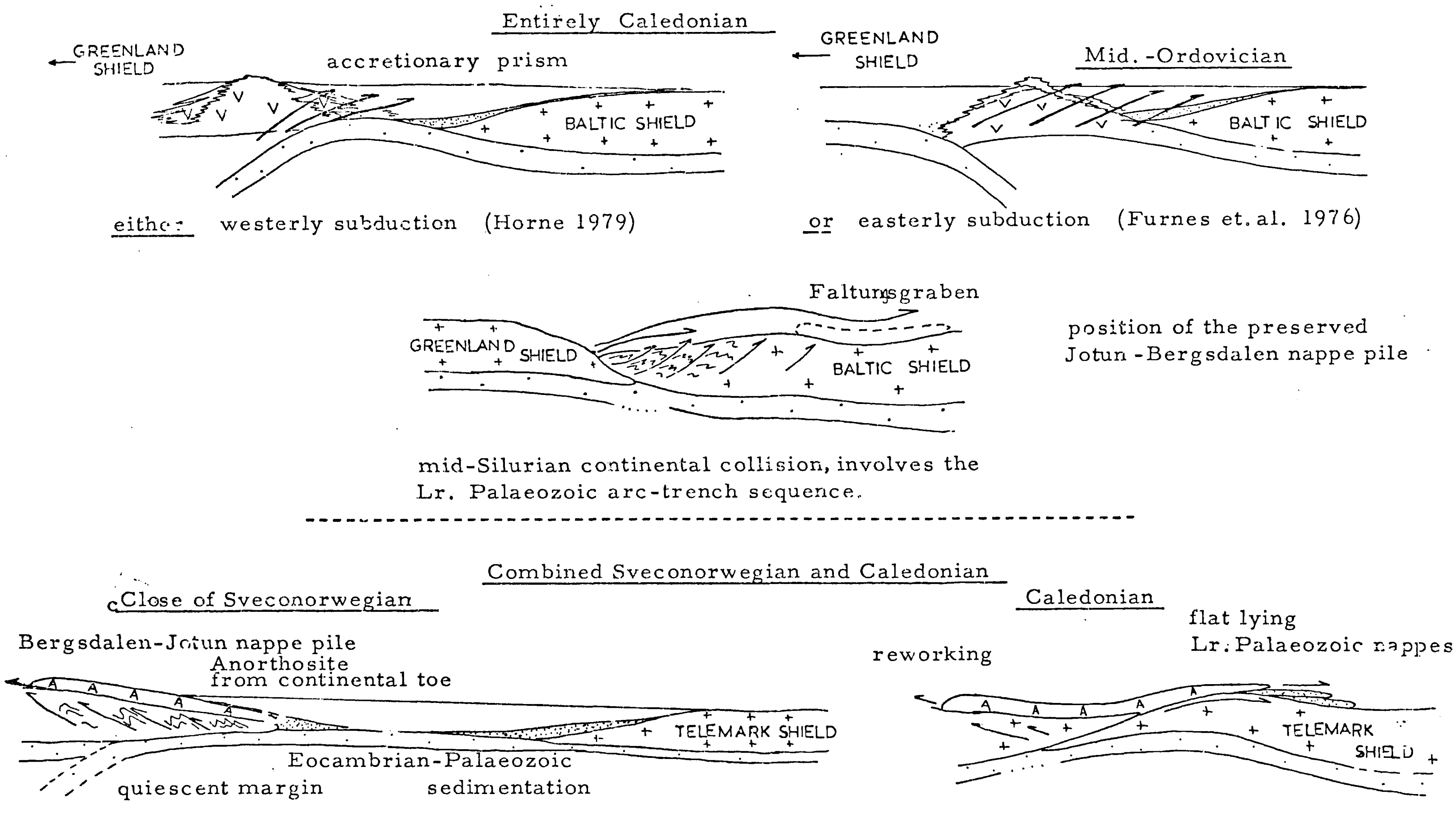


FIG 6 Alternative plate tectonic hypotheses for Southwest Norway.

Jotun Nappe; these led Smithson et.al. (1974) to interpret the Jotun Nappe as a slice of the lower crust that has been upthrust along an Ivrea type root zone. Seismic profiles (Kanestrøm 1977) show slight thickening of the crust beneath the Nappe complexes, from approximately 30km to 40km.

In contrast, aeromagnetic data (Aalstad 1977) has been interpreted to indicate only a thin nappe cover, with no evidence for any root zone.

Although structural evidence on the south eastern margin of the Jotun and Hardanger-Ryfylke nappe complexes indicates undoubted south easterly transport directions, the north western margin is more problematical. Skjerlie (1957), Battey and McRitchie (1973, 1975) and Banham et.al. (1979) consider that structural features indicate nappe transport towards the northwest. Hopper (1980) supports a similar transport direction for the north western margin of the Bergsdalen Nappes. In contrast, Roberts (1978), concludes from structural observations that the north-western margin of the Jotun Nappe complex was transported towards the south-east.

To account for the discrepancy in proposed nappe movement directions on either side of the central "Faltungsgraben", Smithson & Ramberg (1970) suggest a model involving fold nappes locally derived from a central suture (fig 6), whilst Banham et.al. (1979) propose a model whereby the Upper Jotun Nappe is a flake, detached from local, lower crust, that has thrust over (underthrust by) gneissose basement and marginal sedimentary basins both to the northwest and southeast. (fig 6).

Very recent work (Horne 1979) in the Trondheim area has indicated, on the evidence of sedimentary facies, igneous activity and structures, a possible northern extension/equivalent of the Jotun suture, with westerly directed subduction. (fig 6)

Section 2 LITHO-TECTONIC UNITS

2.1 Introduction

The area studied is divided into four tectonic units (fig 7) each of which has its own characteristic Precambrian (Gray 1978) lithological assemblage, excepting the Mixed Gneisses, which are a combination of the other lithologies.

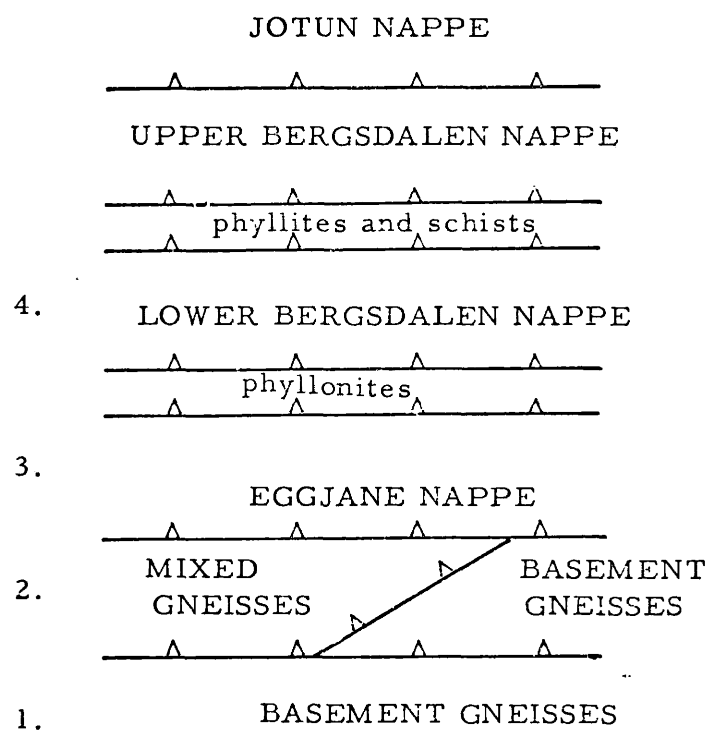
The region was first mapped by Kvale (1946) who introduced specific terminologies for the rocks, based on their mineralogical compositions. In general, the same lithological types have been recognised in this study, although in some cases a change in terminology has been made, due to the genetic implications inherent in the original. (fig 8).

Starting with the structurally lowermost tectonic unit, the following lithologies are recognised within each unit, and where appropriate, the terminology of Kvale (op. cit.) is compared to that introduced in this account :

a. Tectonic unit - The Basement Complex

Kvale classified (op. cit.) the gneisses of the Basement Complex into granodioritic and migmatitic. In this account, it is felt that the term "granodioritic" has specific genetic overtones that are unfounded, implying igneous parentage to the highly deformed and metamorphosed gneisses. Also, the Basement Complex has

FIG. 7 Simplified tectonic succession



The numbered units refer to those encountered in this study.

additional elements that cannot be classified as granodioritic on mineralogical grounds.

Thus, the following lithologies have been recognised, together forming the Basement Complex (no stratigraphic order is recognised):

Gneissose granites	)
Quartzofeldspathic gneisses	) the granodiorites and
Epidote quartzofeldspathic gneisses	) migmatites of Kvale
Hornblende quartzofeldspathic gneisses	) (1946)
Amphibolites	)

All of these lithologies have been invaded by abundant pegmatite veins, and so may be considered as injection migmatites. (Mehnert 1968).

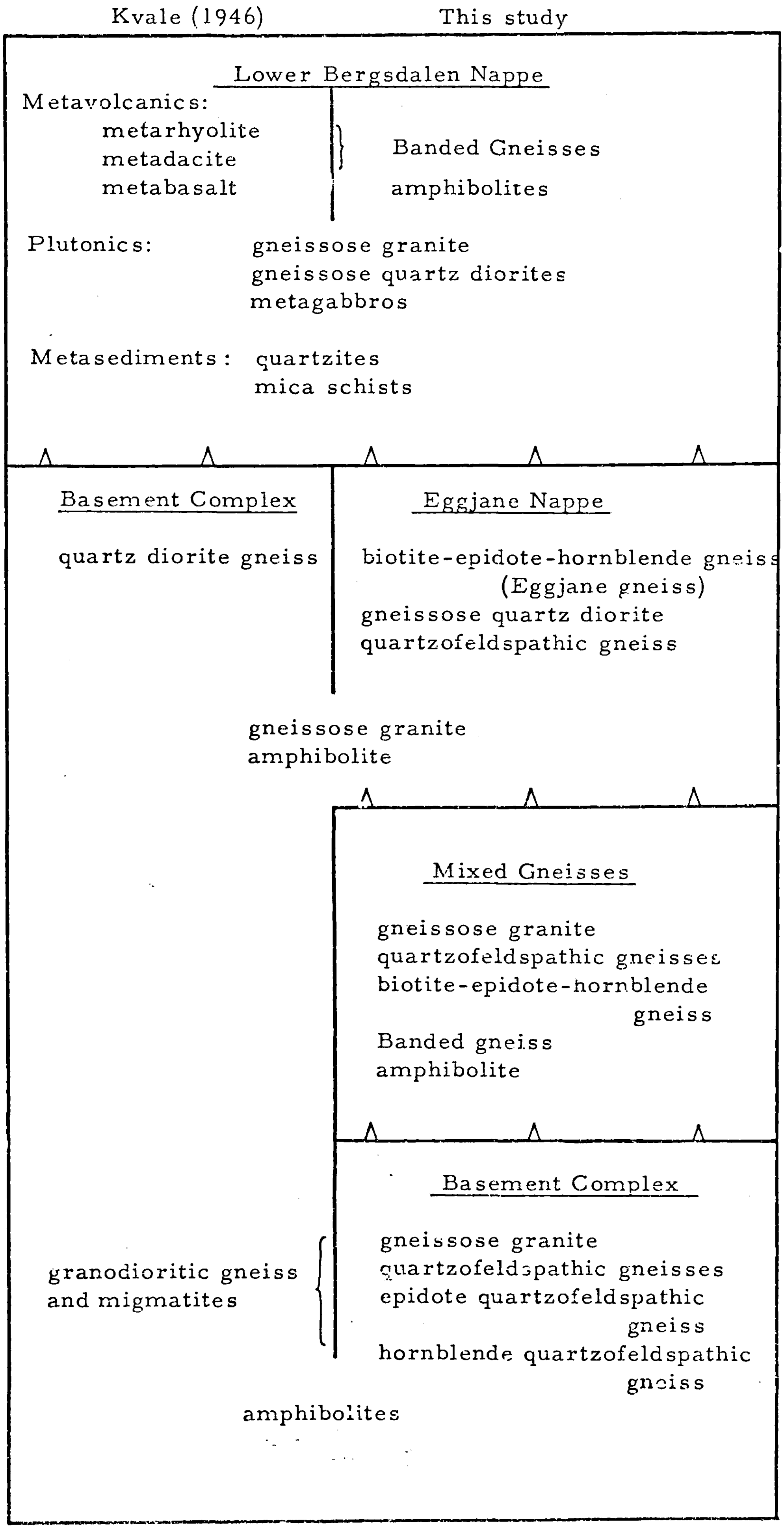
b. Tectonic Unit - The Mixed Gneisses

The Mixed Gneisses are an inhomogeneous unit, containing lithological elements of the three other tectonic units.

Kvale (1946) does not recognise them as a separate unit, preferring to relate them to a body of quartz diorite gneiss that he considered to be part of the Basement Complex, lying immediately beneath the Lower Bergsdalen Nappe.

It is considered here that the Mixed Gneisses, although partially derived from the quartz diorite gneisses (essentially equivalent to the Eggjane Nappe - Section 2.4), that lie above them, belong to an individual tectonic unit, and contain such varied lithological

FIG 8 Summary of the lithologies recorded from the Bergsdalen area, and a comparison with those of Kvale (1946)
(no stratigraphic order implied)



elements that they should be described separately.

The following lithologies are recognised within the Mixed Gneisses, along with their equivalents from the other tectonic units:

Gneissose granites	) equivalents in the Basement
Quartzofeldspathic gneisses	) complex.
Hornblende gneisses	equivalents in the Eggjane Nappe
Banded Gneisses	) equivalents in the Lower
Gneissose quartz-diorite	) Bergsdalen Nappe
Amphibolites	

Pegmatite bodies are common throughout.

c. Tectonic Unit - the Eggjane Nappe

The Eggjane Nappe is lithologically simple, and contains the following lithologies:

Gneissose granite	
Biotite-epidote-hornblende gneiss	
Quartzofeldspathic gneisses;	equivalents in the Basement complex
Gneissose quartz-diorite;	equivalents in the Lower Bergsdalen Nappe
Amphibolites	

The Biotite-epidote-hornblende gneiss is essentially equivalent to that mapped by Kvale as the extensive quartz-diorite lithology within the uppermost structural levels of the Basement Complex. (fig 9).

d. Tectonic Unit - The Lower Bergsdalen Nappe

Kvale (1946) described the Bergsdalen Nappes as comprising metavolcanics, metasediments and plutonic rocks.

The metavolcanics he divided into metarhyolites, metadacites and metabasalts, considering them to represent lavas and/or tuffs. The metasediments are seen as quartzites and mica schists. The plutonic rocks are gneissose granites, gneissose quartz diorites and metagabbros. All of the lithologies, with the exception of the mica schists, have been shown to be Precambrian in age (Gray 1978). The mica schists remain of unknown age.

In the area studied, the metasediments and metagabbros have only a limited outcrop, essentially being confined to higher structural levels of the Lower Bergsdalen Nappe that are not investigated here.

The genetic names for the plutonic rocks have been kept in this account, despite the intense deformation and metamorphism that they have undergone, because their homogeneous appearance and intrusive forms suggest an igneous origin.

However, it is preferred, on field characteristics, to simplify the terminology of the metavolcanics; instead referring to them as Banded Gneisses, with the extensive metabasalts being termed amphibolites. This moves away from the genetic implications inherent in using the terms metarhyolites-metadacites- metabasalts, for gneisses that are devoid of any primary features, having undergone an extensive tectono-metamorphic evolution.

Thus, the following lithologies are recognised in the Lower Bergsdalen Nappe:

Intrusive into these are:

Banded Gneisses)	Gneissose granites
Amphibolites)	Gneissose quartz diorites
Quartzites)	Metagabbros
Mica schists	
Undifferentiated mylonites	

2.2 The Basement Complex

2.2a The Gneissose Granites

The gneisses of the Basement Complex (Sections 2.2b and 2.2c) were intruded on at least two separate occasions by granites. (Section 4.2). The two ages of granite intrusion will be described separately:

The D1 Gneissose Granite:

The foliated D1 granites crop out over an area of about 6km^2, with the major outcrop located on Flatafjell (GR 0322667165) above Stanghelle; smaller outcrops occur throughout the Basement complex (fig9). The granite is intruded into both the quartzofeldspathic gneiss and the hornblende quartzofeldspathic gneiss. Intrusive contacts are rare - the most definitive being described (plate 22) in the structural section (Section4.2b) Elsewhere, the granite has a lit-par-lit relationship with the Basement gneisses, with the subsequent fabric developed parallel to the contacts.

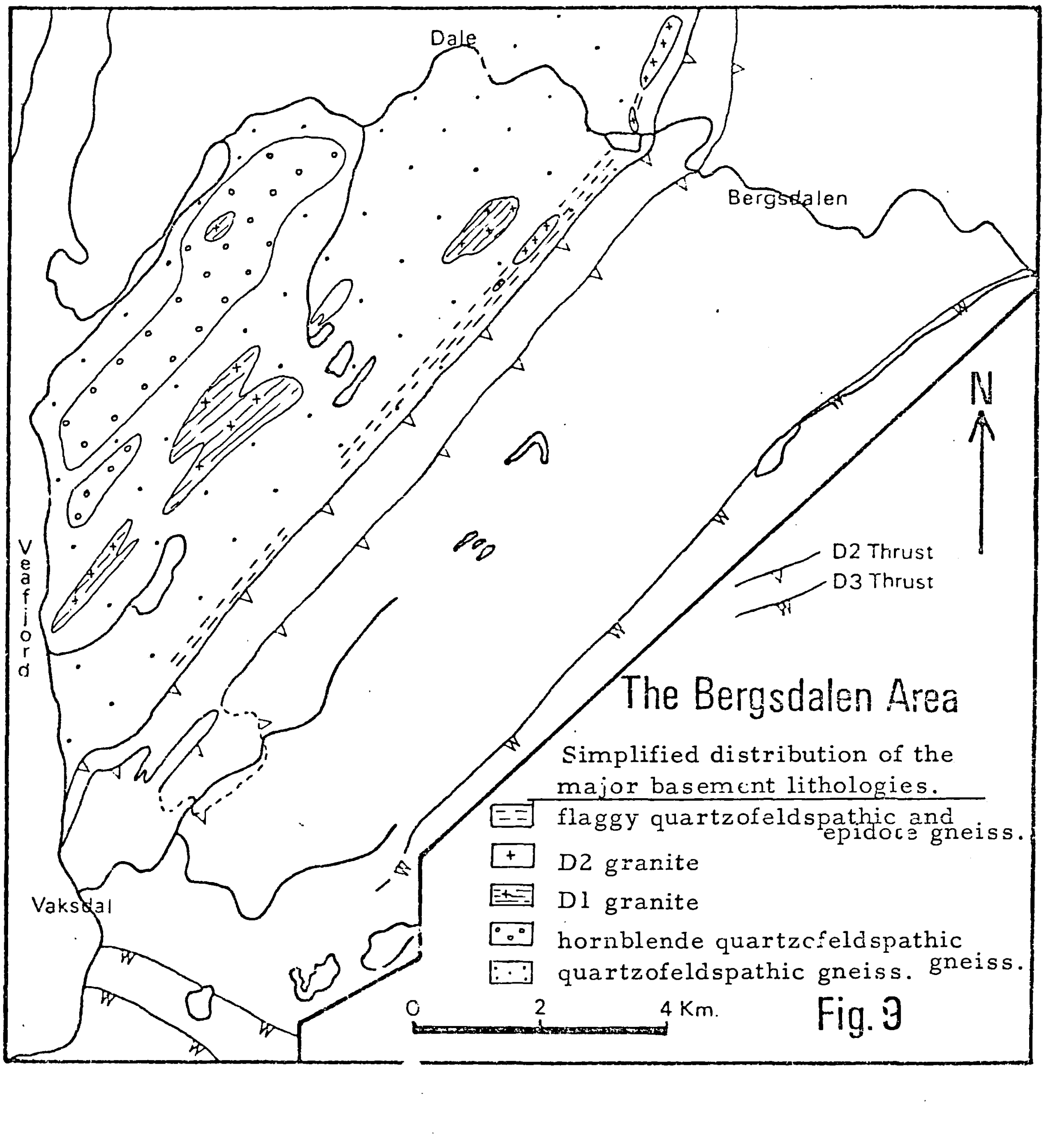

Dale
Bergsdalen
Veafjord
Vaksdal
N
D2 Thrust
D3 Thrust
The Bergsdalen Area
Simplified distribution of the major basement lithologies.
flaggy quartzofeldspathic and epidote gneiss.
D2 granite
D1 granite
hornblende quartzofeldspathic gneiss.
quartzofeldspathic gneiss.
0 2 4 Km.

Fig. 9

The D1 granites differ from the D2 granites by having an heterogeneous appearance, being mixed in all proportions with both mafic bodies and the basement gneisses, and are intruded by abundant D2 pegmatites that lie both concordant and obliquely to, the gneissic foliation of the granites.

The fine to medium grained D1 granites have the essential mineralogy of quartz, feldspars, biotite with minor amounts of garnet. It has a pink weathering colour, and despite the good foliation, has a more massive appearance than that of the adjacent basement gneisses. Minor disruption of the granite bodies has occurred due to thrusting, accounting for their rather amoeboid outcrop forms. (fig 9)

A shape fabric lineation of ellipsoidal quartzofeldspathic aggregates is generated in the granite, identical in appearance and geometry to that of the basement gneisses.

Mineralogy of the D1 Gneissose Granite:

The complete range of mineralogical proportions have been estimated visually:

quartz	25-30%
plagioclase feldspar	35-40%
potassic feldspar	20-25%
biotite	6-10%
sphene	traces
iron oxides	traces
garnet	traces - 2%
apatite	traces
muscovite	traces

Texturally, the D1 granite is quite homogeneous, containing a strong foliation defined by biotites (pleochroic from X - pale brown, to Y, Z - dark brown) up to 0.4mm in length. The quartz and feldspars have a granoblastic form, but are locally elongate parallel to the biotite foliation. However, subsequent deformation has generated stress induced recrystallisation, with the resulting grain size reduction so typical of mylonites, (fig. 10)(Bell&Etheridge 1973)

The feldspars occur in a very similar form, along with quartz, as host grains up to 0.5mm in size, with marginal granulation, leaving a whole spectrum of grain sizes between 0.5-0.05mm. The plagioclase is rarely twinned, but where seen it is invariably on the albite law, whilst the potassic feldspars have rare microcline or rare carlsbad twinning. Microperthitic exsolution is locally seen within the potassic feldspars, along with some sericitisation.

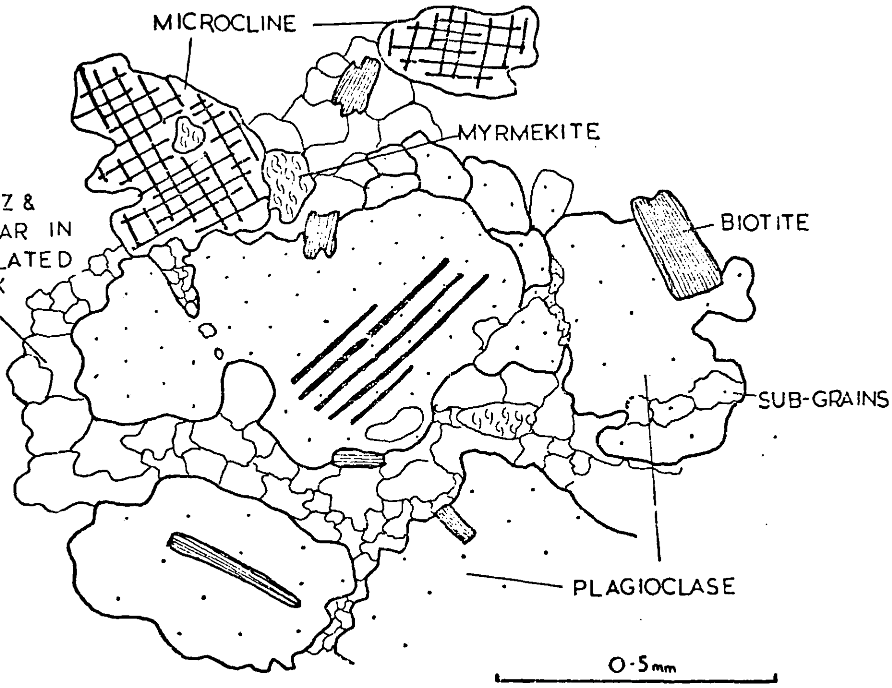
Plagioclase composition, as determined by the Michel Lèvy test, is oligoclase (An_{24}- An_{26})

From the plagioclase/potassic feldspar ratio, the granite would be classified as adamellitic. (Hatch, Wells & Wells 1972).

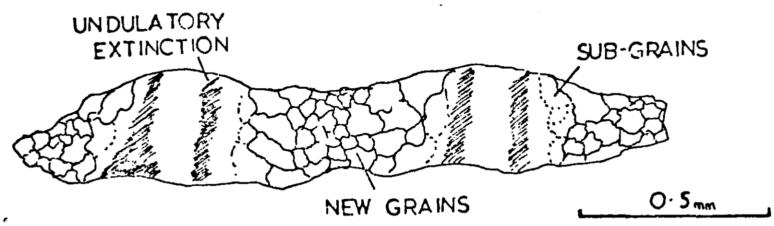
The D2 Gneissose Granites:

The D2 granites outcrop primarily in the north eastern part of

FIG 10 Mylonitic textures common to all of the basement gneisses.



(a) coarse feldspar grains marginally recrystallised to leave a granulated quartzofeldspathic matrix.



(b) straining of quartz ribbons with the development of undulatory extinction, sub grains and new grains.

the Basement complex, forming prominent vegetation free masses (fig 9 and plate1). Individual bodies are relatively small in extent, the largest being approximately 2km^2. However, the several individual bodies are considered to represent either the same body, tectonically disrupted, or to have been closely associated during intrusion. Together, the D2 granite bodies are exposed over an area of some 4km^2. Minor granitic sheets and veins are common throughout much of the Basement gneisses.

Field observations suggest that the granites were intruded syntectonically in D2, into a PT environment sufficient to preclude the development of marginal features - either chilling, or the production of an aureole. (Section 4.2c)

A pervasive gneissic foliation, along which the granite splits, has developed along with a strong shape fabric lineation. The weathered granite is pink, as opposed to the grey of fresh exposures.

The plutons are readily distinguished from the Basement gneisses and D1 granite by their homogeneous texture, with grain size varying between coarse/medium (1-3mm) and medium/fine. (<1mm). The essential minerals are quartz, feldspars and biotite. (plate 21)

Late stage pegmatites (sharing the gneissic foliation) occur sporadically within the granites, never exceeding 25cm in thickness.

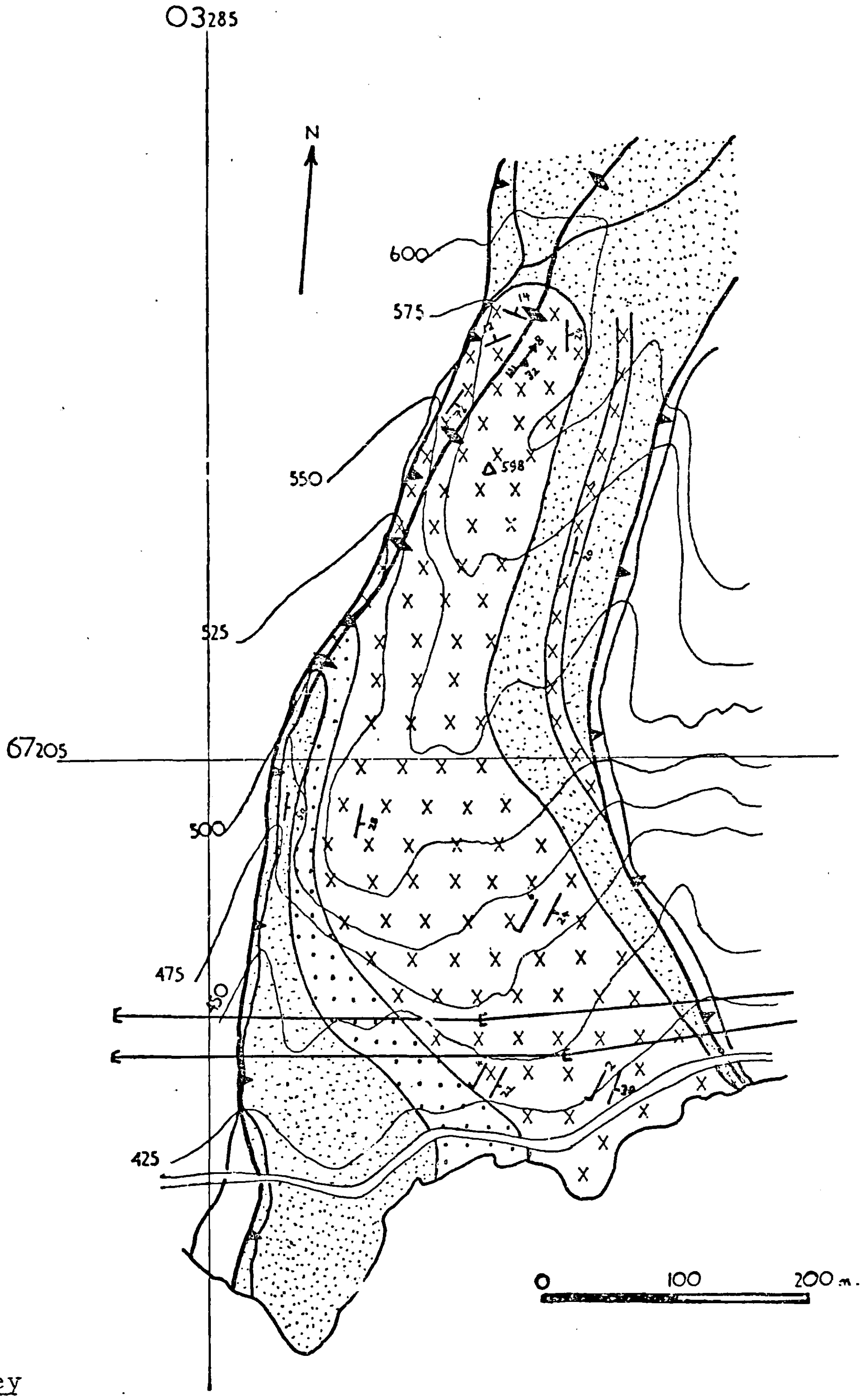
The D2 granite that outcrops on the roadside by Storfossen (fig 11) has been dated by Dr O. van Breemen, using samples collected by the author. A total of ten samples, each with a minimum weight of 15kg were collected from the fresh road-cutting; of these, two were rejected as not being considered to be suitably fresh. The remaining 8 samples were of variable grain size, ranging from fine to medium (1mm-3mm), but were texturally homogeneous.

The Rb/Sr isochron age obtained for the granite was 1050 ± 20 ma ($^{87}Rb = 1.42 \times 10^{-11}\ yr^{-1}$) with an initial ratio of 0.7037 ± 0.0004. (fig 12 and table 1)

Mineralogy of the D2 Gneissose Granite:

Microscopic observations confirm the overall homogeneous nature, both mineral ogically and texturally, of the granite. However, on the microscopic scale, a part segregation into quartz rich and feldspathic rich bands can be observed throughout. This segregation is on the scale of 1-2mm, and does not affect the bulk modal analysis of the granite, which is, as follows:

FIG. 11 The Mittbotnlia gneissose granite; samples from the road section were collected for Rb/Sr isotopic dating.



Key
- D2 gneissose granite
- flaggy quartzofeldspathic gneiss
- quartzofeldspathic gneiss
- topographic contour (in metres)
- power lines
- road
- foliation, S2
- lineation
- F3 fold axial plane and axis
- F3 antiformal axial trace
- D3 thrust

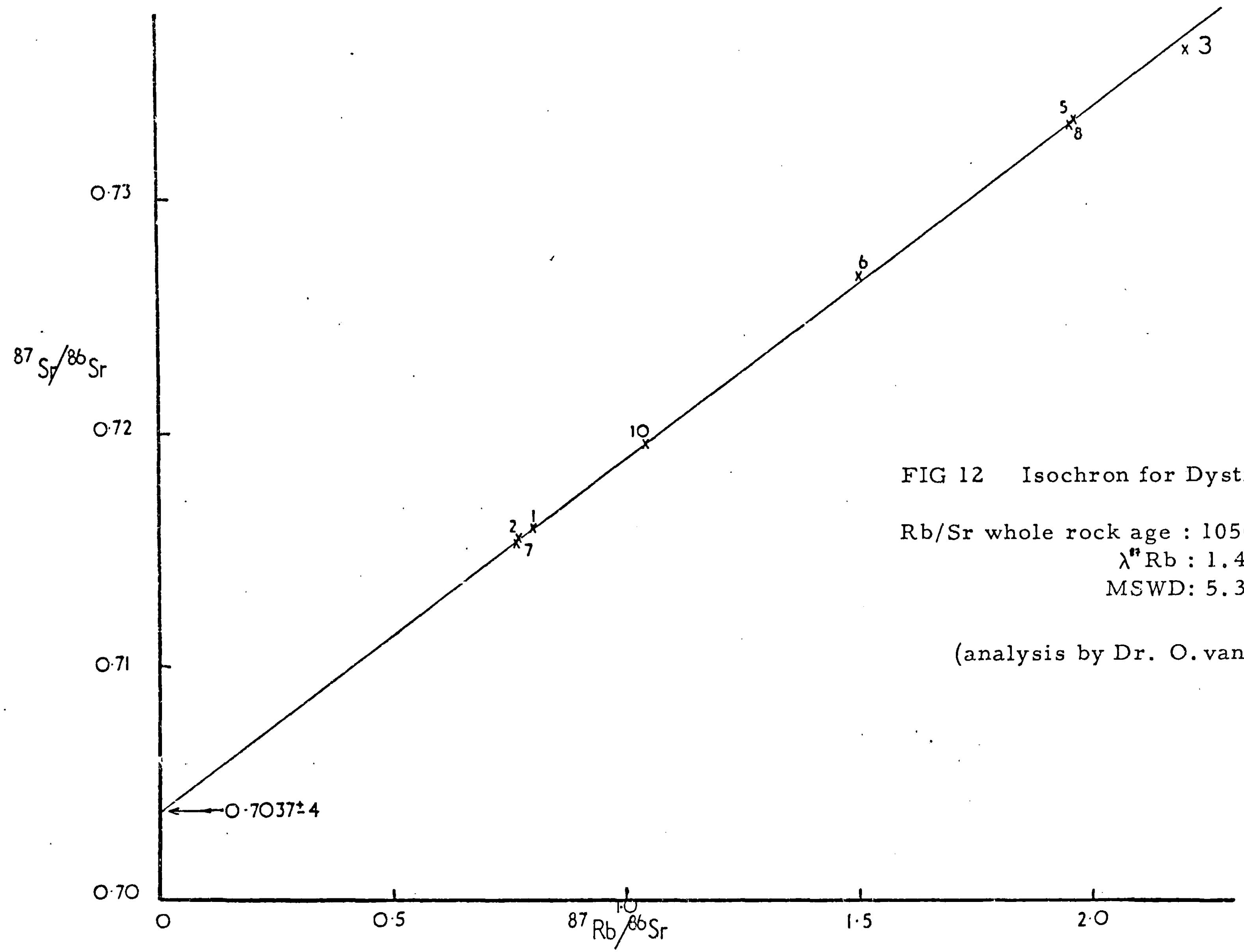


FIG 12 Isochron for Dystingen granite

Rb/Sr whole rock age : 1050 ± 20 ma (2σ)
λ^{87}Rb : 1.42 x 10^{-11} yr^{-1}
MSWD: 5.3

(analysis by Dr. O. van Breemen)

Table 1

Rb-Sr Isotope Dilution Data Dystingen Granite

Sample number	Rb (ppm)	Sr (ppm)	Rb/Sr wt. ratio	$^{87}Rb/^{86}Sr$ at. ratio	$^{87}Sr/^{86}Sr$ at. ratio
G1	164	586	0.279	0.8091	0.71586±10
2	210	783	0.269	0.7775	0.71527±10
3	88.5	116	0.762	2.210	0.73622±18
5	251	370	0.678	1.966	0.73327±12
6	201	387	0.520	1.508	0.72661±14
7	183	683	0.268	0.7748	0.71517±10
8	249	369	0.676	1.959	0.73305±14
10	205	565	0.362	1.049 ±0.7% (2σ)	0.71941±10 (2σ)

sample number:	G6 (medium grained)	G1 (fine grained)	
			1000 points
quartz	26.4%	30.1%	counted for
plagioclase feldspar	33.2%	35.3%	each sample
potassic feldspar	28.4%	24.0%	
biotite	8.0%	7.6%	
muscovite	1.2%	0.4%	
allanite	0.8%	trace	
epidote	0.5%	trace	
chlorite	0.6%	0.7%	
calcite	0.2%	0.6%	
iron oxides	0.5%	0.3%	
garnet	-	0.4%	
apatite	trace	trace	
zircon	trace	trace	
sphene	0.2%	0.5%	

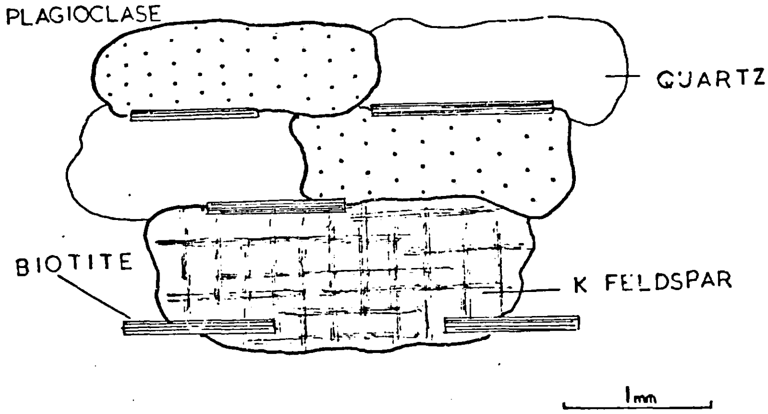
From the modal analysis, it can be seen that the ratio of potassic feldspar to plagioclase is $>\frac{1}{3}<\frac{2}{3}$; compositionally therefore, the granites can be classified as adamellites. (Hatch, Wells & Wells 1972 p.204).

The granites are noticeably segregated into quartz rich, plagioclase rich and potassic feldspar rich aggregates that are invariably parallel to the foliation, and may be up to 5cms. in length. (fig. 13)

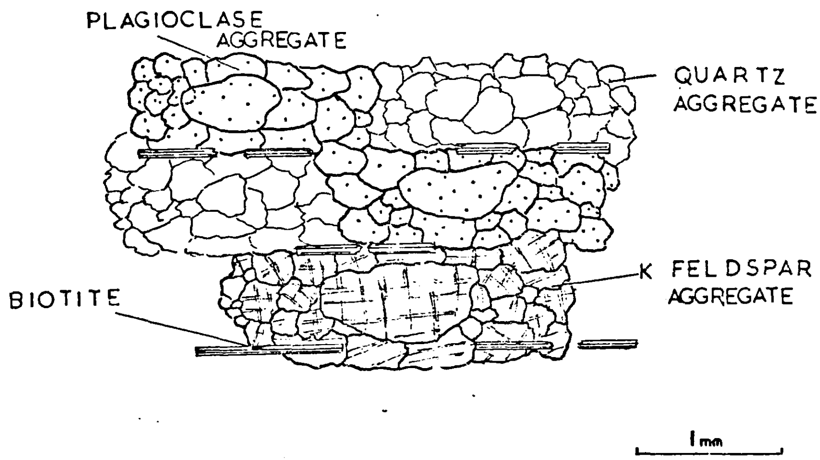
Quartz has two modes of occurrence, either as occasional small (<0.2mm), irregular intergranular grains within the feldspathic aggregates, and blebs within myrmekitic reactions, or as long (several cm) narrow (<1mm) monomineralic aggregates, separating felsic aggregates. The quartz aggregates are

FIG 13

Proposed method for the development of monomineralic aggregates within the D2 gneissose granites.



(a) initial coarse grained crystallisation



(b) grain size reduction by mylonitic processes.

composed of coarse grains (2mm-5mm in length), which in an individual string possess an original common optical orientation, (as defined using the sensitive tint accessory plate). This primary optical continuity of the grains has subsequently been partially obscured by strain, which has broken down the coarse grains into marginal sub and new grains, that are under 1mm in length. (fig 13)

Plagioclase feldspar occurs in both twinned (albite law) and untwinned forms, and has a composition of An_{24} - An_{28} (oligoclase), as determined by the Michel Lévy test. The plagioclases are confined almost entirely to the plagioclase aggregates, with only rare small grains within the potassic feldspar aggregates, and none within the quartz aggregates. The individual grains of plagioclase range in size up to 1.5mm in the coarser granites, and up to 0.75mm in the finer granites. Their shape tends to be granoblastic or tabular, elongate parallel to the foliation, often with optical continuity across adjacent grains.

Twinned microcline feldspar, and an untwinned potassic feldspar with perthitic exsolution lamellae combine to form the potassic feldspar aggregates. The grains are slightly coarser than the quartz and plagioclase in their own aggregates, being up to 2mm in size. Again, optical continuity across the grains is observed. The potassic feldspars are locally replaced by muscovite.

Biotite is the dominant mafic component of the granites, and everywhere has a strong shape and crystallographic orientation parallel to the foliation. It is pleochroic from pale brown (Z) to dark brown (X, Y), and is confined almost entirely to the feldspar rich bands, or to the margins of the quartz aggregates. Grain size varies, being <0.75mm in the finer granites, and <1.5mm in the coarser granites.

The accessory minerals are confined to the feldspar aggregates.

Sphene varies in shape between euhedral and anhedral, with a size ranging up to 1mm, although it is often intergrown with iron oxides. Garnet is only observed in close proximity to iron oxide, where they tend to be fine grained (<0.5mm) and subhedral.

Yellowish brown allanite is a common accessory mineral, occurring as large (up to 2mm) euhedral metamict grains, that are occasionally zoned, possessing an outer rim of epidote. The alteration of the allanite has resulted in expansion, and the production of radiating cracks in the surrounding felsic groundmass.

Interpretation of the D2 gneissose granite texture

The gneissose granite has a texture, which when considered in 3 dimensions, comprises elongate ellipsoidal, virtually monomineralic aggregates which together form the marked foliation and shape fabric lineation.

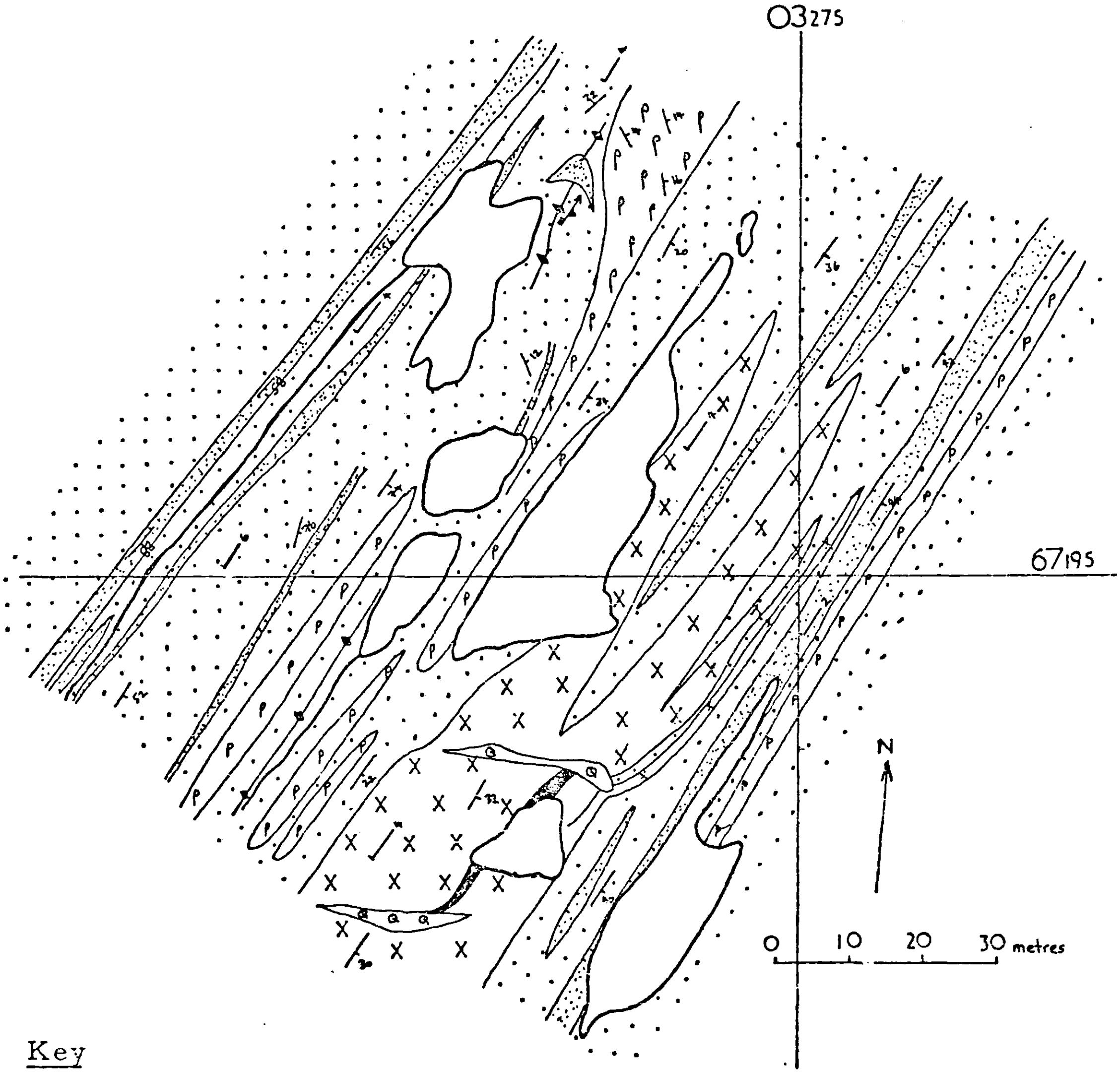
The occurrence of potassic feldspar, plagioclase and quartz aggregates as separate entities, (fig 13) with grains within the aggregates often having optical continuity across their boundaries indicates that the texture observed at the present time is derived from an initially coarser rock. Therefore, it is probable that a coarse (up to 2cm or more) granitic rock, of adamellitic composition, was subjected to intense deformation, resulting in the breakdown of an early coarse texture, and the generation of a strong L-S tectonite.

2.2b Quartzofeldspathic and epidotic quartzofeldspathic gneisses

The quartzofeldspathic gneisses are the most common basement lithology, occurring over about 60% of the mapped basement area. They outcrop predominantly in the north east of the region, and along a 1km wide corridor beneath the nappes, where thrusts affect the outcrop pattern. (fig 9). Elsewhere, the quartzofeldspathic gneiss has a sporadic outcrop within areas of the hornblende quartzofeldspathic gneiss, in part being interbanded on a medium/coarse scale (tens of metres).

The epidotic quartzofeldspathic gneisses are sporadically developed throughout the quartzofeldspathic gneisses, although they reach prominence in the zone immediately beneath the nappes.(fig 14)

FIG. 14 A small area of the Basement Gneisses, showing the interbanding of the flaggy quartzofeldspathic gneisses, epidote gneiss and gneissose granite.



Key

- flaggy epidote gneiss
- flaggy quartzofeidspathic gneiss
- D2 gneissose granite
- pegmatite
- amphibolite
- quartz vein
- composite foliation
- lineation
- F3 fold axial plane and axis
- F3 antiformal axial trace
- lake and stream

The essential minerals are plagioclase and potassium feldspar, quartz and biotite, with the local development of epidote and minor amounts of magnetite, sphene, apatite and chlorite.

The gneisses are invariably medium to fine in grain size, (plate 20) individual crystals rarely exceeding 3mm in diameter, but occasional porphyroclasts of feldspar occur up to 1cm in diameter. The gneisses weather to a dark grey colour, with occasional pinkish hues; fresh specimens are pale grey. The abundant pegmatite veins within the gneisses weather either pink or white.

The gneisses are invariably banded on a small scale (millimetres - centimetres) with some segregation into quartzofeldspathic and biotite rich bands. The banding is accentuated by the presence (plate 21) of thin pegmatite veins, and occasional thin amphibolite units. A penetrative foliation is developed throughout. The gneisses split into slabs, preferentially along biotite rich bands, or along the thin amphibolite units, leaving many exposures with mafic surfaces. The thickness of the slabs is variable, and appears to depend in part on the degree of flattening undergone by the gneisses. (Section 4.2c)
This is most readily seen in the zone of quartzofeldspathic and epidotic quartzofeldspathic gneiss immediately beneath the nappes (fig 9). Tectonic flattening has given rise to the generation of a flaggy interbanded quartzofeldspathic and epidotic

quartzofeldspathic gneiss, that has been mapped as a separate unit to the "unflattened" quartzofeldspathic gneisses, covering an area of approximately 12km^2. (plate 28)

Mineralogy of the quartzofeldspathic and epidote quartzofeldspathic gneisses. (plate 2)

Mineralogically, the gneisses are homogeneous, with a compositional range reflecting primarily the locally developed segregation banding, which occurs on the scale of millimetres.

The following minerals are recognised and are tabulated along with a visual estimate of their range of proportion:

plagioclase feldspar	35-50%	
potassium feldspar	7-25%	
quartz	20-35%	
biotite	5-25%	
epidote	trace - 3%	- increases to 12% in the epidote quartzofeldspathic gneiss
sphene	trace	
chlorite	trace	
iron oxides	trace	
apatite	trace	

Both plagioclase and potassic feldspar have an average grain size of 0.75mm - 1.0mm, although rare potassic feldspar porphyroblasts, up to 1cm in diameter do occur. The feldspars occur as either individual grains, with irregular granoblastic (fig 10) margins, or as elongate aggregates with margins bounded by biotite.

The potassic feldspars have occasional microcline twinning, although an untwinned form is most common, with only slight alteration to sericite. Myrmekitic intergrowths between plagioclase and quartz occur at the margins of some of the potassic feldspars; however, perthitic exsolution lamellae are rare, seen only in porphyroblasts.

The plagioclases occur in both untwinned and twinned form; the albite and combined albite - carlsbad twins have been used to determine the composition of the plagioclase using the Michel Lèvy tests. They lie compositionally on the boundary between oligoclase and andesine. (An_{28} - An_{32}).

Quartz occurs in three forms: 1. individual granoblastic grains, with a range of grain sizes between 0.1 - 0.5mm. These are either granular, or have a slight elongation parallel to the foliation. These grains, along with the granular feldspar grains, form the matrix to the gneiss.

2. as elongate aggregates, forming quartz strings that may be up to 1.3mm in length. The strings have straight boundaries, and are invariably parallel to the foliation. The quartz strings occur predominantly within the quartzofeldspathic segregation bands. (fig 10)

3. as small blebs associated with myrmekite intergrowths.

The quartz is variably strained - some grains are free of strain features, whilst others show extreme undulose extinction and have marginal developments of sub and new grains. (fig 10)

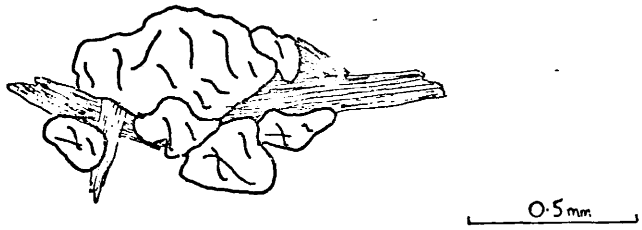
Biotite occurs predominantly in the mafic parts of the segregation bands, as aggregates or as individual grains, where it has an average grain size of about 0.5mm, with some rare individual grains up to 1mm in length. In contrast, the biotites in the quartzofeldspathic fractions are usually less than 0.2mm. Both fractions of the segregation banding have biotites of similar appearance - a tabular form with rather corroded ends, and a pleochroic scheme of X = pale/medium brown, Y= dark brown, Z = greenish brown. This colour scheme suggests biotites of moderately Fe rich compositions. (Deer, Howie & Zussman 1966 p.213).

The colourless epidotes occur rather infrequently in the quartzofeldspathic gneisses, but are common in the epidotic quartzofeldspathic gneisses. In both they have the same habit and optical features: high 2V ($\sim 60^{o}$), optically negative and interference colours in the second order. They occur as either tiny grains within saussuritised plagioclase, or as individual subhedral grains up to 0.3mm in diameter, or as clusters up to 0.7mm in size. Typically, the epidote clusters (fig 15) are in contact with the biotites. Occasional subhedral epidotes have cores of metamict allanite.

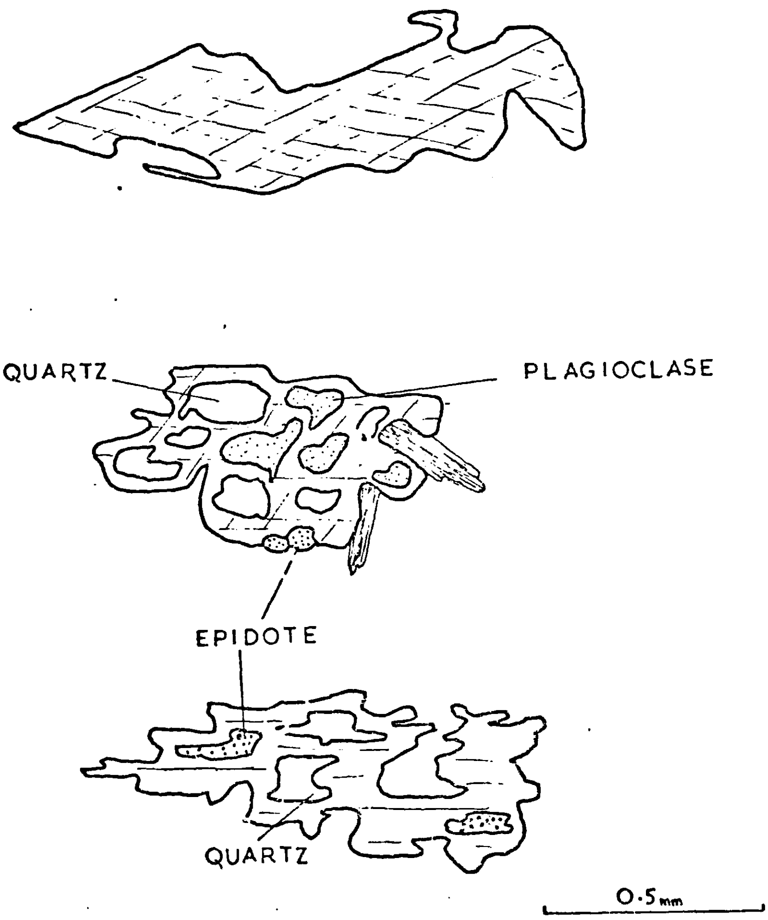
The iron oxides, sphene and apatites occur as small ($<$0.2mm)

FIG 15

(a) epidote clusters within an epidotic quartzofeldspathic gneiss.



(b) forms of hornblende within the hornblende quartzofeldspathic gneiss.



euhedral or subhedral grains.

2.2c. The Hornblende quartzofeldspathic gneisses

This gneissic lithology occurs predominantly within the western portion of the mapped basement, with an areal extent of about $8km^2$; (fig 9), however, thin horizons are locally observed throughout the Basement complex.

The hornblende quartzofeldspathic gneiss has the essential minerals: quartz, feldspars, biotite and hornblende, with local occurrences of garnet, epidote, sphene, iron oxides, chlorite and apatite. The gneiss is readily distinguished from the quartzofeldspathic gneiss by its higher mafic content and coarser grain size. Often, the hornblende quartzofeldspathic gneiss has a foliation defined by elongate, flattened quartzo-feldspathic augen which may be up to 7cm or so in length, with an envelope of biotite and hornblende (plate 3). These augen give the rock its coarse appearance; however, in detail the minerals within and enveloping the augen are medium to fine grained (generally $<$ 1.0mm).

The foliation in the hornblende quartzofeldspathic gneiss is accentuated by the presence of pegmatite and quartz veins. The massive mottled black and white gneiss breaks only poorly along the foliation plane, which have streaked out augen defining a strong lineation. (plate 25)

Mineralogy of the Hornblende quartzofeldspathic gneiss

Mineralogically, the hornblende quartzofeldspathic gneisses are only moderately variable, with quartz, potassic feldspar, plagioclase, hornblende and biotite being invariably present. The full range of mineral contents, estimated visually, are:

quartz	20-30%
K feldspar	10-30%
plagioclase feldspar	20-30%
biotite	10-20%
hornblende	2-15%
epidote	trace - 12%
garnet	0.3%
sphene	trace - 2%
iron oxides	trace
apatite	trace

Quartz occurs in three differing habits within the felsic augen:

1. as strings and individual grains; the strings are invariably parallel to the foliation, and range up to 1cm in length. The grains that together form the quartz strings are often coarser (up to 1.5mm) than those of the augen matrix, and have straight boundaries, compared with the rather irregular, sometimes sutured margins of the individual matrix grains. These matrix grains may be elongate, parallel to the foliation, but are rarely greater than 0.4mm. Strain features are common in both the string and matrix grains. (fig 10)

2. as individual grains, less than 0.2mm in size, included, or partially included by hornblende. The grains have the characteristics of the matrix quartz.

3. as tiny blebs within the myrmekite textures.

The felsic augen also contain both potassic and plagioclase feldspar, both of which occur as either monomineralic aggregates, up to 1.5cm in length, or as individual grains that are usually less than 0.5mm. However, porphyroblastic grains are very rare, the feldspars typically forming an equigranular granoblastic matrix, along with the quartz, and minor amounts of the mafic minerals. Texturally, there are two varieties of potassic feldspar - microcline, with the typical cross-hatched twinning, and an untwinned variety, often containing perthitic exsolution lamellae. Myrmekitic intergrowths with plagioclase often occur at the potassic feldspar grain margins.

Plagioclase grains are of composition An_{26}- An_{28} (upper oligoclase) as determined by the Michel Lèvy tests; saussuritic alteration textures are occasionally seen.

The felsic augen are enveloped by more mafic rich bands, that retain matrix quartz and feldspar. However, the higher proportion of biotite, hornblende and epidote is obvious.

The prismatic biotite is pleochroic from greenish brown (Z) to pale brown (X, Y), and occurs as either individual grains up to 1mm in length, with slightly corroded margins, or as aggregates up to 1.0cm or so in length. It is common for the biotite aggregates to be intergrown with hornblende and epidote, and for all 3 minerals to define the foliation and lineation.

Hornblende has variable grain size and shape with anhedral to euhedral grains ranging from 0.1mm up to 1.5mm or so, although the average size is about 0.75mm. The anhedral forms invariably include abundant matrix inclusions (quartz and feldspar), (fig 15) in contrast to the inclusion free sub or euhedral forms. The maximum recorded extinction angle ($Z \wedge C$) is 30°, with the average being around 22°. The pleochroic scheme is X - bluish green, Y - green, Z - dark green. Interference colours are masked by the strong body colours. Taken together, the optical properties, along with a high (~ 60°) 2V, indicate that the amphibole is common hornblende.

Epidotes are seen as small (<0.2mm) anhedral to subhedral colourless grains, sometimes with metamict allanite cores. The combination of interference colours ranging up to 2nd order reds and yellows, a negative optical figure, and extinction slightly inclined (up to 10°) to the prominent cleavage indicate that the mineral is epidote, as opposed to clinozoisite or zoisite.

Red garnets are rare, and are seen only within the mafic aggregates. They occur either as subhedral or euhedral individual grains (< 0.3mm) or in aggregates up to 2mm in size.

Sphene, apatite, and iron oxides occur as sporadically distributed small (<0.5mm) euhedral grains within the mafic rich bands.

2.3 Origin of the Basement Gneisses

It is difficult to propose an origin for the quartzofeldspathic, epidote quartzofeldspathic and hornblende quartzofeldspathic gneisses, due to the extensive tectono-metamorphic processes that they have undergone in their evolution. (Section 4.2) All the textures seen are considered to be metamorphic with no relic igneous features.

The lack of any distinctive alumino-silicate mineralogy, distinctive compositional banding or presence of quartzitic bands suggests that a sedimentary origin is probably unlikely. Similarly, the regional homogeneity of the gneissic mineralogy points to igneous parentage. In support of this, Rb/Sr isotopic investigations on the quartzofeldspathic gneisses of an adjacent region indicates that the gneisses have a low initial Rb/Sr ratio (0.7015 ± 0.0018), suggesting that they are not derived from reworked crustal material, but are of mantle origin. (Gray 1978).

Without geochemical analyses, classification is made only on the basis of mineralogy. Thus, the quartzofeldspathic and epidotic quartzofeldspathic gneisses would be classified, under igneous terminology, as bordering adamallites/granodiorites, whilst the hornblende quartzofeldspathic gneisses would be classified as bordering quartz monzonites/quartz diorites. (Hatch, Wells & Wells 1972). In both cases, the moderate proportion of potassic feldspar may reflect some K metasomatism subsequent to the initial evolution of the rocks.

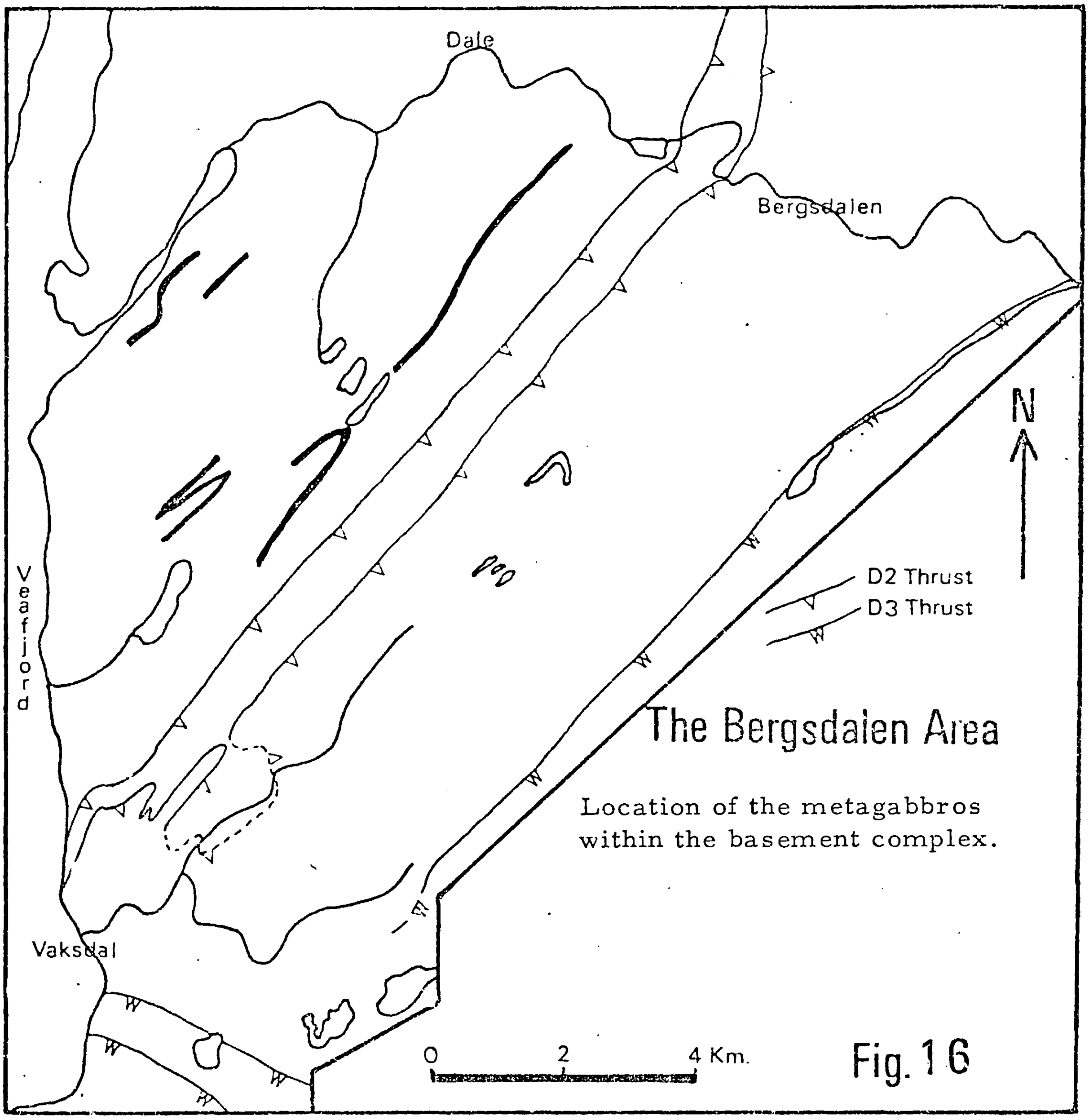
2.4 Amphibolites

Amphibolites within the Basement gneisses fall into two categories:

1. coarse grained "metagabbros"
2. medium grained biotite amphibolites

2.4a The "metagabbros"

The "metagabbros" have only a limited occurrence as sheet like bodies up to 5km in length that have not been seen to exceed 10-15 metres in thickness. (fig 16). They outcrop mainly within the quartzofeldspathic gneisses, although one small unit has also been traced within the hornblende quartzofeldspathic gneiss. The bodies are invariably highly deformed, resulting in the obliteration of most marginal features, and the generation of a pervasive foliation that is parallel to that of the regional gneissic foliation (S2). The structural age of the "metagabbros" has been assigned to "pre D2". (Section 4.2b)



The Bergsdalen Area

Location of the metagabbros within the basement complex.

Fig. 16

The essential minerals are hornblende, plagioclase and quartz. Individual hornblendes may reach 1cm in diameter, with the average about 5mm; however the hornblendes usually occur in monomineralic clusters, giving the impression of much coarser grains in hand specimen, locally up to 5cm. The hornblendes sit in a felsic matrix, giving the rock a distinctive coarse "blotchy" appearance, that are streaked out defining the foliation.

Mineralogy of the "metagabbros"

The "Metagabbros" have a generally restricted mineralogical content, with only the more highly deformed bodies having a slightly greater biotite content, and a sympathetic decrease in hornblende.

The estimated mineral contents are:

hornblende	43-50%
plagioclase	40-50%
biotite	1-5%
quartz	3-6%
iron oxides	1-4%
apatite	0.5-1.0%
sphene	traces
chlorite	traces
epidote	traces

Hornblendes within the "metagabbro" show two stages in recrystallisation (fig17) Coarse grained (0.5-1.5cm) central hornblendes are symplectically intergrown, with quartz, with the amount of quartz forming between 20-40% of the total area covered by the hornblende grain. These coarse hornblendes are pleochroic from pale green (X), bluish green (Y) to dark green (Z) and have an euhedral to subhedral form. The quartz inclusions show minor strain features, such as undulose extinction and sub grain development, and tend to be included along cleavage planes within the hornblende, but themselves show no obvious c axis orientation, as identified by using the sensitive tint accessory plate.

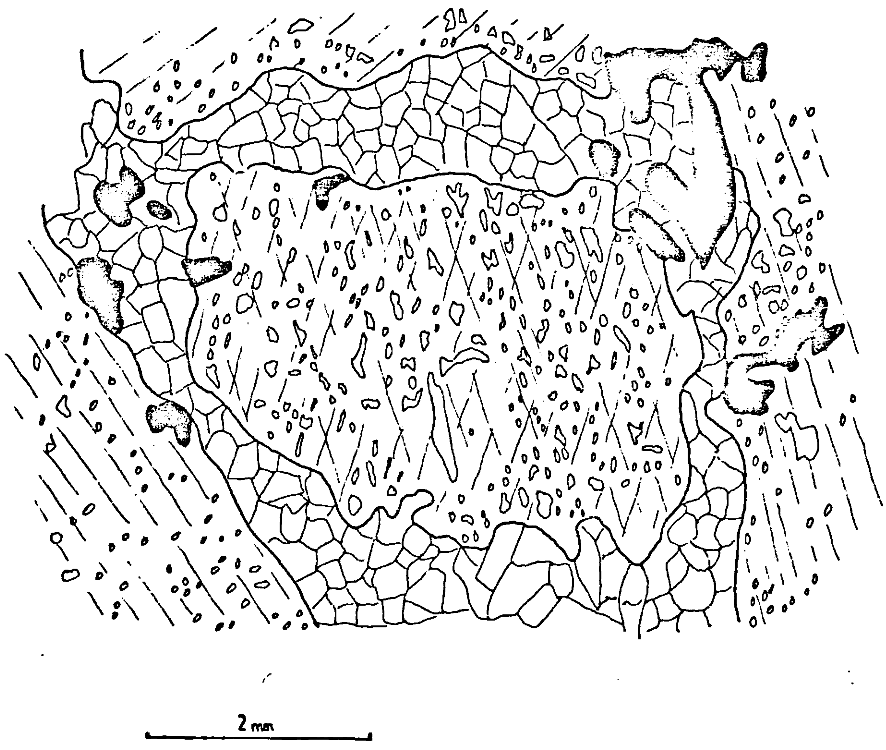
These central, coarse grained hornblendes are invariably mantled by almost monomineralic aggregates of finer grained (0.3-1mm) (fig 17) hornblendes; the mantles are rarely > 2mm in thickness. The mantle hornblendes have the same pleochroic scheme as the central grain, and possess an equigranular granoblastic texture, with anhedral grains of iron oxide (up to 1mm in diameter) included.

The contact between core and mantle is usually sharp, with some of the mantle hornblendes replacing the core hornblendes along the cleavage planes.

The areas between the hornblende aggregates are almost monomineralic themselves, with plagioclase dominating; minor amounts of orientated biotite, quartz and epidote occur interstitially to the plagioclase. The plagioclase has a granoblastic

FIG. 17

Coarse poikiloblastic hornblende with quartz inclusions and granoblastic hornblende rims; from the metagabbro of the basement complex.



texture, sometimes elongate, but often with approximate triple junctions. Grain size is regular, typically between 0.3-0.5mm and they occur in either twinned (albite) or untwinned form. Michel Lèvy determinations indicate that the plagioclase composition lies within the mid-Andesine range (An_{38} - An_{44}).

The large poikiloblastic hornblendes, with their quartz inclusions and hornblende rims could reflect the retrogression and pseudomorphing of earlier (igneous?) pyroxenes in the manner described by Sutton and Watson (1951) for metamorphosed dolerites at Laxford, Scotland. The sequence resulting in the replacement of pyroxene recorded by these authors is:

1. secondary hornblende forms rims to the pyroxene

2. the pyroxene is replaced by multi-phase, multi-crystal hornblende and quartz pseudomorph, followed by the reorganisation of the multi-crystal pseudomorphs to form single crystal pseudomorphs (large poikiloblastic hornblendes with quartz inclusions) with the rim hornblendes preserved from the previous stage.

3. recrystallisation of the plagioclase destroys any igneous texture, and forms granoblastic aggregates.

The result therefore, is to leave a rock in which pyroxenes are completely pseudomorphed by hornblende, within a plagioclase matrix. The original metagabbro is retrogressed to an amphibolite.

2.4b The Biotite - amphibolites

The biotite-amphibolites are medium to fine grained rocks that are widely, but sparsely distributed throughout all of the basement gneisses. They occur as thin, untraceable bodies, rarely greater than 15m in length, and are often intensely schistose. The bodies are almost invariably parallel to, and contain the regional foliation; the exception being one exposure on the side of Veafjord, at GR 0320467150, where the intrusive nature of the amphibolite body is clear. (plate 23)

The essential mineralogy in the schistose amphibolites is biotite, feldspar, and quartz, with relic hornblende; however, the more massive biotite amphibolites contain important hornblende.

Mineralogy of the Biotite-amphibolites

The biotite-amphibolites within the basement complex are most often in a sheared and retrogressed state, indicated by the granulation of grains and the replacement of hornblende by biotite. These highly sheared amphibolites are described in the section on Nappe emplacement (Section 4.6a), so will not be reported further here.

Amphibolites in an unretrogressed state have the following mineralogical content (visually estimated):

hornblende	40-45%
biotite	10-15%
plagioclase	30-35%
sphene	1-3%
quartz	3-5%
apatite	trace
iron oxides	trace

Hornblende is pleochroic from dark green - green - khaki green, and has an extinction angle ($Z \wedge C$) up to 28^{o}. The subhedral grains lie in the range from 0.5-1.5mm in size, and are orientated, with their c axes defining the foliation, along with biotites. The hornblendes are evenly distributed throughout the amphibolites.

Quartz, sphene and iron oxides are seen as inclusions within the hornblende. Biotite is separated from hornblendes, occurring within patches of plagioclase, and is pleochroic from pale brown to dark brown, with grain sizes less than 0.3mm. Biotite may also locally replace hornblende along cleavage planes and fractures.

Plagioclase (<0.5mm) forms a granoblastic, locally elongate, matrix, with twinned (albite, carlsbad-albite forms) and small quartz grains lying interstitially. Plagioclase composition lies in the lower andesine range (An_{30} - An_{34}), as determined using the Michel Lévy test.

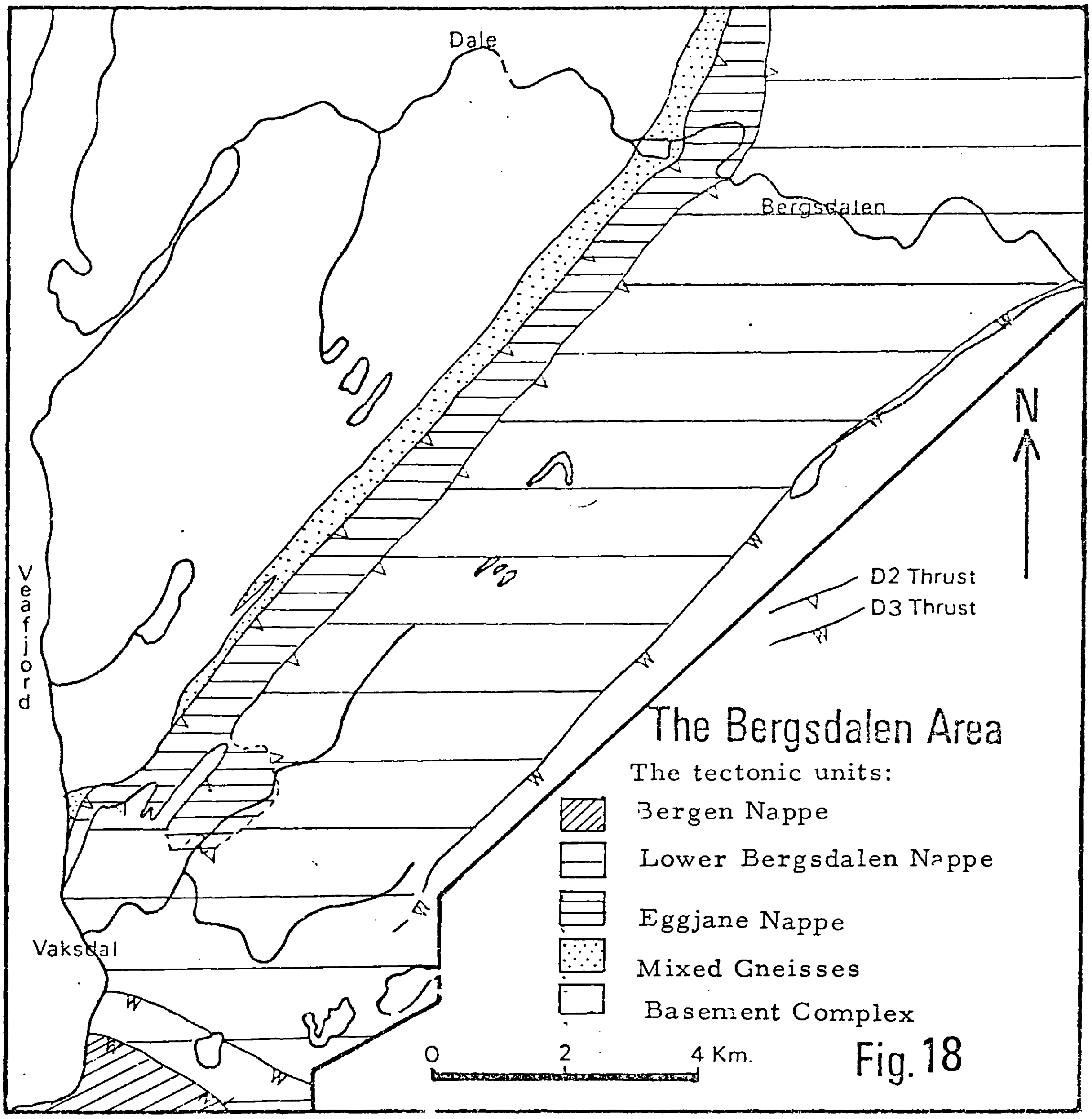
The biotite - amphibolites represent deformed and metamorphosed intrusive basic dykes or sills.

2.5 The Mixed Gneisses

The Mixed Gneisses occupy a lengthy tract of ground, bounded on either side by D3 thrusts, sandwiched between the underlying Dale Basement, and the overlying Eggjane Nappe (fig 18)
The outcrop is never greater than 400m in width, yet can be followed for at least 15km from the southwest, on the flanks of Bjørnsfjell towards the northeast, on the eastern flanks of Dystingen. However, it can not be traced farther to the southwest, on the north facing slope of Bjørnsfjell (GR 0321667130) owing to the combination of vegetation cover and topography.
It does however, reappear in road exposures north of Skreii (GR 0320667116).

The Mixed Gneisses are almost everywhere juxtaposed against either basement or Eggjane gneisses, by the D3 thrusts (Section 4.3c) However, at two locations, they are seen to be structurally overlying flattened basement gneisses along an early (D1) tectonic break. (Section 4.3b)

The Mixed Gneisses comprise several gneiss varieties, with a


Dale
Bergsdalen
Veafjord
Vaksdal
N
D2 Thrust
D3 Thrust
The Bergsdalen Area
The tectonic units:
Bergen Nappe
Lower Bergsdalen Nappe
Eggjane Nappe
Mixed Gneisses
Basement Complex
0
2
4 Km.
Fig. 18

biotite-epidote-hornblende bearing gneiss dominant, accounting for an estimated 60% of the total. All of the gneisses are intruded by thick (up to 5m) pegmatite and granite bodies - the latter often being traced for several kilometres. (plate 4)

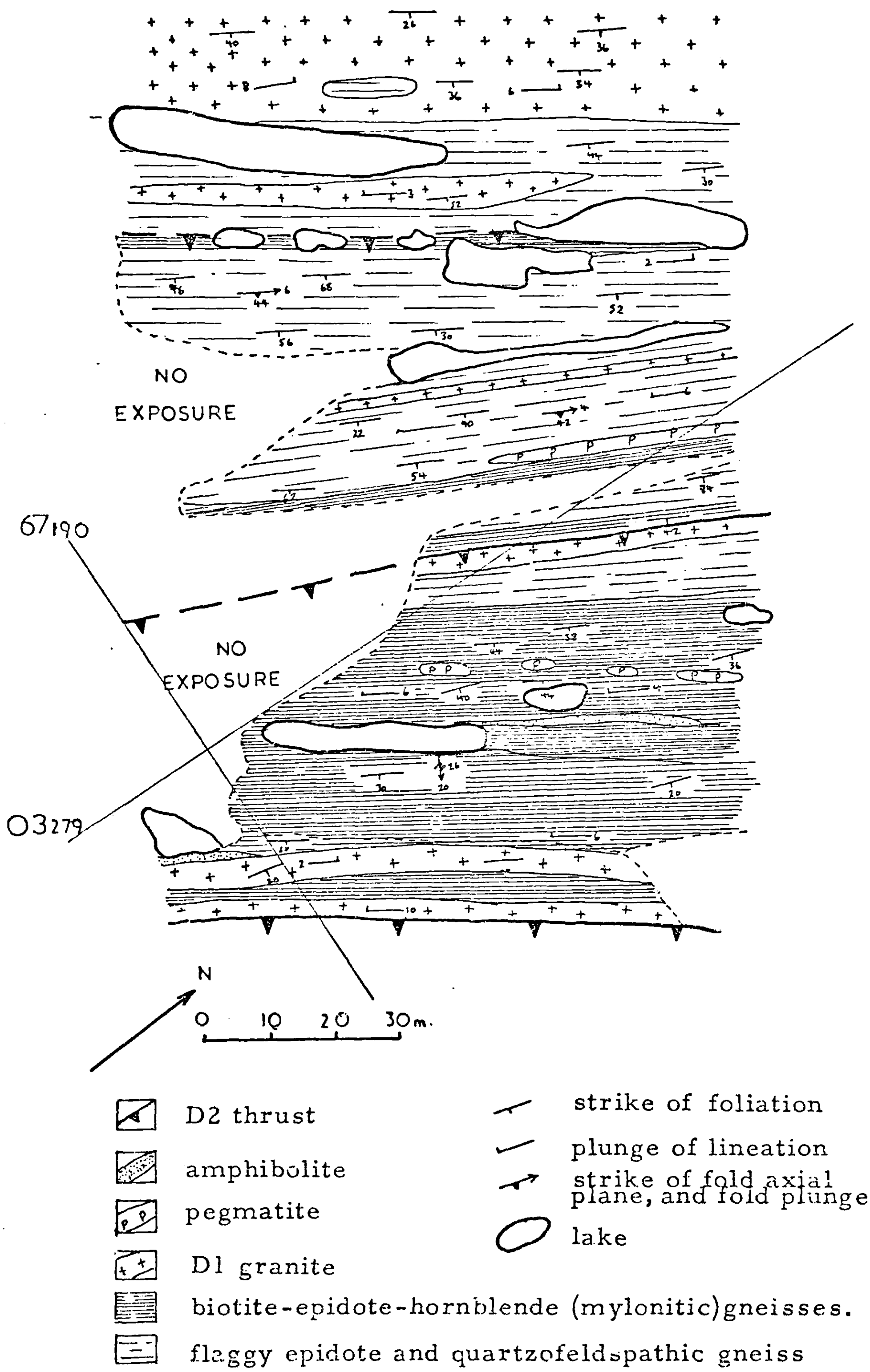
Individual gneissic lithologies are inhomogeneously distributed through the Mixed Gneisses, preventing them from being mapped at the scale of 1:15000 (fig 19)

The outcrop of the Mixed Gneisses is rather poor, compared with the excellent exposures of the gneisses on either side (plate 5)

Individual components of the Mixed Gneisses

Biotite-epidote-hornblende gneiss: these fine to medium grained, homogeneous gneisses are the dominant lithology within the Mixed Gneisses; they are very flaggy (1-2cm partings) and brown weathering - superficially very similar to the gneisses within the Bergsdalen Nappe. Although distributed throughout the Mixed Gneisses, the Biotite-epidote-hornblende gneiss is also invariably located immediately beneath the Eggjane Nappe. The mafic mineral content define a very strong foliation, and are also orientated to form a mineral lineation (L1) on the foliation planes. Occasional thin compositional banding, defined by layers enriched in hornblende, is concordant to the regional

FIG 19 Map of the heterogeneous Mixed Gneisses



foliation. Thin pegmatite veins and quartz bands accentuate the foliation.

Banded Gneisses: horizons of Banded Gneiss, very similar in appearance to that of the Lower Bergsdalen Nappe are seen within the Mixed Gneisses. When weathered, they are often superficially indistinguishable from the extensive biotite-epidote-hornblende gneisses, being fine to medium grained, brown, with an extremely flaggy parting. However, in fresh road cuttings north of Skreii, the typical colour banding is common, with the pale grey biotite gneisses alternating with the pale green biotite-hornblende gneisses (see Section 2.10). In the plateau region, the Banded Gneisses are distinguished only by the presence of biotite gneiss, which may contain feldspar augen up to 1.5mm in diameter, along with some garnet. (Plate 6)

Within the fresh road cutting north of Skreii (GR 0320667116), two unusual lithologies are recognised within a horizon of Banded Gneisses within the Mixed Gneisses:

1. a discrete, medium grained muscovite schist, less than 1 metre in thickness, and laterally extensive on the outcrop scale.

2. thin, ($<$ 50cm) discontinuous lenses of pyroxene bearing amphibolite. These pale green amphibolites have pyroxene porphyroclasts up to 1.5cm in diameter, surrounded by

a biotite/amphibole fabric. (fig 20)

Quartzofeldspathic Gneisses: these foliated, grey weathering quartzofeldspathic, medium grained, gneisses are distinctive, often forming low, exposed ridges within the grassy width of the Mixed Gneisses. Locally, they contain pods of less flattened gneiss, which is identical in both lithological and structural appearance to the typical quartzofeldspathic gneisses of the basement. (Section 2.2b)

The outcrops range in size from about 50km in length, up to 2km, although the thickness never exceeds about 20 metres. They account for about 10% of the Mixed Gneisses.

Gneissose Granites: several long, thin bodies of gneissose granite, constituting about 10% of the Mixed Gneisses, have been mapped. Together with the quartzofeldspathic gneisses, they form prominent exposed ridges, with lengths up to 3km, but thickness is never greater than 15 metres.

The granites are very homogeneous, medium grained acidic bodies, with a well defined foliation, and north easterly trending shape fabric lineation. They are invariably concordant to the surrounding flaggy gneisses, with only rarely preserved intrusive features. (plate 36)

Amphibolites: small, medium grained amphibolite bodies are common, invariably concordant with adjacent biotite-epidote-hornblende gneisses, or the Banded Gneisses.

The original relationships between these various lithologic types is very obscure. Together the various gneisses have undergone deformation, so that primary contact features have been destroyed. They are almost invariably seen as concordant, individual bodies with sharp junctions.

Mineralogy of the Mixed Gneisses

Of the various lithologies that together are termed the Mixed Gneisses, only the biotite-epidote-hornblende gneiss, and the rare horizons within the Banded Gneisses, will be described here. The remaining lithologies are described in their individual sections. (Section 2.2, 2.4)

The Biotite-epidote-hornblende gneiss (plate 6)

The three minerals used as a prefix to describe the gneiss are almost invariably seen; the exceptions to this occur in rare lithologies, where only two of the mafic minerals are present.

Modal analyses of the biotite-epidote-hornblende gneiss specimens give:

Sample no:	SA5.11	SA5.10	SA5.9	SA5.4	SA5.1
quartz	22.0%	18%	24%	16%	15%
plagioclase	35%	38%	30%	44%	43%
k feldspar	1%	-	-	2%	-
biotite	4%	18%	9%	20%	22%
hornblende	21%	8%	22%	4%	8%
epidote	15%	16%	15%	11%	12%
garnet	-	-	-	2%	-
chlorite	trace	1%	-	trace	-
sphene	trace	trace	trace	trace	trace
iron oxides	trace	trace	trace	trace	trace

1000 points counted in each case

Although the epidote content appears to be independent to that of biotite and hornblende, the latter are linked, in that a lithology rich in biotite is poor in hornblende, and vice versa.

Texturally, the gneiss is very homogeneous with no mineral segregations, and is fine to medium grained (less than 1.0mm). The mafic minerals are all orientated, defining the foliation and a mineral lineation (L1). Local compositional banding occurs, with thin horizons (< 1cm) rich in hornblende and epidote.

Quartz and plagioclase form either a polygonal or elongate granoblastic groundmass, with the plagioclases slightly coarser (< 1mm) than the quartz (< 0.6mm). Twinned plagioclase (albite, carlsbad-albite and pericline laws) have been analysed using the Michel Lèvy test, and are of mid-upper andesine in composition. (An_{36} - An_{46}), although some plagioclase has undergone saussuritisation. Normal zoning is common within the plagioclases.

Strain features (undulose extinction, sub and new grain development) are common in the quartz and plagioclase of the matrix.

Potassic feldspar is rare; where seen it is untwinned, with an appearance similar to plagioclase, but having marginal myrmekite.

Biotite is less than 0.5mm in length, and has a pleochroic scheme from pale brown (Z) to dark brown (X, Y). It is evenly distributed through individual rock samples, and defines the strong foliation.

Hornblende has a pleochroic scheme from green to dark green, although bluish green hornblende has also been observed. Interference colours range up to the 2nd order, and extinction ($C \wedge Z$) has been recorded up to 28°. The grains are sub or euhedral, and only rarely exceed 1mm in length, the average being around 0.7mm.

Epidote occurs in variable forms, from tiny grains associated with plagioclase saussuritisation through to 0.7mm grains forming part of the mafic foliation. As with the hornblende, the epidote is evenly distributed through the individual gneiss samples.

Optically negative epidotes, with interference colours ranging up to the upper second order may have pseudohexagonal cross sections, or may occur as granular or subhedral aggregates. They are unzoned, and have tiny inclusions of euhedral sphene.

Garnet is not common; where seen it is sub or euhedral, less than 0.5mm in diameter and has a pinkish tinge. It has circular rings of tiny inclusions of quartz, epidote and biotite.

Rare horizons within the Banded Gneisses

Other than the regular Banded Gneiss Lithologies (Section 2.10) a muscovite schist and a pyroxene amphibolite have also been noted within the Banded Gneisses of the Mixed Gneisses.

Mineralogy of the Muscovite Schist

The schist is medium grained with an homogeneous development of muscovite throughout. The following mineral ranges are visually estimated:

quartz	55%
plagioclase	3%
k feldspar	2%
muscovite	37%
biotite	1%
iron oxides	2%
sphene	traces
apatite	traces

The quartz and feldspar occur as tabular grains up to 1mm, with muscovite books and individual grains growing along their grain boundaries (< 1.5mm), and locally including the quartz.

Irregular patches of iron oxide, up to 1mm in size, enclose all of the minerals.

Mineralogy of the Pyroxene amphibolite

One sample of the pyroxene amphibolite has been studied; this was medium to coarse grained, with a high mafic content:

(visually estimated)	clinopyroxene	55%
	hornblende	24%
	biotite	8%
	clinozoisite	2%
	plagioclase	6%
	quartz	3%
	iron oxides	1%
	calcite	½%

The clinopyroxene occurs as large crystals, up to 1.5cm in diameter (although more typically they lie within the range 2-6mm) that are augened by a strong fabric comprising aggregates of finer grains (< 1.5mm) of biotite and hornblende, along with minor grains of clinozoisite. (fig 20)

The subhedral clinopyroxenes are identified as diopside from their very pale green to colourless body colour in thin section, upper 2nd order interference colours, maximum extinction ($C \wedge Z$) of 44^{o}, and a positive biaxial interference figure with 2V about 60^{o}. The perpendicular pyroxene cleavages are obvious in basal sections.

The diopsides have small inclusions of quartz and biotite, and are locally replaced along cleavage and fracture planes by small grains of subhedral hornblende (< 0.5mm). The quartz and plagioclase occur as fine (<0.2mm) interstitial grains to the mafic fabric, and also as coarser grains (<0.6mm) within the diopsidic augen.

The texture is entirely metamorphic, with no relic igneous textures recognised from within the augen.

2.6 Discussion of Mixed Gneisses

A correlation has already been suggested between the massive quartzofeldspathic gneisses and gneissose granites of the Mixed Gneisses, and the equivalents in the Basement complex.

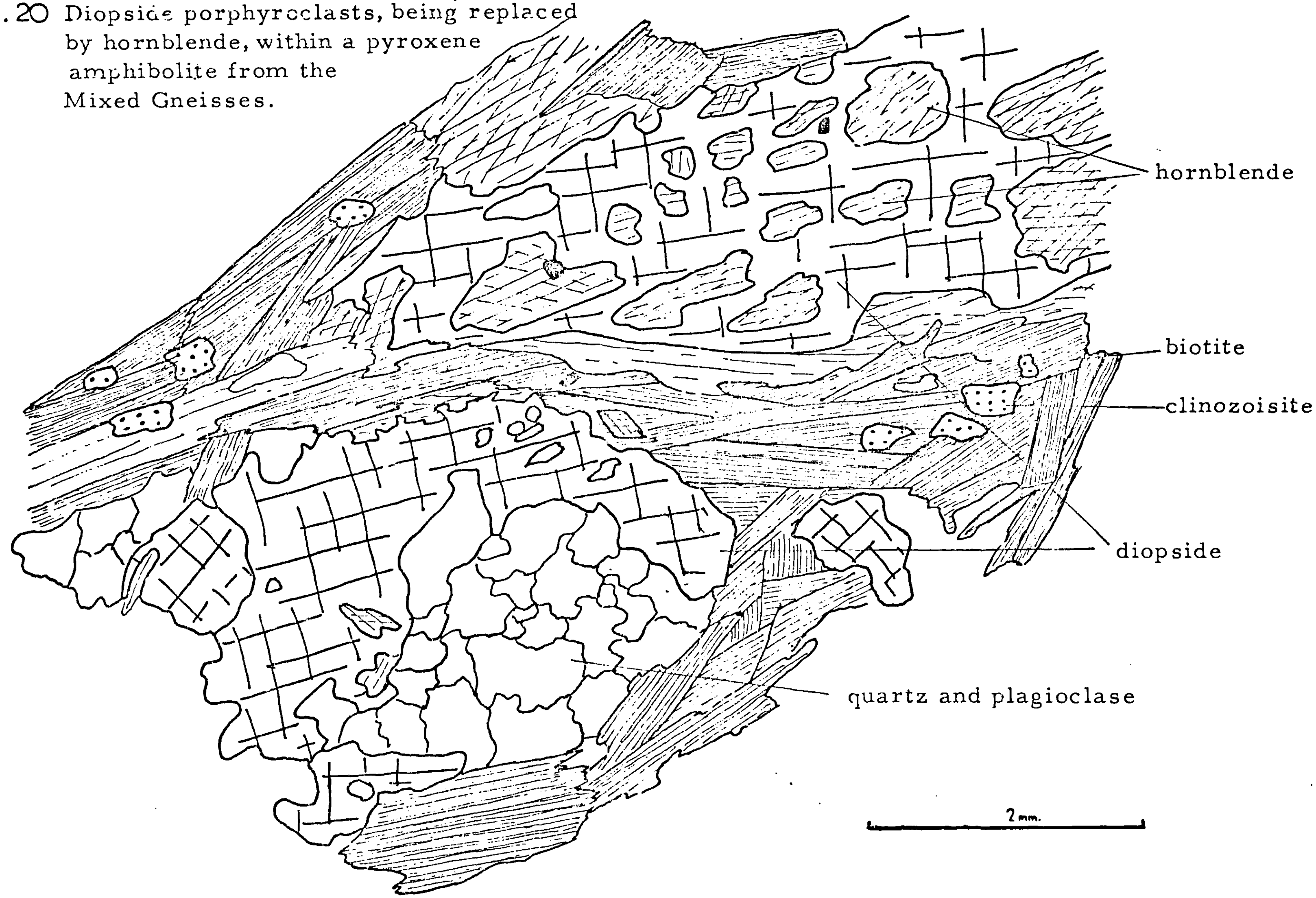


FIG. 20 Diopside porphyroclasts, being replaced by hornblende, within a pyroxene amphibolite from the Mixed Gneisses.

Similarly, a correlation is made between the Banded Gneisses and lithologically similar gneisses of the Lower Bergsdalen Nappe on the basis of the distinctive field and mineralogical characteristics, especially the colour banding and the presence of biotite ± garnet horizons.

However, the volumetrically most important gneiss within the Mixed Gneisses is the biotite-epidote-hornblende gneiss that is mineralogically and texturally similar to both the epidote and hornblende gneisses of the Eggjane Nappe (Section 2.8) although with a more flaggy parting, and the biotite-hornblende gneisses of the Lower Bergsdalen Nappe (Section 2.10)

Without chemical data, positive correlation of these gneisses is not possible. However, several field and mineralogical characteristics suggest that it could represent a more highly flattened variety of the Eggjane gneisses:

1. the gneiss immediately underlies the gneisses of the Eggjane Nappe, thereby providing a spatial reason for derivation from the Eggjane gneisses.
2. occasional more massive horizons within the biotite-epidote-hornblende gneiss belong unequivocally to the Eggjane gneiss, in field appearance, mineralogy and texture.

3. at one location in a fresh road cutting (north of Skreii), the biotite-epidote-hornblende gneiss is adjacent to, and at the contact, interleaved with Banded Gneisses that include biotite-hornblende gneiss. When viewed together, it is obvious that the two lithologies have a separate origin, and that one is not the flattened equivalent of the other.

4. Mineralogically, the flaggy biotite-epidote-hornblende gneiss is more akin to the Eggjane gneiss, with its high epidote content.

2.7 The Eggjane Nappe

The Eggjane Nappe contains several lithologies that are encountered in other tectonic units, viz: quartzofeldspathic gneisses, gneissose quartz diorites, gneissose granites and amphibolites, and so these will not be described here.

However, the significant lithology within the Nappe is the Eggjane gneiss, which accounts for about 90% of the excellent outcrop. (plate 5)

2.8 The Eggjane Gneisses

The hornblende and epidote gneisses that together form the Eggjane Gneisses, are the gneisses that Kvale (1946) recognised as quartz diorites of the basement, lying immediately beneath the Lower Bergsdalen Nappe. (fig 21).

The outcrop is continuous from the southwest to the northeast of the mapped area (a distance of about 5km) and forms the prominent scarp slope to the ridge defined by Grånipa, Gløvrefjell, Eggjane and Storafjell (fig 22)
The gneiss occurs as a thrust bound unit, with an areal extent of about 9km^2.

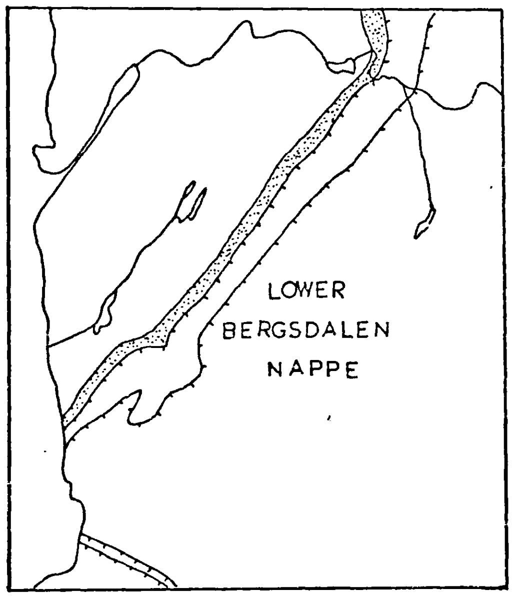
A poorly exposed outlier of the Eggjane gneiss also occurs in Sedalen (fig 22). Fresh roadside exposures are available immediately to the north of Skreii (GR 032066711l).

Structurally deeper levels of the Eggjane gneiss are exposed in the southwest of the outcrop, on the northern side of Bjørnsfjell, where it can be seen that there is an interbanding with quartzofeldspathic basement gneisses. Subsequent deformation has destroyed any evidence that this banding may be a primary intrusive or a secondary tectonic feature.

The Eggjane gneiss has the essential mineralogy; quartz, feldspar, biotite, epidote$\pm$hornblende, with accessory chlorite, sphene, apatite and iron oxides. The presence or absence of hornblende has been used in the field as a mappable

FIG 21

The Bergsdalen area, as mapped by Kvale (1946)



quartz diorite gneiss

Cambro-Ordovician schist horizons

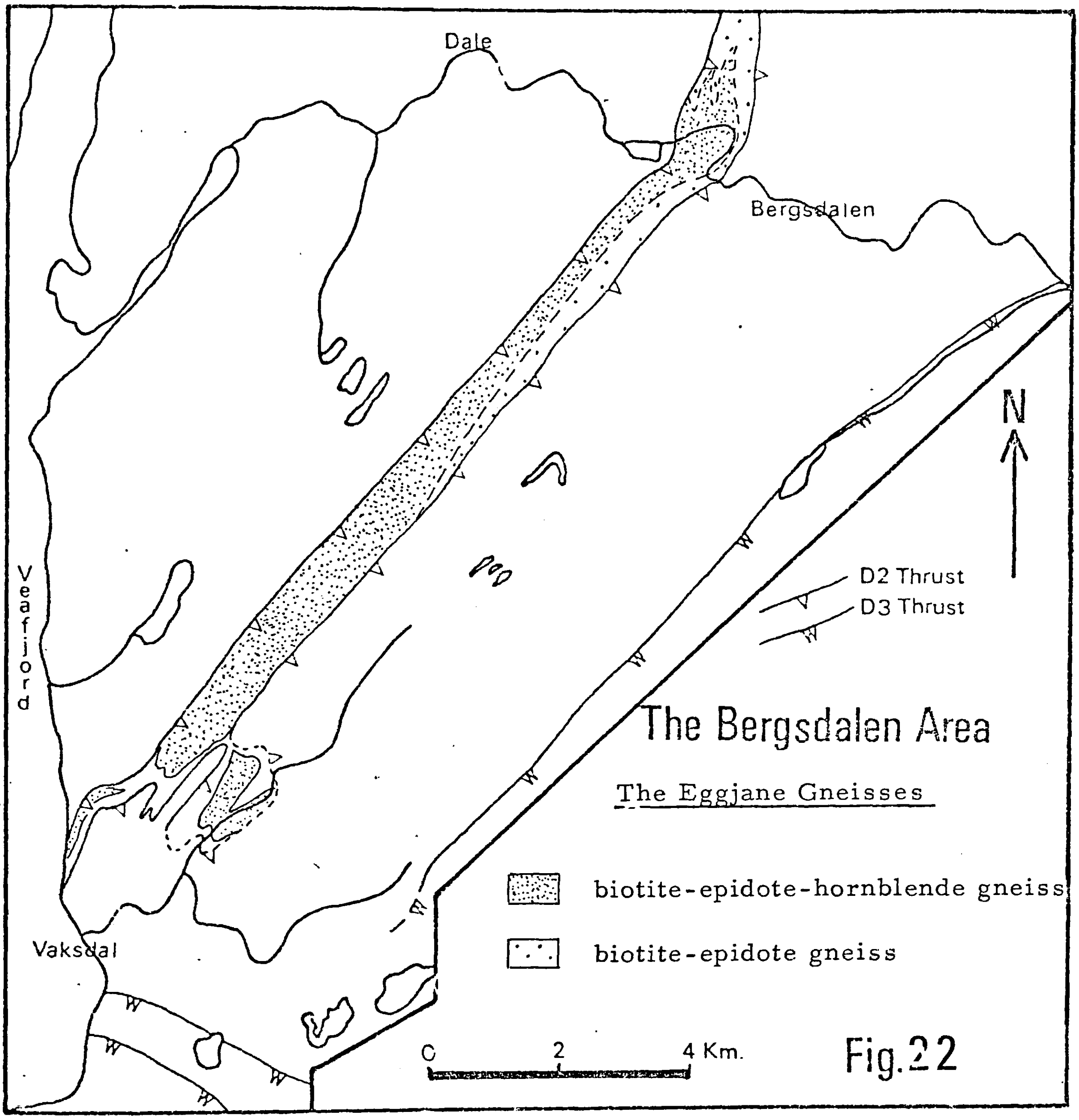

Dale
Bergsdalen
N
D2 Thrust
D3 Thrust
Veafjord
The Bergsdalen Area
The Eggjane Gneisses
biotite-epidote-hornblende gneiss
biotite-epidote gneiss
Vaksdal
0 2 4 Km.

Fig. 22

feature, with the hornblende typically occurring at the deeper structural levels of the gneiss. Despite the variable occurrence of hornblende, the gneiss has a very uniform appearance throughout the outcrop. Compositionally it is homogeneous, with both a strong foliation and mineral lineation, that is defined by orientated biotites, epidotes and hornblendes. The foliation is accentuated by occasional thin (< 10cm) amphibolite bands, by innumerable concordant pegmatite bodies of variable thickness (< 1m) and by thin concordant quartz veins.

Mineralogy of the Eggjane Gneiss

The Eggjane gneiss has an important variable - the presence or absence of hornblende, although mesoscopically a gneiss with hornblende is indistinguishable from one without.

The following modal analysis for the Eggjane gneisses are based on 1000 points counts per sample:

Sample no:	SA3.2	A6.10	A10.2	A10.5	A10.8	A1.10	SA3.3
quartz	16%	21%	20%	16%	21%	14%	20%
plagioclase	52%	53%	49%	45%	45%	47%	45%
biotite	17%	16%	10%	19%	18%	20%	18%
epidote	15%	9%	10%	10%	14%	1%	6%
hornblende	-	-	11%	7%	-	18%	11%
chlorite	trace	trace	-	trace	-	-	-
sphene	trace	trace	trace	1%	trace	-	-
iron oxides	-	trace	-	-	-	-	-

Quartz is homogeneously distributed throughout the matrix, although it is generally finer grained ($<$ 0.5mm) than the plagioclase. The polygonal or slightly elongate grains are strained, with undulatory extinction; sub and new grains are developed. The plagioclase, in both twinned and untwinned form, has two modes of occurrence; porphyroblastic or as part of the felsic matrix. The porphyroblasts, which were predominantly tabular, reached dimensions of 4mm, but subsequent straining has resulted in their breakdown into plagioclase aggregates, of individual grain size $<$ 0.8mm. The matrix plagioclases, with a grain size less than 0.7mm tend to be granoblastic, or locally tabular, parallel to the foliation. As with quartz, strain features are common.

The plagioclases are compositionally similar within both the biotite-epidote, and biotite-epidote-hornblende varieties of the Eggjane Gneiss. Within both, they border the oligoclase/andesine boundary (An_{26} - An_{34}), as determined from 11 samples using the Michel Levy test.

Saussuritisation of the plagioclases also occurs in both gneiss varieties, although where epidote is a minor phase (i.e. mainly hornblende), saussuritisation is less common.

Biotite occurs as both individual grains or in small aggregates. (plate 8)

There is little size variation, with it rarely exceeding 1mm in length, except in very occasional coarse bands; more typically the biotite is less than 0.5mm. The biotites, with a pleochroic scheme from pale brown to khaki brown, define the gneissic foliation; they are evenly distributed throughout the rock, although rare biotite rich bands are overprinted by the main foliation, indicating earlier compositional banding masked by deformation.

Rare, thin pressure solution strings of biotite occur.

The colourless epidote is restricted in occurrence either to within plagioclase, or in clusters with biotite and hornblende. It is common to see a small aggregate of biotite partially overgrown by either individual epidotes, or small aggregates of grains (plate 8). Epidotes range in shape from anhedral to euhedral, commonly with inclusions of biotite and quartz. Grain size rarely exceeds 0.3mm, or 1.0mm if in aggregate form. Exceptionally, brown allanite cored, euhedral epidotes are seen up to 1mm in size.

The epidotes are identified by their upper second order interference colours, and negative biaxial optical figure.

The epidotes have the same form of occurrence in both the hornblende rich and hornblende poor gneiss varieties. No banding, due to preferential epidote growth has ever been recorded; they are distributed evenly throughout the body of the gneiss, as are the hornblendes. These anhedral to euhedral hornblende grains occur individually and in small aggregates. The anhedral individual grains have irregular margins that overgrow the matrix, giving the hornblende a skeletal appearance, with inclusions of quartz, feldspar, epidote and sphene. Grains rarely exceed 1mm in length, although rare porphyroblasts have been observed up to 4mm.

The hornblendes have common optical features, with a pleochroic scheme from pale green (X) to green (Y) to dark green (Z), and extinction angles ($Z \wedge C$) up to 28°.

Pale green chlorite with anomalous blue interference colours is seen to replace biotite and hornblende along cleavage planes.

Origin of the Eggjane Gneisses

The Eggjane Gneisses are the same lithological unit that Kvale (1946) termed "quartz diorite gneisses". This interpretation of the gneisses as plutonic igneous rocks is supported here owing to the extensive homogeneous nature of the gneiss body, and the rarity of any compositional banding. The mineralogical variations between the presence of hornblende and epidote probably reflects metamorphic effects.

Thus, in the absence of any geochemical data to the contrary, the Eggjane gneiss is considered to represent an intrusive body of quartz diorite that has undergone extensive metamorphism and deformation.

2.9 The Lower Bergsdalen Nappe

Lithologically, the Lower Bergsdalen Nappe is relatively simple, comprising the following units:

1. Banded Gneisses and amphibolites
2. Gneissose quartz diorites
3. Gneissose granites
4. Metagabbros
5. Quartzites and quartz schists
6. Mylonite gneisses
7. Mica schists

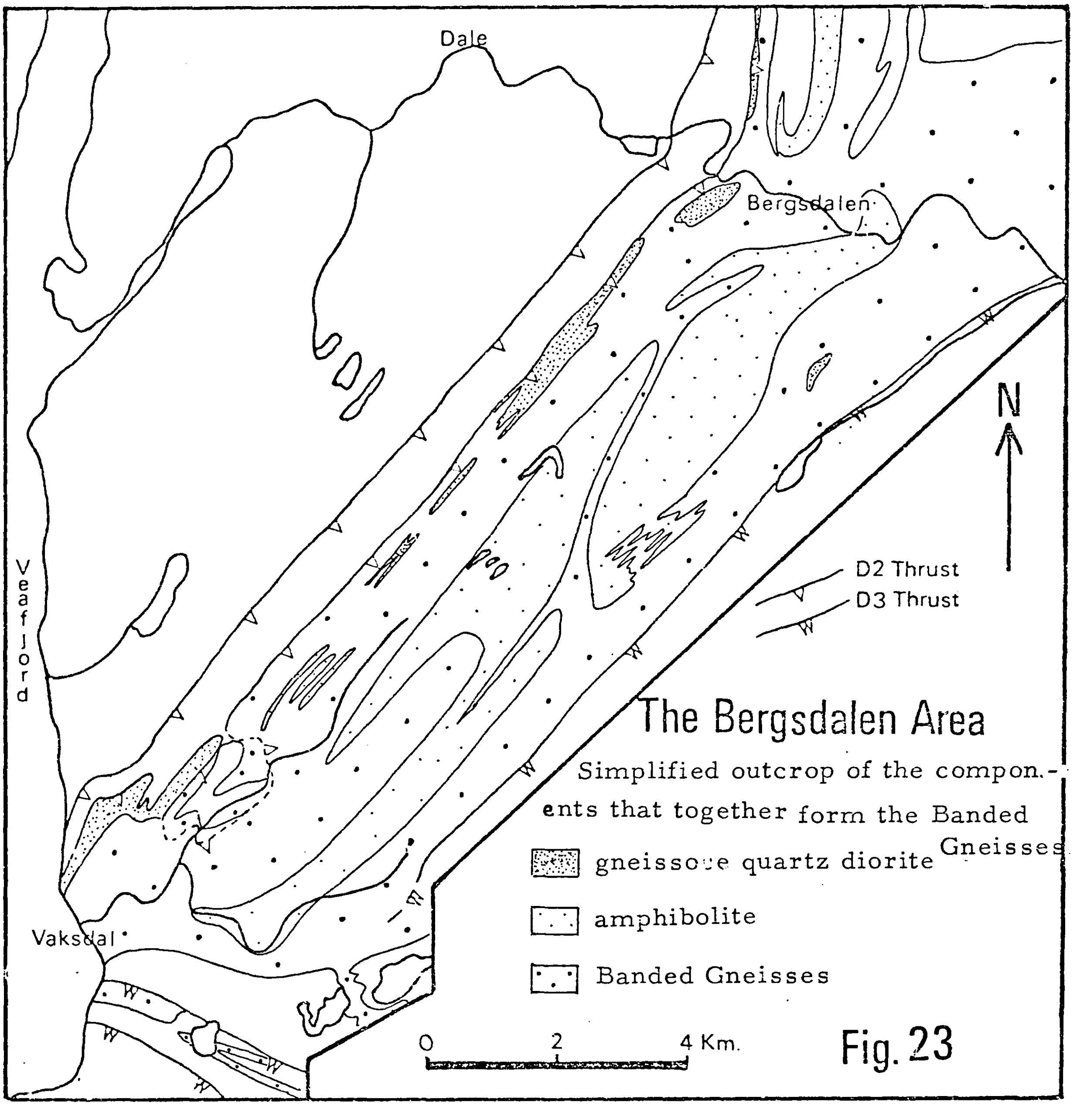
2.10 Banded Gneisses and Amphibolites

This combined lithology is equivalent to the metadacites and metabasalts described by Kvale (1946) from this area. He considered that the metadacites were highly variable in character, a feature noted in this study, and used to account for their being renamed - Banded Gneisses. The metabasalts are termed amphibolites.

The nature of the banding has provided difficulties in mapping. Amphibolite forms, nearly everywhere, part of the banding, and thus a division between Banded Gneisses and amphibolites has been made on the bulk composition of the banding. The gneiss was mapped as amphibolite where approximately more than 50% of the banding was amphibolitic. Often this division was readily recognised, as large tracts of amphibolite are quite homogeneous.

However, further complications occur, as one of the dominant assemblages within the Banded Gneiss does itself vary between a biotite-hornblende gneiss, to being amphibolitic. Thus a second arbitrary criterion has been made for division between amphibolite and biotite-hornblende gneiss, utilising the amphibole content: $>$ 40% - amphibolite; $<$ 40% biotite-hornblende gneiss.

The Banded Gneisses and amphibolites occur over a large tract of ground within the Lower Bergsdalen Nappe, covering an area of approximately 50km^2. The dominant outcrop is (fig 23) confined to a northeasterly trending strip of ground, that runs from Vaksdal to Bergsdalen. Smaller outcrops occur further to the southeast, close to the margin of the Bergen Arcs, and



The Bergsdalen Area

Simplified outcrop of the components that together form the Banded Gneisses

Fig. 23

within the Mixed Gneisses beneath the Eggjane Nappe. (Section 2.5)

On a larger scale, the Banded Gneisses, and to a lesser extent, the amphibolites are a common lithology within the Bergsdalen Nappes, with a total area of outcrop in the order of hundreds of km^2.

The Banded Gneisses and amphibolites weather relatively homogeneously, consequently forming large tracts of flat-lying ground, with a topographic variation rarely greater than 120m. The vegetation cover (grass above the tree line) tends to be sparse where the bedrock is Banded Gneiss, resulting in about 50% exposure. In contrast, the amphibolite areas are less exposed - a feature shown up on aerial photographs. Below the tree line, birch trees grow in abundance, precluding mapping. (plate 9)

Road exposure is limited in Bergsdalen to isolated exposures, often weathered - although recent road improvements have left some fresh cuttings. The best place to observe the Banded Gneisses is on the roadside at Øyane (03308 67198) and to the east of Brekka (03335 67189) in Bergsdalen. A new road cutting just to the north of Vaksdal (0320 67100) also provides excellent fresh exposures.

In the structurally deeper parts of the Lower Bergsdalen Nappe in the vicinity of Vaksdal, the flaggy Banded Gneisses (primarily biotite gneiss) are seen interbanded with more massive grey quartzofeldspathic gneisses and augen gneisses in an area of very poor outcrop, of less than 1½km^2.

The quartzofeldspathic gneisses are fine grained, and have quartz, aplite and pegmatite bands accentuating the strong foliation. Mineralogically, they are comprised of quartz, feldspar and biotite.

The augen gneiss is massive, with augen of pink weathering feldspar up to 3cm in diameter; the percentage of augen in the gneiss is very variable, from about 4-60%.

These two gneissic types are not seen anywhere else in the area mapped; from their position, it would seem likely that they tectonically underlie the Banded Gneisses. Although not recognised elsewhere in the Bergsdalen area, gneisses of very similar characteristics (especially augen gneiss) have been mapped by Hopper (1980) on the island of Osterøy, 2-3km to the northwest of Vaksdal, across Veafjorden. (fig 46)
These Osterøy gneisses are considered to lie in an allochthonous position on the Basal Gneiss complex, having

been derived from them by mylonitic processes. (Hopper op. cit).

Field Description of the Banded Gneisses (plates 10 , 11)

The banding is divided into four main elements in the field:

1. biotite $\pm$ garnet gneiss and schists
2. biotite - hornblende gneiss
3. amphibolites
4. quartz diorites

All of the lithologies are typically medium to fine grained ($<$1mm) and possess a strong tectonic fabric that is co-planar with the banding, which occurs on both a medium and small scale (several metres down to several centimetres) with the result that one exposure may appear homogeneous, whilst another may be banded on a fine scale.

The biotite ($\pm$ garnet) gneissic banding dominates in the north-west of the outcrop, whilst the biotite-hornblende gneiss is more closely allied to the amphibolites, in the central and eastern portion of the area.

The Banded Gneiss has a very flaggy, weathered appearance, and readily splits along planes that weather a rusty colour, due to the oxidation of late iron rich veining. There is little variation in the weathered appearance of the various bands, although locally the biotite-hornblende gneiss and the amphibolites exhibit carious weathering. In fresh exposures, the banding is seen to be coloured, with the biotite$\pm$garnet gneiss and schists being grey as opposed to the variable shades of green associated with those bands containing amphiboles. (plate 11)

The Banded Gneisses are intruded by quartz, pegmatite and granite veins that are parallel or sub-parallel to the composite banding/foliation due to tectonic flattening. The effect is to enhance the initial banding.

The internal contacts of the Banded Gneisses, i.e. band against band, are either conformable or slightly discordant along tectonic breaks.

Mineralogy of the Biotite Gneiss

The descriptive field term, Biotite Gneiss, encompasses a selection of mineral assemblages, each of which tends to be restricted to a sub-banding within the biotite gneiss bands. This sub-banding is rarely recognised in the hand specimen, unless represented by either the schistose bands, or alternations between coarser and finer biotites. The schistose table 2

Modal Analyses of the Biotite Gneisses (based on 1000 points per sample)

Sample no:	AM060/2a23	AL058/16.16	AL058/16.17	A15.6	A7.7	BG4	Q2	X1	BG6	Z3
Quartz	23%	37%	35%	40%	25%	30%	32%	36%	52%	26%
Feldspar (total)	27%	30%	33%	36%	45%	35%	39%	31%	10%	32%
Biotite	36%	21%	31%	20%	25%	28%	24%	20%	5%	23%
Garnet	-	1%	-	2%	3%	-	1%	5%	7%	15%
Muscovite	-	-	-	-	-	-	1%	-	22%	-
Clinozoisite	12%	10%	trace	-	-	2%	2%	-	-	-
Hornblende	1%	-	-	-	-	-	-	-	-	-
Sphene	1%	trace	trace	-	-	-	-	-	-	trace
Chlorite	-	-	-	-	-	-	-	-	-	1%
Apatite	trace	trace	trace	-	-	2%	-	-	-	trace
Iron oxides	trace	trace	trace	trace	trace	1%	trace	trace	trace	trace

bands only rarely exceed 10cm in thickness, more commonly being only 3-5cm thick.

The sub-banding assemblages invariably include quartz and feldspar (plagioclase) along with the following:

1. biotite (gneiss or schist)
2. biotite-garnet (gneiss)
3. biotite-clinozoisite-garnet (gneiss)
4. biotite-muscovite-garnet (schist)

Biotite gneiss and schists (plate 12)

The difference between the gneiss and the schist essentially lies in the amount of biotite, (table 2) with the high percentage of biotite in the schists reflected by the depletion in felsic content. In both schist and gneiss, the quartz and feldspar have a granoblastic texture, often elongate parallel to the foliation.

Gneiss: the biotite and felsics are homogeneously distributed throughout, with the biotite occurring as either individual cleavage flakes, or in small elongate aggregates. Individual grain sizes rarely exceed 1mm, and are often less than 0.5mm. Locally, the aggregates are up to 3-4mm in length, but more commonly are under 1mm. The biotites are pleochroic from straw brown (Z) to reddish brown (X, Y).

Plagioclase feldspars are usually fresh, in both twinned (albite and pericline) and untwinned habits, often with reverse zoning. The grains are commonly less than 0.4mm in size, although they may be coarser (0.7mm) where the whole rock grain size is increased. Potassic feldspar can be difficult to identify where plagioclases are untwinned, usually being identified by the presence of distinctive myrmekite and microcline twinning. Their size and habit is no different from that of the plagioclases.

Quartz is regularly interspersed between the plagioclases, although slightly finer grained ($<$0.3mm). Rare quartz strings and veins up to 1-2mm occur.

Schists: the increase in modal biotite (table 2) is made more obvious by its occurrence as large aggregates that define the schistosity, and may be up to 4-5mm in length. Individual grains have the same pleochroic scheme as those in the gneisses, and rarely exceed 1mm in length. The aggregates tend to augen the felsic content of the schist, which otherwise is similar in appearance to that of the gneisses, therefore will not be described again in full.

Accessory minerals have the same habit within both the schist and gneiss: garnets occur sporadically as euhedral grains up to

0.75mm in diameter, with central rings of tiny irresolvable inclusions. Clinozoisite, with the typical bluish yellow interference colours, positive optical figure and large 2 V, is seen as subhedral grains up to 0.3mm in diameter, randomly distributed amonst the biotite and plagioclase grains. Small hornblendes (< 0.4mm) with dark green body colour, are occasionally seen within clusters of biotite. In addition, tiny sphenes and apatite grains occur within the biotite foliation.

Biotite-garnet gneiss and biotite-clinozoisite gneiss

The biotite-garnet gneiss (plate 13) and biotite-clinozoisite gneiss are identical in appearance to the biotite gneisses, except for the addition of garnet or clinozoisite as a major phase. (plate 73) (table 2)

In the biotite-garnet gneiss, euhedral to subhedral pink garnets, up to 0.5mm in diameter are evenly distributed throughout the gneiss. Commonly, they contain inclusions of small quartz grains that are confined to the more central parts of the garnet, often arranged in circular fashion.

Clinozoisites, with the same optical characteristics as described in the foregoing section, also are evenly distributed throughout the gneiss, although small aggregates do occur. The subhedral grains ($\leqslant$ 0.5mm in diameter) are almost invariably either totally or partially enclosed by biotite.

Biotite-muscovite-garnet schists

The schists are fine grained, with the schistosity defined primarily by muscovite, although thin ($\leqslant$ 2mm) biotite bands are also present. The muscovite occurs as either individual grains, or as small aggregates, evenly distributed throughout the schist. Grain size never exceeds 1.5mm, more commonly lying in the range from 0.3-0.7mm. The appearance of the muscovite contrasts with the coarse aggregates that define the schistosity of the phyllonites. (Section 4.6b)

Garnet is red in hand specimens, and occurs as small ($\leqslant$ 0.4mm) euhedral and subhedral grains with irregular quartz inclusions. It is more commonly developed in the biotite enriched bands, although may also be seen within the muscovite schistosity.

The quartz and plagioclase matrix is granoblastic, and fine grained with plagioclases $<$ 0.7mm and quartz $<$ 0.5mm.

Mineralogy of the Biotite-hornblende gneisses (plate 14)

The biotite-hornblende gneiss is a fine to medium grained, well foliated gneiss, containing the essential minerals; biotite, hornblende, quartz and plagioclase feldspar. As such, they hold an intermediate position between the biotite gneisses and the amphibolites, with a gradational boundary between the three lithologies. This gradation is reflected in the range of the modal values for hornblende, from 5-23%. Despite this wide range for hornblendes, the biotite, quartz and plagioclase have only a limited range. Both garnet and epidote (clinozoisite) can be seen as important additions to the usual mineralogy, although their presence is by no means ubiquitous. One sample also contained diopside, which is fully described in section 5.4a.

Modal analyses were obtained for the following "typical" biotite-hornblende gneisses, showing the hornblende range: (1000 points counted per sample)

Sample no:	A16.5	A15.3	A15.10	A16.7	AM060/2a19
quartz	19%	25%	24%	24%	23%
plagioclase	36%	39%	40%	41%	32%
biotite	21%	20%	25%	17%	20%
hornblende	23%	10%	5%	14%	15%
garnet	-	2%	4%	3%	-
clinozoisite	1%	2%	trace	-	3%
sphene	-	trace	trace	trace	1%
iron oxides	trace	trace	trace	-	trace
apatite	trace	trace	trace	trace	trace
diopside	-	-	-	-	6%

Texturally, the biotite-hornblende gneiss is very homogeneous, being a fine to medium grained well foliated gneiss, with no mineral segregations. Modification of the texture is confined to localised planes of subsequent shearing.

The quartz and feldspar have a granoblastic texture, that is locally elongate parallel to the foliation. The plagioclase, both twinned and untwinned, occurs in a coarser form than the quartz, being up to 1mm, whilst the quartz rarely exceeds 0.4mm. The plagioclase is often seen to be augened on a fine scale by the biotite and hornblende fabric that defines the foliation. (plate 14)

The biotite is pleochroic from pale brown to reddish brown, and is invariably well orientated, in the form of either individual grains or as small aggregates evenly distributed through the gneiss. Grain size rarely exceeds 1mm. (plate 98)

The evenly distributed hornblende is pleochroic from pale green to green, with extinction angles ($C \wedge Z$) up to 26°, whilst birefringence (which is only rarely masked by the body colour of the grain) ranges up to lower or middle second order. It occurs in euhedral or subhedral forms, with grain size rarely exceeding 2mm. The grains are oriented with their c axes parallel to the biotite cleavage flakes, together forming the foliation. Locally, some hornblende grains are augened by those defining the foliation.

Red garnet is only sporadically developed, but when seen is usually euhedral with variable grain size up to a maximum of 2mm. It is most commonly augened by the biotite and hornblende foliation, and has inclusions of quartz.

The clinozoisite occurs as small (<0.3mm) sub to anhedral grains scattered throughout the gneiss. Only rarely do clusters of clinozoisites occur - more commonly they are individual grains, overgrowing biotite. The grains are biaxial with a positive optical figure, and a $2V \sim 60^{o}$; interference colours are anomalous blue and yellow blue.

Amphibolites

No attempt was made in the field to distinguish between amphibolite varieties; however, microscopically they have been divided into:

1. hornblendites (plate 15)
2. plagioclase amphibolites

The distinction is made on the plagioclase and hornblende contents:

	hornblende	plagioclase
hornblendite	70-90%	1-10%
plagioclase amphibolite	40-50%	35-45%

Limited chemical analyses (appendix) indicates that the plagioclase amphibolites are intermediate in character, as opposed to the basic hornblendites, and are more akin to the calc-alkaline biotite-hornblende gneisses; the hornblendites have a close chemical affinity to tholeiitic basalts (section 3.5)

Although the hornblende content, and often the biotite content is variable, leading to the erection of an arbitrary division between amphibolite and biotite-hornblende gneiss, the further division into hornblendite and plagioclase amphibolites was not made in the field due to the similarities in appearance.

The amphibolites occur as very well banded and foliated rocks, readily splitting along planes of thickness ranging from 1-3cm, and locally appearing fissile. The banding within the amphibolites is primarily defined by thin aplitic and zoisite veins that are either parallel or sub-parallel to the foliation.

Compositional banding within a body of amphibolite can occur with some thin bands of biotite rich amphibolite prominent. However, in general the amphibolites are moderately homogeneous rocks that can occur through a range of thicknesses - from being part of the Banded Gneiss sequence with bands ranging from 10cm-2 metres, or as mappable lensoid bodies up to 200m in thickness.

They are medium to fine grained, dark green rocks, although the higher plagioclase content is reflected by a slightly lighter colouring. The essential mineralogy is hornblende and plagioclase, with minor amounts of quartz, biotite, zoisite, sphene and iron oxides.

Mineralogy of the hornblendites (plate 15)

The hornblendites have a simple mineralogy, with a high proportion of hornblende. However, this simplicity is locally confused by the presence of early zoisite-hornblende-quartz veins that have undergone extensive deformation, thereby often appearing to be an integral part of the hornblendite mineralogy. The veins have an estimated mineral content:

quartz	15%
plagioclase	5%
hornblende	35%
zoisite	43%
iron oxide	2%

Plagioclase composition within the zoisite veins, determined from only two samples using the Michel Lèvy test, is mid-labradorite (An_{62}). The zoisites, up to 1mm in length occur as columnar prismatic sections, or in pseudohexagonal basal forms; they have anomalous grey and blue interference colours and a positive optical figure.

The estimated mineral contents for the hornblendites is as follows:

hornblende	70-90%
plagioclase	1-10%
zoisite/clinozoisite	1-4%
biotite	0-3%
quartz	1-3%
sphene	trace - 1%
iron oxides	trace - 2%
apatite	traces
chlorite	trace
garnet	trace

The hornblende present has a weak pleochroism from pale green to green, with extinction angles ($C \wedge Z$) up to 28°. The body colour of the mineral does not mask the birefringence which is up to middle second order. The grains occur as extremely well orientated prismatic and basal sections, with a euhedral or subhedral form. Grain size is usually less than 1mm, although occasional coarser grains (up to 3mm) may be seen as porphyroclasts within the finer grained hornblende foliation.

Quartz and plagioclase occur as small discrete grains within the finer grained hornblende matrix. They may be either polygonal or elongate parallel to the hornblendes. Plagioclase compositions have only been determined from five grains, (Michel Lèvy test) with a range from mid-andesine to lower labradorite (An_{38} - An_{54}).

Zoisite and clinozoisite occur within the hornblendites, but only rarely in the same sample, and then they are never in contact. The zoisite is identified from the presence of narrow blades with anomalous deep blue or grey interference colours, straight extinction and a 2V of about 30°. The subhedral pseudohexagonal form typically has grey interference colours. Subhedral clinozoisites are recognised by their yellowish blue interference colours, variable extinction and a 2V ~ 60°.

The zoisite blades and the more elongate subhedral clinozoisites are invariably aligned parallel to the hornblende fabric, and have grain size 0.5mm.

Garnet, where seen, occurs as small (<0.3mm) subhedral grains within the hornblende matrix.

Mineralogy of the plagioclase amphibolites

The plagioclase amphibolites have the following mineralogy; mineral contents are estimated:

hornblende	40-50%
plagioclase	35-45%
quartz	1-10%
biotite	0-14%
clinozoisite	traces
chlorite	traces
iron oxides	traces
sphene	traces
apatite	traces

Hornblende and minor biotite define the foliation in this fine to medium grained amphibolite. The pale green - dark green hornblende is equigranular, with grain sizes less than 0.7mm, and maximum extinction angles ($C \wedge Z$) up to 28°. Rare porphyroclasts up to 1.3mm in length occur.

The plagioclase is granoblastic, and is evenly distributed throughout the rock along with the hornblende. Twinned grains have been analysed (from 5 samples) using the Michel Lèvy test, and a composition of mid andesine (An_{36} - An_{42}) has been determined. Plagioclase grain size is less than 0.5mm, while quartz grains that are interstitial to the plagioclase are rarely greater than 0.3mm in size.

2.11 Gneissose Quartz Diorites (plate 16)

The gneissose quartz diorites occur, in part, as a member of the Banded Gneiss sequence, and as such, are seen as thin layer parallel bands within the more widely distributed biotite and biotite-hornblende gneisses. However, the gneissose quartz diorite also occurs as large mappable bodies within the Banded Gneisses with an areal extent of about $5km^2$. The bodies are distributed almost invariably within the zone of phyllonite development, in the basal part of the Lower

Bergsdalen Nappe. (fig 23). In addition, a sizeable body occurs in the uppermost part of the Eggjane Nappe, and outcrops on the Vaksdal - Dale road, at Skreii (0320667111) forming a good fresh exposure.

The essential mineralogy for the quartz diorite is: quartz, plagioclase feldspar, and hornblende with common accessory minerals being biotite, epidote, sphene, apatite and iron oxides.

The gneissose quartz diorite is a medium to coarse grained homogeneous rock, with individual hornblende grains readily observed in hand specimen. There is only rare compositional banding, defined by coarseness of grain size and increased mafic content. The foliation is strong, being defined by crystallographically orientated biotites and hornblendes which also are aligned with the c axis of the hornblende defining a mineral lineation.

The homogeneous nature of the rock is reflected by its massive appearance, compared to the enveloping Banded Gneisses, breaking into slabs about 50cm thick. The foliation is locally accentuated by the presence of concordant, thin pegmatite bodies and occasional calc-silicate veins (section 6.1)

The weathering colour is a distinctive white (reflecting the high felsic content) with coarse green hornblendes; fresh specimens take on a pale grey appearance.

The gneissose quartz diorites invariably have either a concordant or tectonic contact with the enveloping Banded Gneisses. Owing to their homogeneity, the bodies are considered to be of plutonic igneous origin, and are probably equivalent to the older quartz-diorite plutons recorded elsewhere within the Bergsdalen Nappes (Kvale 1946).

These gneissose quartz-diorites contrast in appearance with the Eggjane gneisses, that are also considered to have originated as quartz diorites. (Section 2.8). The Eggjane gneisses have a higher biotite and epidote content and lower hornblende content, and are finer grained. In addition, they appear structurally more complex.

Mineralogy of the gneissose quartz diorites (plate 17)

The gneissose quartz diorites are mesoscopically homogeneous, a feature not well reflected in the range of mineral contents: (visually estimated)

quartz	12-18%
plagioclase	38-50%
k feldspar	traces
hornblende	20-25%
biotite	1-14%
chlorite	trace - 5%
epidote	0-1%
sphene	trace
iron oxides	trace

The granoblastic quartz and plagioclase matrix, with only rare indistinct k feldspars, is of variable coarseness, ranging up to 1.5mm. The fresh plagioclases are often twinned on albite or pericline laws, and have been analysed (8 specimens) using the Michel Levy test to be of low or mid andesine in composition (An_{32} - An_{36}). Rare plagioclases are breaking down to epidote.

Euhedral and subhedral hornblendes are recognised from their moderate pleochroic scheme pale green (X) to bluish green (Y) to dark green (Z), negative optical character and maximum extinction angle ($C \wedge Z$) of 26°. Grain size is moderately homogeneous, with most lying in the range from 1-2mm, with some porphyroblasts up to 8mm; the grains are evenly distributed.

Biotite, pleochroic from pale brown to dark brown occurs as either individual grains ($<$2mm) in length or in aggregates up to 7mm in length, and often have small euhedral sphenes and grains of iron oxide along their cleavages.

Pale green chlorite, with only a weak pleochroism, has anomalous brown and first order blue interference colours, and occurs as either elongate aggregates of radiating grains, or as individual cleavage flakes often replacing hornblende.

2.12 Gneissose granites

Extensive granitic bodies crop out in the north east and south west edges of the mapped area (fig 24), an indication of the restriction on their occurrence to the higher structural levels of the Lower Bergsdalen Nappe (map 3). The outcrop patterns are due to the effect of superimposed folding - in the north, F2 and F3, whilst in the south F4 must be considered as well. (sections 4.5b, 4.10 a)

The granite bodies mapped, cover an area of outcrop of about 7km^2, yet are only parts of more extensive bodies that continue away from the Bergsdalen area.

Nearly all of the contacts between the granite and gneissic rocks, into which it is intruded, are concordant. However, lit-par-lit interbanding is common, and rarely, preserved fold hinges can be seen to be disrupted by the granites. In structurally higher units of the Lower Bergsdalen Nappe (away

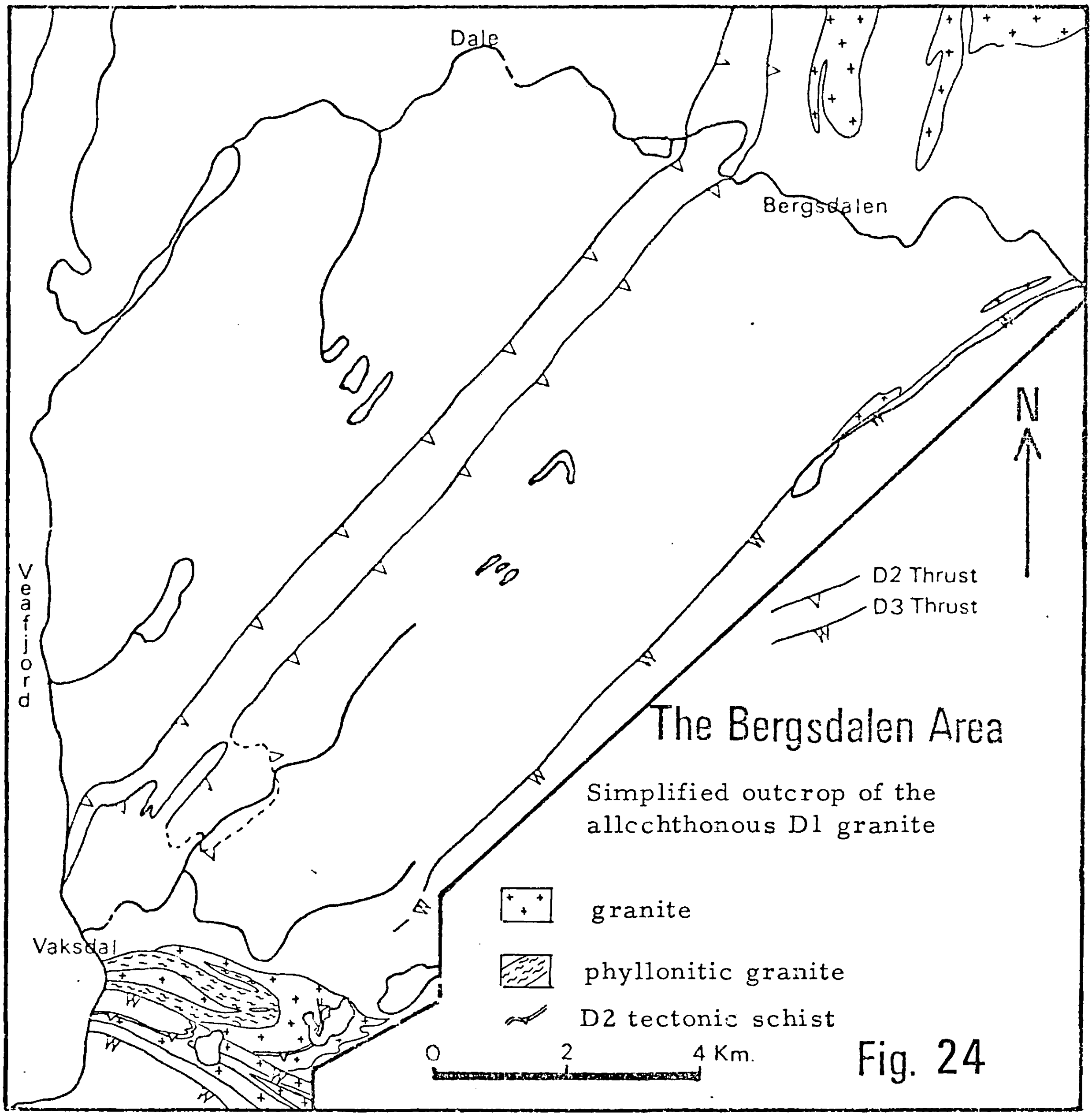

Dale
Bergsdalen
Veafjord
Vaksdal
N
D2 Thrust
D3 Thrust
The Bergsdalen Area
Simplified outcrop of the allcchthonous D1 granite
granite
phyllonitic granite
D2 tectonic schist
0
2
4 Km.

Fig. 24

from the area studied), the intrusive nature of the granite is more easily observed, with fold hinges cut out and xenoliths incorporated. (J. Evans and D. Winter pers. comm. 1978). (fig 25 and plate 49)

The medium grained (1-3mm) granite has a strong foliation defined by biotite and elongate quartz and feldspar; an ellipsoidal shape fabric formed by mineral aggregates, creates a lineation that is well developed parallel to that of the surrounding gneiss.

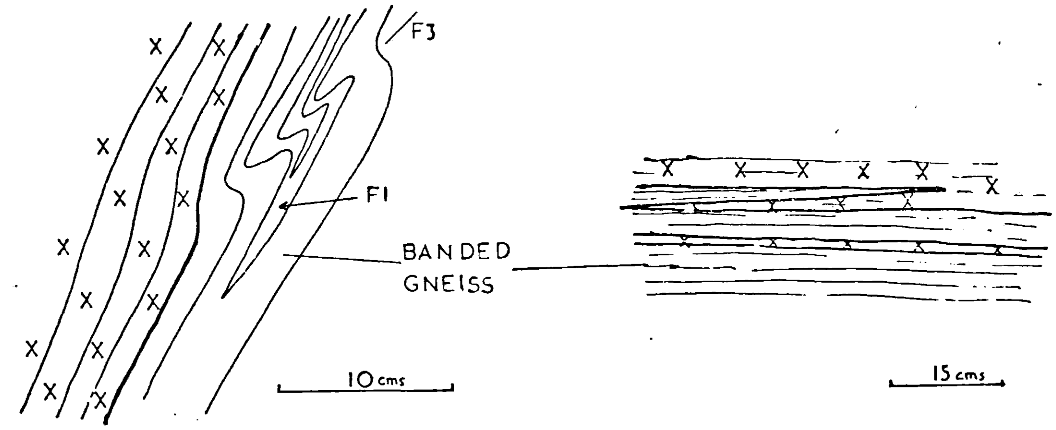
The granite bodies form pink weathering homogeneous masses, identical in appearance to the D2 granites of the basement (section 2.2a), with only rare cross cutting pegmatites.

In the southwest, the granites are commonly closely interbanded, on a scale of a few centimetres, with amphibolites. In addition, they have undergone more intense deformation, resulting in the generation of a stronger gneissic foliation, with some mica schists (phyllonites) generated along shear zones. (section 4.6b)

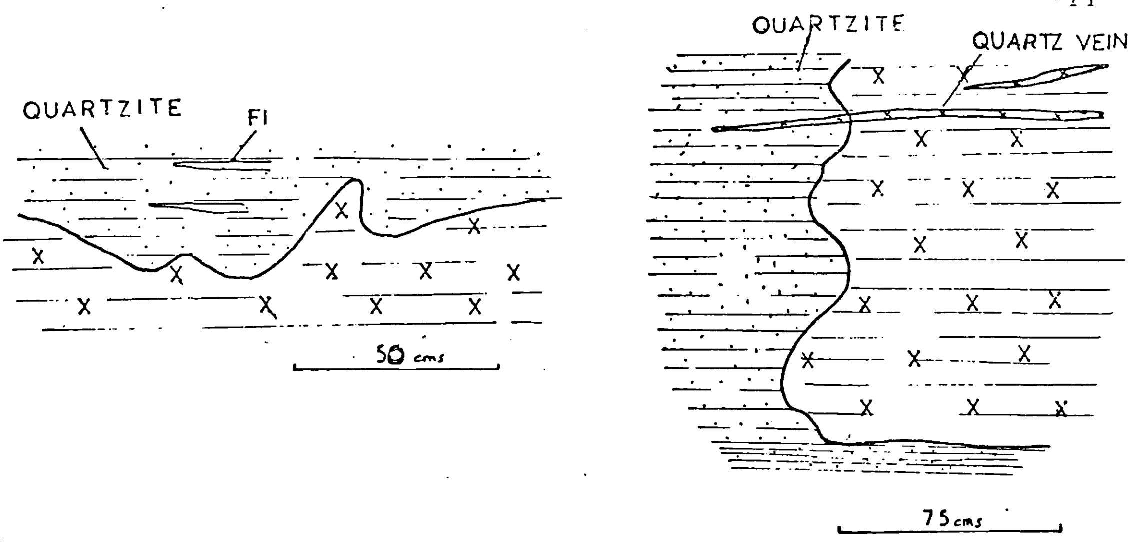
Granites of identical appearance, intruded during the same deformational event are recognised in most of the other (higher) units of the Bergsdalen Nappe. Several have been analysed

FIG. 25

(a) Banded Gneiss/D1 granite contacts in the Lower Bergsdalen Nappe



(b) Quartzite/D1 granite intrusive contacts, Lower Bergsdalen Nappe



(from J. Evans, D. Winter pers. com.)

isotopically:

Fosse granite (Eksingdalen)	:	971±71ma (Gray 1978)
Bukkefjell granite (Bergsdalen)	:	948±56ma (Pringle, in Gray 1978)
Hernes granite	:	1274±48ma (Pringle et. al. 1975)
Hamlagrø granite	:	1004±90ma (Brueckner 1972)

These compare well with the very similar granite intruded into the basal gneisses at 1050±20ma (section 2.2a).

2.13 Metagabbros

Metagabbros occur quite extensively within the Bergsdalen Nappe (Kvale 1946), but are restricted to the higher structural levels. Only three small bodies were recognised in the investigated area, along with one larger body in the extreme southwest. The three smaller bodies crop out along the eastern margin as elongate bodies orientated within the regional foliation. The largest of the three, with an outcrop width of less than 100 metres, can be traced for 2km to the northeast although the outcrop pattern is complicated by F3 folding; the other two bodies have a comparable outcrop width, but are less extensive being less than 200 metres in length.

The large body in the southwest of the area has been mapped only along its margins, consequently its full extent has not been realised.

The metagabbro bodies are only poorly exposed and appear as coarse grained (up to 2cm) dark rocks with a pervasive foliation defined by streaked out hornblende and plagioclase. These minerals also define a strong lineation that is parallel to the regional north easterly linear fabric.

The bodies occur within Banded Gneisses and amphibolites; contacts, where seen, are invariably planar and concordant to the regional foliation. In the southwest, the larger metagabbro body is in contact with quartzite; again marginal relationships are concordant, although locally, quartzite blocks occur within the metagabbro. It is unknown whether these reflect tectonic or intrusive processes.

<u>Mineralogy of the Metagabbro</u>

The metagabbros are very similar mineralogically to the plagioclase amphibolites (section 2.10) with the following mineral ranges (visual estimates);

plagioclase feldspar	38%
amphiboles	48%
chlorite	8%
quartz	1%
epidote	1.5%
sphene	1.5%
garnet	traces
biotite	traces
apatite	traces
iron oxides	traces

The only significant variation from the plagioclase amphibolites is the coarseness in grain size of the hornblendes, and their retrogression to chlorite and actinolite.

The hornblendes occur as euhedral to subhedral porphyroblasts, some up to 2cm in prismatic sections, but usually in the range from 3-5mm, and are pleochroic from pale green to green with maximum extinction ($C \wedge Z$) up to 24^{o}. Textures are entirely metamorphic, and the hornblendes are retrogressed to actinolite which has a pleochroic scheme from pale green to bluish green and maximum extinction angle up to 18^{o} ($C \wedge Z$). The prismatic sections of the actinolites define a weak fabric at the margins of the coarse hornblendes, and are also developed as small grains along cleavage planes and fracture planes of the hornblendes.

Chlorite occurs as either individual grains, or in books with only a weak dimensional orientation, replacing the hornblendes. Straight extinction, pale green body colour and anomalous blue interference colours indicate that the chlorite is of the variety penninite. (plate 99)

2.14 Undifferentiated mylonitic gneisses (plate 89)

The undifferentiated mylonitic gneisses only occur in small outcrops at the southwest margin of the Bergsdalen area, immediately adjacent to both the Bergen Arcs and interbanded gneissose granites and amphibolites of the Lower Bergsdalen Nappe.

The mylonites are very fine grained, light coloured acidic gneisses with small (<0.5cm) porphyroclasts of feldspar, and have an exceptionally strong coplanar foliation and banding. The compositional banding involves thin (<5cm) biotite-epidote rich mafic horizons; quartzitic and mica schist bands are also mixed in with the mylonites.

It is suspected that the mylonitic gneisses are derived, in the main, from the adjacent gneissose granites of the Lower Bergsdalen Nappe, and that the mafic bands reflect the original amphibolitic horizons within the granite.

2.15 Metasediments

Rocks of obvious metasedimentary origin are rare within the Bergsdalen area, although extensive quartzitic and pelitic facies occur in the higher structural units of the Nappe.

All of the recognised metasediments in the mapped area are carried in by the D3 (Nappe) thrusts (section 4.10c) apart from a small sliver of quartzite tectonically introduced within the Banded Gneisses in the east (GR 0332567173)

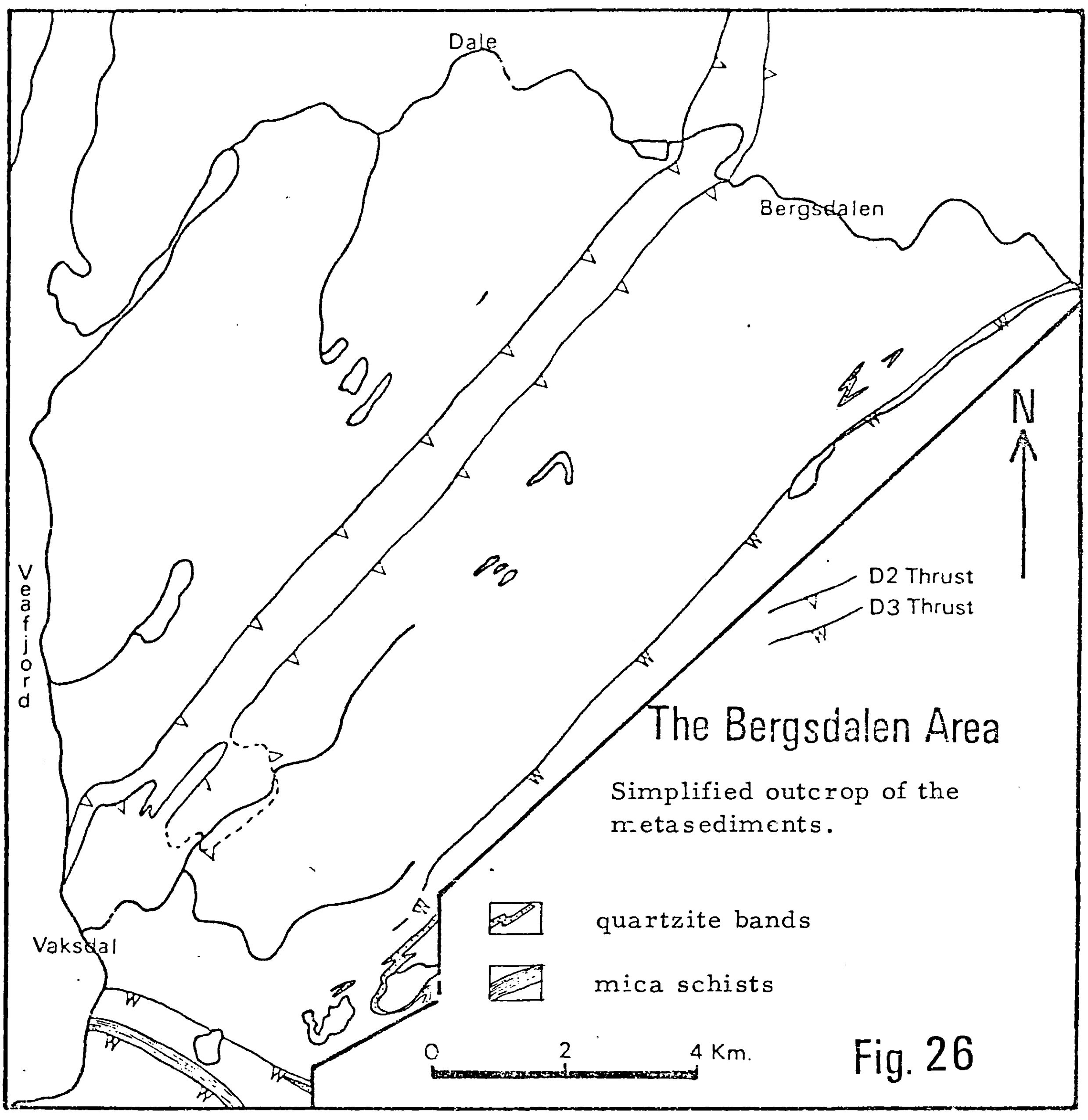
Two main metasedimentary units occur above the thrusts:

1. Quartzites and quartz schists, that are restricted to an outcrop of about 3/4km^2, lying in the hinge region of an F3 antiform and synform on Blåfjell (GR 03250 67086). (fig 26) This outcrop is an isolated extension of one of the major quartzite bodies of the Lower Bergsdalen Nappe, that extends to the east-north-east, away from the mapped area.

The quartzites and quartz schists everywhere have a tectonic contact, defined by a tectonic schist, with the underlying Banded Gneisses. The nature of the contact with the overlying metagabbros remains unknown, although Kvale (1946) has previously shown that elsewhere within the Nappe, the quartzites are intruded by the metagabbros.

Similarly, evidence from other localities within the Lower Bergsdalen Nappe (Gray 1978, Winter & Evans pers. comm. 1978) indicates that the Sveconorwegian age granites are intrusive into the quartzites.

The medium grained quartzites are well banded, with thin ($<$ 3cm) dark pelitic and semi-pelitic horizons set within a generally creamy quartzite rock, of variable feldspathic



Dale
Bergsdalen
Veafjord
Vaksdal
N
D2 Thrust
D3 Thrust
The Bergsdalen Area
Simplified outcrop of the metasediments.
quartzite bands
mica schists
0
2
4 Km.

Fig. 26

content, some bands being arkosic.

The quartz schists occur as thin (<1 metre) units within the quartzite, and have a typical mineralogy of quartz and muscovite, although locally, red porphyroblasts of garnet occur.

2. <u>Mica schists:</u> the southern margin of the mapped area includes a small zone of schists, up to 50 metres in thickness, that are sandwiched between the gneisses of the Bergsdalen complex, and the Anorthosite complex of the Bergen Arcs.

The schist zone is described by Kvale (1946) to be a continuation of the schist horizon that lies between the lower and Upper Bergsdalen thrusts (fig 2) and can be followed north westwards onto Osterøy, where they form part of the major Bergen Arc. (fig 2)

The zone of schists is steeply dipping (60^{o}-80^{o} towards the southwest) and is isoclinally folded on a large scale (section 4.11) The zone is heterogeneous and includes slivers of quartzite, granite and mylonitic gneiss.

Mineralogically, the schists are composed of quartz and muscovite, with local horizons containing garnet, up to 2cm in diameter. (plate 17) Biotite and plagioclase (albite) also occur, and Kvale (1946) has reported the presence of graphite.

Section 3

GEOCHEMISTRY OF THE BANDED GNEISSES AND AMPHIBOLITES

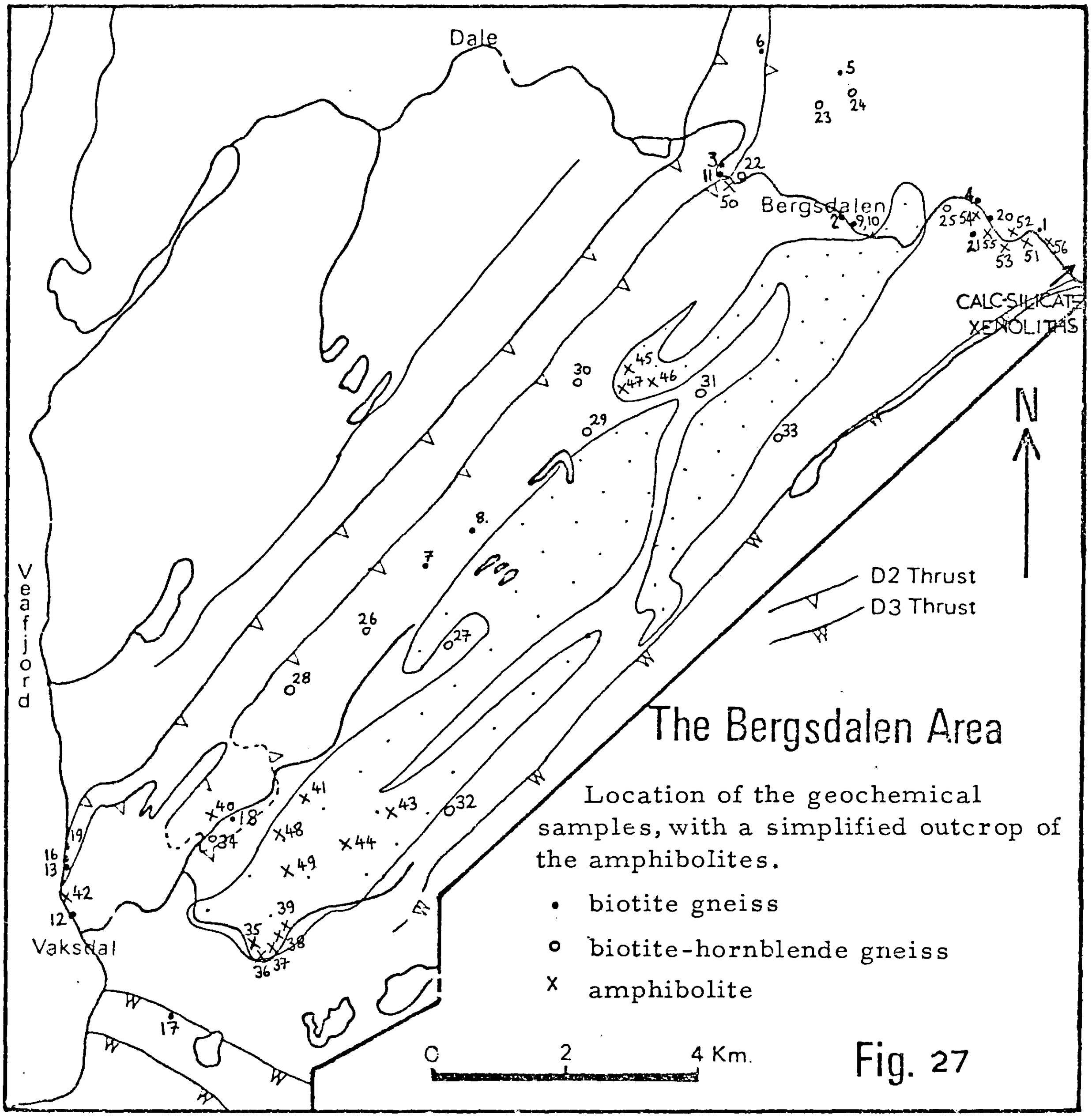
3.1 Introduction

A reconnaissance geochemical survey of 51 samples from the three major lithologic units of the Lower Bergsdalen Nappe has been carried out. The three units, which together form the Banded Gneisses, are:

1. Biotite$\pm$garnet gneiss
2. Biotite-hornblende gneiss
3. Amphibolite

The three lithologies are closely associated, being interbanded on all scales. However, thick (several hundreds of metres) units of each are present although the amphibolite is the only one distinguished on the map. (fig 27). The three units occur with approximately equal frequency over the area mapped, along with associated quartz-diorite plutons and metagabbros. (section 2.11, 2.13)
Occasional thin metasedimentary layers (quartz-olig.-musc$\pm$ gt. schists and gneisses) complete the banded nature of the gneisses.

These lithologies are not restricted to the Lower Bergsdalen Nappe; the Banded gneisses also occur in the underlying Mixed Gneisses.



The Bergsdalen Area

Location of the geochemical samples, with a simplified outcrop of the amphibolites.

- • biotite gneiss
- o biotite-hornblende gneiss
- x amphibolite

Fig. 27

All of the gneisses and amphibolites analysed have been highly deformed and metamorphosed up to middle amphibolite facies. (section 5.4)

The three lithologic units were chosen for analysis in order to investigate the assertion of Kvale (1946 p.47-52) that once they together formed a volcanic pile, of primarily dacitic composition, interstratified with basalts. The original nature of the gneisses and amphibolites cannot be determined from field data alone, due to the tectonic and metamorphic reworking, and contact relationships (section 2.10).

Thus the thick succession of acidic-intermediate gneisses could be of either igneous or sedimentary origin. The problem of identifying the original nature of such rocks is common in acidic gneiss terrain and has been studied by several authors (e.g. Krøner 1971, Shaw 1972, Dougan 1976, Løfgren 1979).

The banded nature and the mineralogy of the gneisses suggest four possible, alternative origins:

1. semi-pelitic origins: arenaceous sediments; the presence of thin obvious metasedimentary units within the pile might support this hypothesis.
2. basic and silicic volcanic flows or tuffs.
3. either sediments or silicic volcanics intruded by basic sills and dykes.

4. acid, intermediate and basic bodies intrusive into one another.

A restraint common to any of these interpretations is that the banding of the gneisses is not necessarily a primary feature; much, if not all of it, could be due to metamorphic differentiation and/or deformation.

Of the four possibilities, the third is considered unlikely, due to the areal extent and thickness of the amphibolites. However, this does not preclude the possibility that some of the amphibolites could be intrusive. Further, no intrusive relationships have been recorded. Thus, the gneisses are considered initially as either semi-pelites/arenites in association with para- or orthoamphibolites, or as silicic volcanics (after Kvale 1946) with associated basalts or para-amphibolites, or a mixed pile of both sediments and volcanics.

Sampling and Analysis

Samples of each lithology were collected from locations distributed across the Lower Bergsdalen and Eggjane Nappes. The two road sections, one travelling north from Vaksdal, and the other travelling east-south-east through Bergsdalen, provided fresh samples of primarily Biotite gneiss and amphibolite. The Biotite-hornblende gneiss and some amphibolites were collected from the interior regions. (fig 27) The samples used were fresh specimens of ½ - 1kg in weight, free of any calc-silicate, pegmatitic, of quartz veining.

3.2 Element mobility during metamorphism

For a meaningful interpretation of geochemical analyses, the assumption is made that rocks, to all intents and purposes, retain their primary chemical characteristics, i.e. that significant element migration does not occur through geological time. This vital assumption is investigated:

Major Oxides

Published information is in conflict as to the importance of element mobility during metamorphism. Low and medium grade metamorphism has been suggested to be isochemical in greywackes and meta-igneous rocks by Coleman (1965), Condie (1967), Caby et.al. (1977) and by Beeson (1978) into the amphibolite facies. Similarly, Steveson (1971) suggests that metamorphism from almandine to sillimanite grade in Moinian pelites is also isochemical.

In contrast, Shaw (1956) suggests that H_2O, CO_2, Fe_2O_3, and CaO all decrease, and FeO increases from low to high grade rocks. This basic pattern of loss of CaO and change in the oxidation state of Fe, although total iron content remains constant, is supported by Engel and Engel (1962) and Elliott (1973). Both considered changes in amphibolitic rocks at high grade (amphibolite-granulite facies), and report a decrease in K_2O, P_2O, H_2O and Fe_2O_3/FeO and an increase in CaO. Elliott (op. cit) considers slight movement of SiO_2 to be possible. Otherwise, TiO_2, total Fe, MgO, MnO, Na_2O and probably Al_2O_3 are static. The undoubted mobility of elements in shear zones, due to the introduction of water, has been well documented by Beach (1973, 1976), who shows that K_2O and CaO are most susceptible to movement; SiO_2, Fe, MgO and Na_2O are also potentially mobile.

Submarine alteration of volcanic rocks is however very important when considering element mobility. The abundant literature on the subject is summarised by Garcia (1978), who states that (p. 153) "making plots of these elements (K_2O, total Fe, SiO_2, MgO, Na_2O) is of limited value for interpreting original magma series for most sequences of altered volcanic rocks". The implication is thus, that interpretations of submarine basalt genesis based on major element analysis must be treated with caution.

The conclusion drawn from published major element data suggests that metamorphism is moderately isochemical (Ca, Na and K being most susceptible to movement) other than in the cases where excess fluid is introduced (i.e. shear zones and in submarine alteration). This, however, must be treated with caution, as the relationship between metamorphism, especially at high temperatures and pressures, and chemical mobility is still only poorly understood; it is best therefore, at the present level of understanding to treat analyses of metamorphic rocks as individual cases, rather than introducing hard and fast rules. In this way, by combining petrological observations and ranges of chemistry for a suite of rocks, it should be possible to recognise sites of excessive local mobility. However, regional mobility, affecting all samples from a suite of rocks will be extremely difficult to identify.

Trace Elements

The mobility of trace elements during metamorphism has been studied by several authors, and is summarised by Garcia (1978). Of the trace elements analysed in this study, Ti, Zr, Y, Nb tend to be immobile (Winchester and Floyd 1976) while P may show some mobility. However, Rb and Sr can show minor to major variation with increasing metamorphism. (Garcia 1978).

In the present study, minimal local major and trace element mobility is suggested because of the relative homogeneity of the gneisses and by the low ranges in chemical variation (section 3.3) recorded between samples collected several kilometres apart. (fig 27). However, the possibility of regional mobility still exists, but the effects, if any, cannot be recognised on the scale of this survey. Therefore, here, the effects of regional mobility has initially been assumed to be negligible.

3.3 Results (appendix)

(a) Major Oxides

The gneisses and amphibolites analysed were divided into 3 groups on the basis of their mineralogical character:

biotite gneisses (± garnet, clinozoisite)
biotite-hornblende gneisses (± garnet)
amphibolites (± biotite)

Chemically, these three groups broadly fall into an acid/intermediate/basic series respectively. However, this series is not strictly supported by the individual groups,

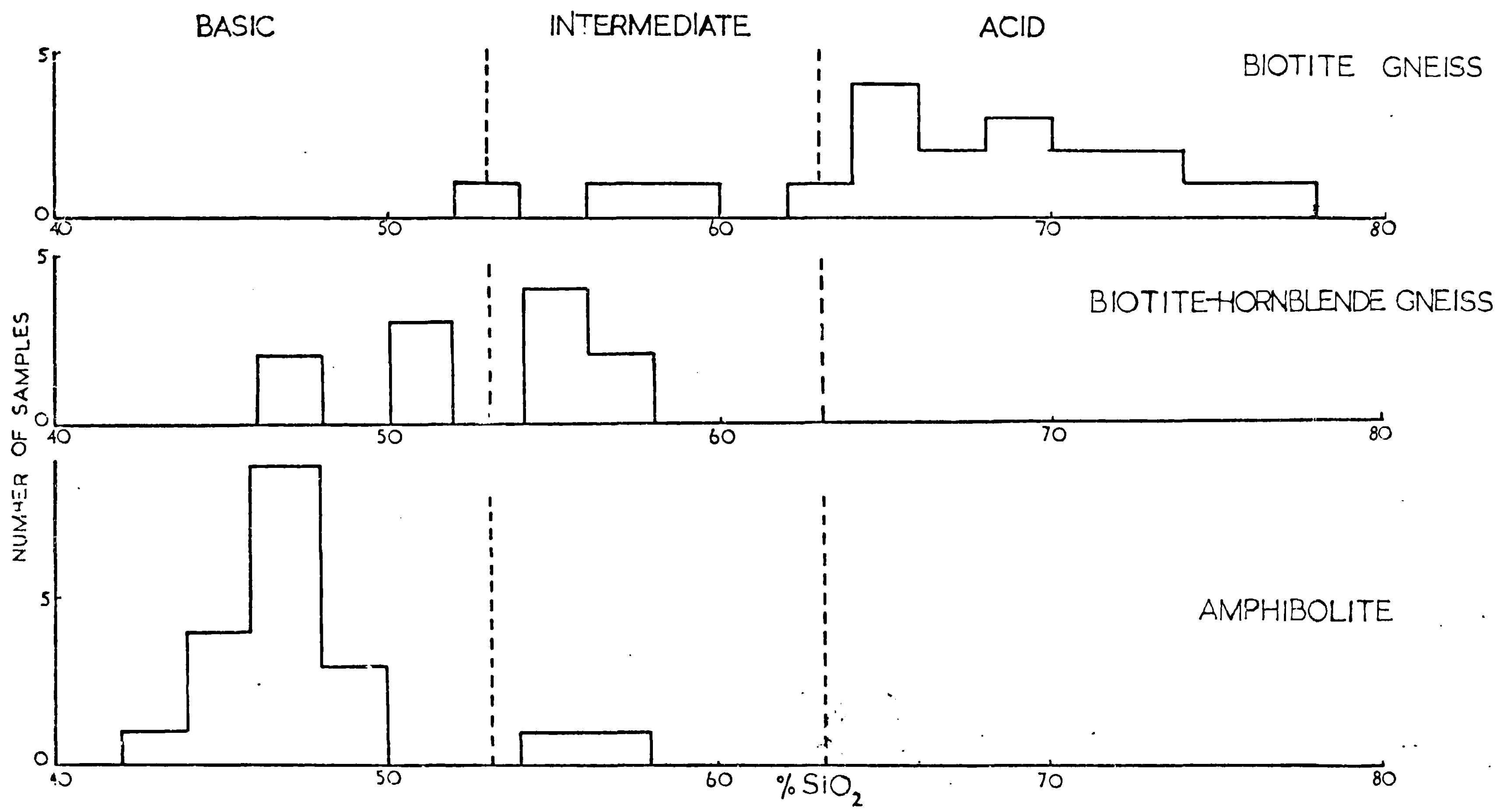


Fig.2.8 Frequency distribution of SiO_2 for the Banded Gneisses

with an overlap, of mineralogy compared with chemistry; this can be seen if the following classification boundaries are set up: (fig 28)

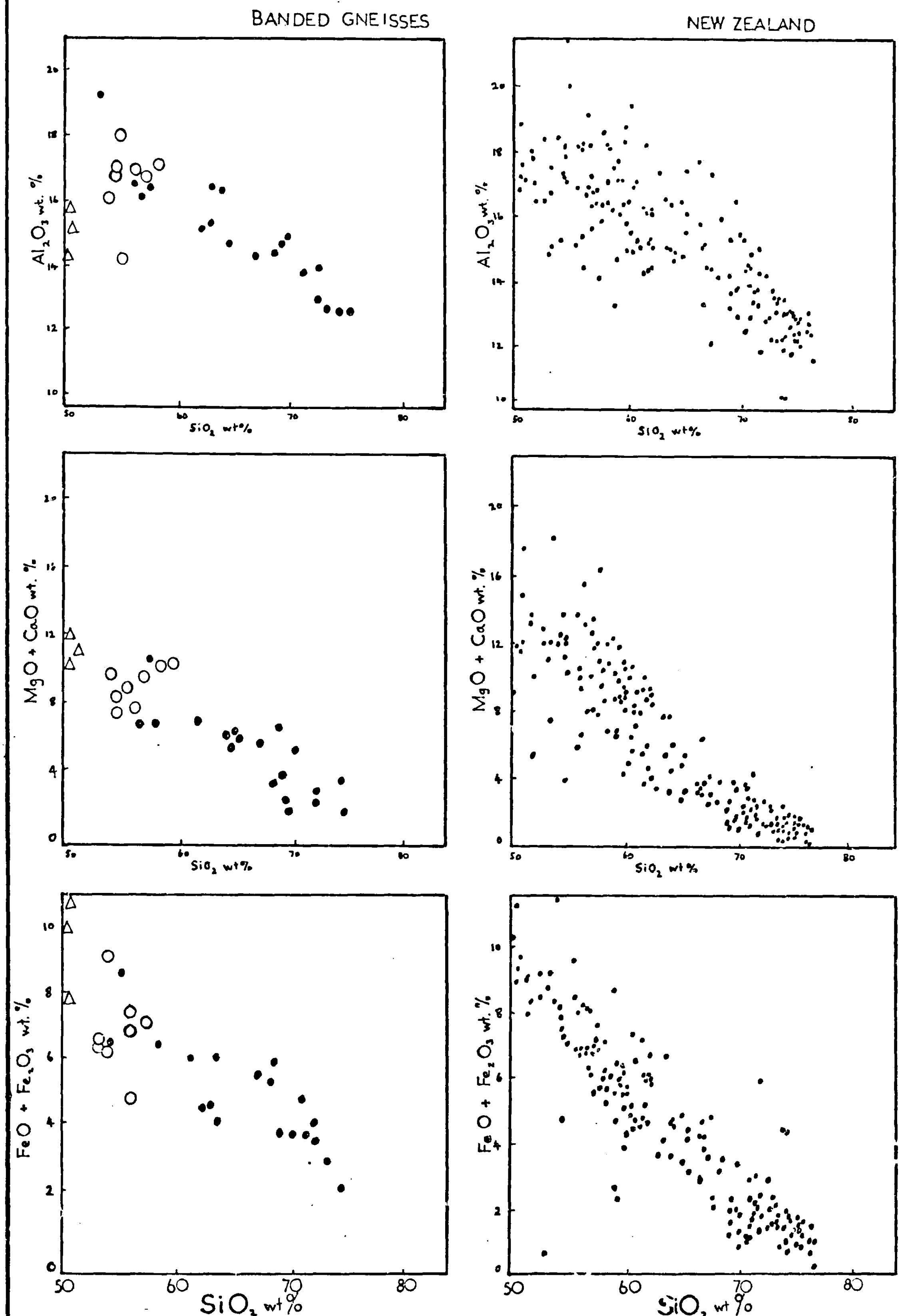
Table 3.

	SiO_2 basic 53%	intermediate 53%-63%	acid 63%-68%	68%-78%	SiO_2 Range
No. of samples					
Biotite gneiss	0	5	6	9	54%-77%
Biotite-hornblende gn.	5	7	-	-	47%-59%
Amphibolites	17	2	-	-	44%-56%

As these rocks have all undergone metamorphism and deformation, the range of SiO_2 values could be either a primary compositional feature or due to secondary mobilisation. However, despite the common presence of quartz veins throughout all of the lithologies the measured SiO_2 values probably closely reflect the primary compositional variation. This is suggested by plots of SiO_2 against other major oxides, which show a positive correlation, with only minor scatter. (fig 29). Excess SiO_2 mobility would preclude this correlation, unless other oxides have moved sympathetically.

The mineralogical variation within each gneiss group (table 3) is reflected by chemistry. Thus, the intermediate biotite gneisses, which have a close chemical affinity to the intermediate

Fig. 29 COMPARISON OF OXIDES FROM BANDED GNEISSES AND MODERN ISLAND ARC VOLCANITES, N. ZEALAND.



SYMBOLS:
● Biotite Gneiss
○ Biotite-hornblende Gneiss - intermediate
Δ Biotite-hornblende Gneiss - basic
X Amphibolite

(ADAPTED FROM LÖFGREN, 1979)

biotite-hornblende gneisses, rather than the acid biotite gneisses, contain no amphibole. This lack of amphibole can be explained by the relatively low values of CaO (av. 4.7%) and higher K_2O values (av. 2.3%) of the intermediate biotite gneisses compared with that of the intermediate biotite-hornblende gneiss (CaO av. 5.4%; K_2O av. 1.9%). The lower CaO and higher K_2O contents could control the preferential development of biotite as opposed to hornblende.

Chemistry also controls the presence of clinozoisite in two of the acidic biotite gneiss samples. These contain an average CaO value almost twice that of the non-clinozoisite bearing samples (av. 4.7% cf. 2.5%).

Thus, the mineralogical differences which result in "biotite only" intermediate gneisses and clinozoisite bearing acid gneisses are seemingly controlled by local levels of concentrations CaO and K_2O. This might reflect either an original compositional difference or a secondary mobility of these elements. No conclusion may readily be drawn, although it is noteworthy that CaO and K_2O are the most mobile of the major elements under metamorphic conditions. (Engel & Engel 1962, Elliott 1973).

Some evidence for CaO and K_2O mobility in the gneisses is provided by the presence of K feldspar rich pegmatites, and calc-silicate and calcitic veins derived from processes involving element mobility, throughout all of the lithologies. (section 6) On a small scale, the presence of clinozoisite in some acidic biotite gneisses might reflect at least small scale CaO mobility. The clinozoisites are replacing biotite, without the presence of any other intermediate CaO bearing phase, (section 5.4) thus implying that CaO has been introduced from an external source. (Tulloch 1979).

Overall, the range of values for CaO and K_2O is not great in any of the samples; with the exception of K_2O and CaO, the values for the other major elements are relatively consistent for any one group of rocks, excepting the amphibolites.
The oxidation state of the Fe in all of the gneisses is such that FeO is always significantly greater than Fe_2O_3. This contrasts with unmetamorphosed modern day dacites and rhyolites where Fe_2O_3 is the dominant form of Fe, (table 4) thereby conforming to the change in oxidation state under metamorphic conditions, as indicated by Shaw (1956).

The amphibolites demonstrate large ranges in major element values. The most excessive ranges, over a moderate silica

Table 4. Comparison of Major Oxide Data.

	1 Bergsdalen Av Amphibolite	1 Bergsdalen Av Basic Bi-hb. gneiss	2 Av Oceanic basalt	3 Av Calc alkaline	4 Av Int bi & bi-hb gneiss	5 Av Andesite
SiO_2	46.7	49.2	49.3	50.2	56.4	54.2
Al_2O_3	15.2	14.7	17.0	17.7	16.7	17.2
MgO	8.1	4.1	7.2	5.4	3.3	4.4
MnO	0.3	0.2	-	-	0.1	-
FeO	9.4	5.9	)	6.3	5.5	)
Fe_2O_3	3.6	1.9	) 9.6*	3.9	1.9	) 9.6*
TiO_2	1.2	0.8	1.5	1.0	0.7	1.3
CaO	12.3	6.5	11.7	9.8	5.5	7.9
K_2O	1.0	1.7	0.2	0.9	2.0	1.1
Na_2O	2.1	3.2	2.7	2.7	3.9	3.7
P_2O_5	0.2	0.3	-	-	0.2	-

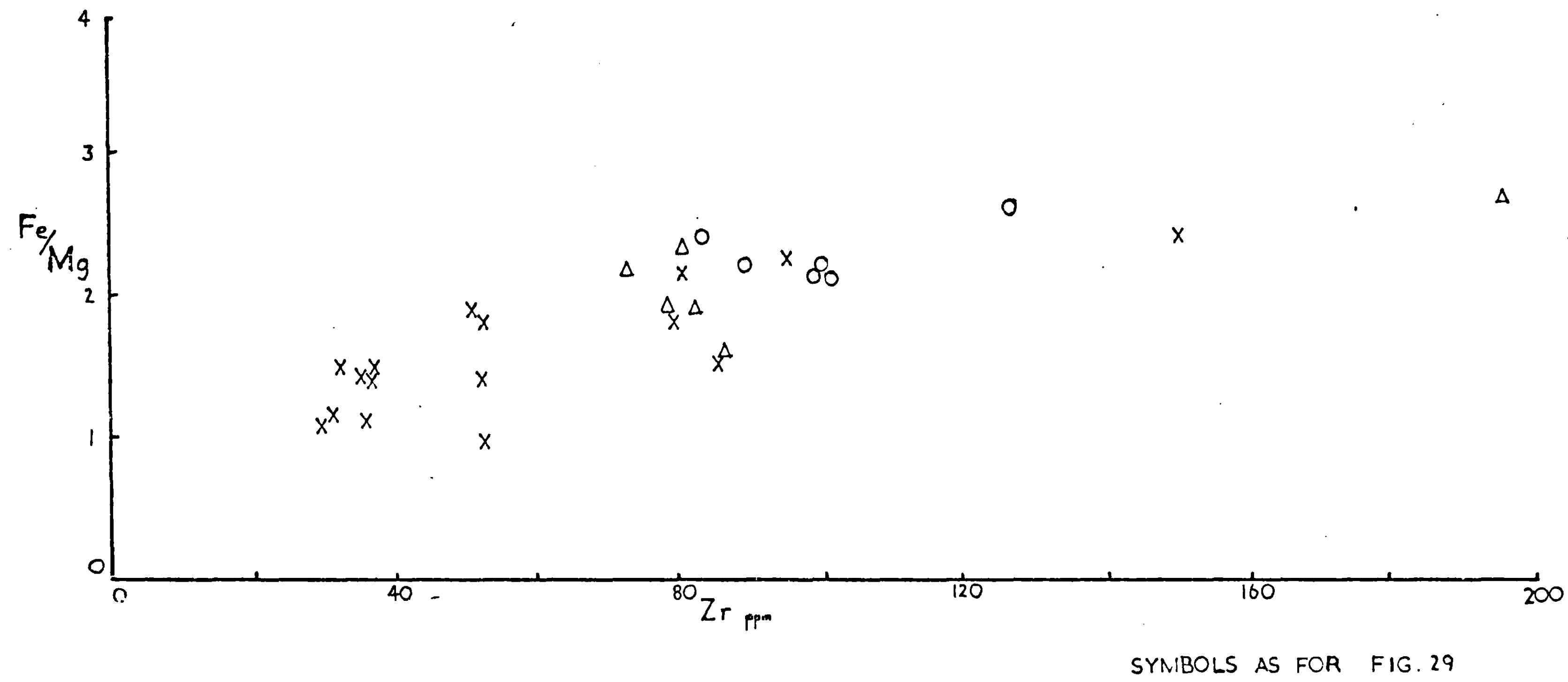
	6 Int Greywacke	7 Av Acidic Biotite gneiss	8 Modern Dacite	9 Pre Cam Telemark Rhyodacite	10 Pre Cam Telemark Rhyolite	11 Modern Rhyolite
SiO_2	53.1	68.2	64.9	71.0	73.5	74.0
Al_2O_3	16.7	14.6	16.0	14.0	12.8	13.3
MgO	4.2	1.5	1.7	1.6	0.6	0.3
MnO	0.1	0.1	-	0.1	0.1	-
FeO	)	3.7	1.0	)	)	0.5
Fe_2O_3	) 10.7*	0.8	3.2	) 3.8*	) 2.1*	1.3
TiO_2	1.2	0.5	0.6	0.2	0.3	0.3
CaO	7.2	2.8	4.7	0.9	0.1	1.5
K_2O	0.6	2.6	1.8	2.2	5.1	3.5
Na_2O	2.2	3.9	4.2	5.0	3.6	4.0
P_2O_5	0.1	0.1	-	-	-	-

	12 Modern Greywacke	13 Pre Cambrian Greywacke	14 Pre Cambrian Telemark Greywacke
SiO_2	66.9	64.7	74.1
Al_2O_3	13.6	13.4	11.3
MgO	2.1	3.2	0.8
MnO	-	-	-
FeO	)	)	)
Fe_2O_3	) 5.3*	) 6.3*	) 3.0*
TiO_2	0.8	0.6	0.4
CaO	3.7	3.1	3.6
K_2O	2.0	2.0	1.9
Na_2O	3.0	3.0	2.7
P_2O_5	-	-	-

* Total Fe.

1. This study
2. Engel, et al 1965
3. Condie, 1976 p399 tableIII
4. This study
5. Condie, 1967 p2142 table2
6. Caby et al 1977 p290 table 1
7. This study
8. Condie 1976 p404 table V
9. Moine & Ploquin 1972 p58 table 1
10. ——— " ———
11. Condie 1976 p404 table V
12. Whetten 1966
13. Pettijohn 1963
14. Moine & Ploquin 1972 p58 table 1

FIG.30 Fe/Mg v Zr fractionation trend for the intermediate and amphibolitic members of the Banded Gneisses.

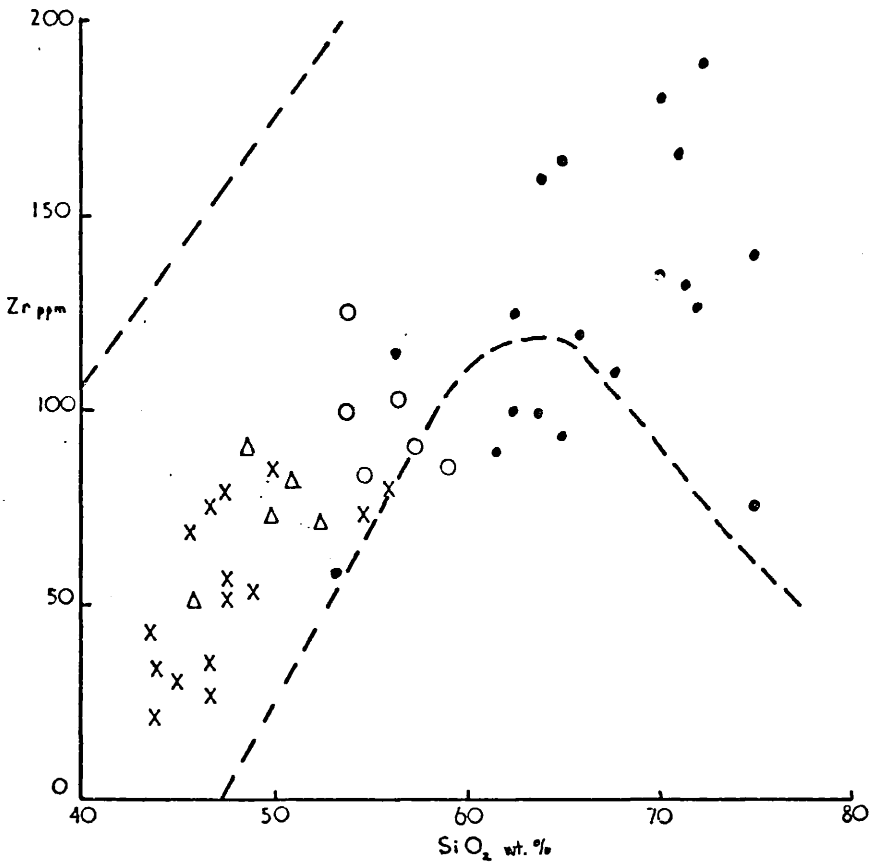


range (44-49%) are: MgO (5.07-11.16%), total Fe (8.98-15.68%), NaO (1.03-3.90%) and K_2O (0.49-1.66%). The total Fe and MgO ranges are large, and are unlikely to be due entirely to alteration processes. By plotting total Fe/MgO against Zr, it can be seen that the amphibolites (and also the biotite-hornblende gneisses) exhibit a trend towards total Fe enrichment with increasing Zr (fig.30). This is a common line of fractionation for tholeiitic rocks (Carmichael et al 1974 p.481; Saunders et al. 1980) suggesting that similar processes may have operated during the evolution of the Bergsdalen amphibolites.

(b) Trace Elements

The immobile elements Nb, Zr, Ti register only minor fluctuations in abundances for a given suite of rocks; of these the Zr variations can be attributed to fractionation trends (fig30, 31) (Carmichael et al 1974). However, large abundance ranges are recorded for both Sr and Rb which, according to the literature, are mobile. (section 3.2). It can be shown, however, that the range of values for Sr is most likely an effect of primary concentration, due to fractionation, with secondary mobilisation being of minimal

FIG. 31 Zr v SiO_2 for the Banded Gneisses and amphibolites



field of calc-alkalines, Antarctic Peninsula.
(Saunders et.al. 1980)

SYMBOLS AS FOR FIG: 29

importance. Plots of Sr v Fe/Mg, and Sr v Zr (both considered to be indices of fractionation - Saunders et al. 1980) show the same features (fig 32) , notably a trend towards Sr enrichment as fractionation of basic rocks proceeds. However, this trend is reversed - a line of Sr depletion develops, as Zr and Fe/Mg values increase, (in effect, with intermediate and acidic compositions). Similar trends are noted for the basalts of Antarctica by Saunders and Tarney (1979).

3.4 Discrimination between Sedimentary and Igneous Parentage

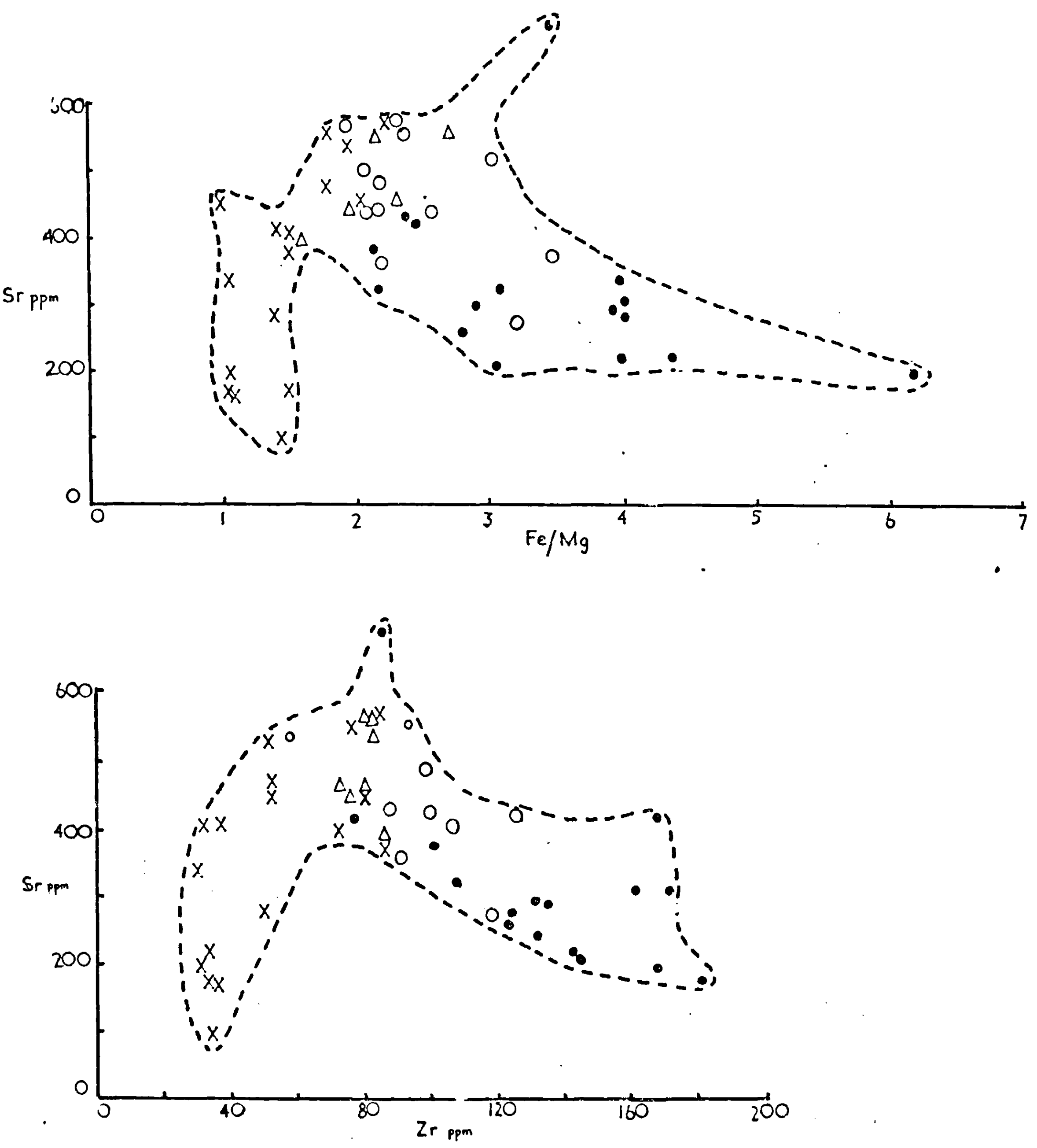
Biotite Gneisses, Biotite-hornblende Gneisses and Amphibolites

Discrimination between paragneiss, with local derivation from an igneous suite, and an orthogneiss derived from that suite is virtually impossible, once textural evidence is lost due to tectono-metamorphic activity. The problem is compounded if element mobility has operated.

Thus, any discrimination techniques can only be used to differentiate between rocks that are:

either sediments that have undergone sufficient transport and sorting for any igneous trends to be destroyed, and new chemical trends to be created.

FIG.32 Sr v. Fe/Mg, and v Zr for the Banded Gneisses and amphibolites



SYMBOLS AS FOR FIG.29

or igneous/paraigneous-sediments locally derived which would retain igneous trends.

The gneisses of the Lower Bergsdalen Nappe are tested from this view point.

Discrimination Techniques involving major elements

Shaw (1972) summarises various scatter diagrams, involving major elements, that have been used in the past for the discrimination between acidic ortho- and para-gneisses. Of the many diagrams, Shaw (op. cit) has selected the most useful including the Weisbrod (fig 33) and the Moine & de la Roche plots (fig 34). Data for the Biotite gneisses have been analysed using these plots, but neither provides a conclusive answer, owing to substantial overlap of the data in both the igneous and sedimentary fields. In the Moine & de la Roche plot, the data clusters closely in the heart of the igneous field, but straddles the boundary of the sedimentary field. Similarly, the data plots within the igneous field of the Weisbrod diagram and follows the igneous trend, but in part, overlaps into the sedimentary field.

A second technique involving major elements has also been investigated by Shaw (op. cit) - he has utilised discriminant

Fig.33 Weisbrod plot

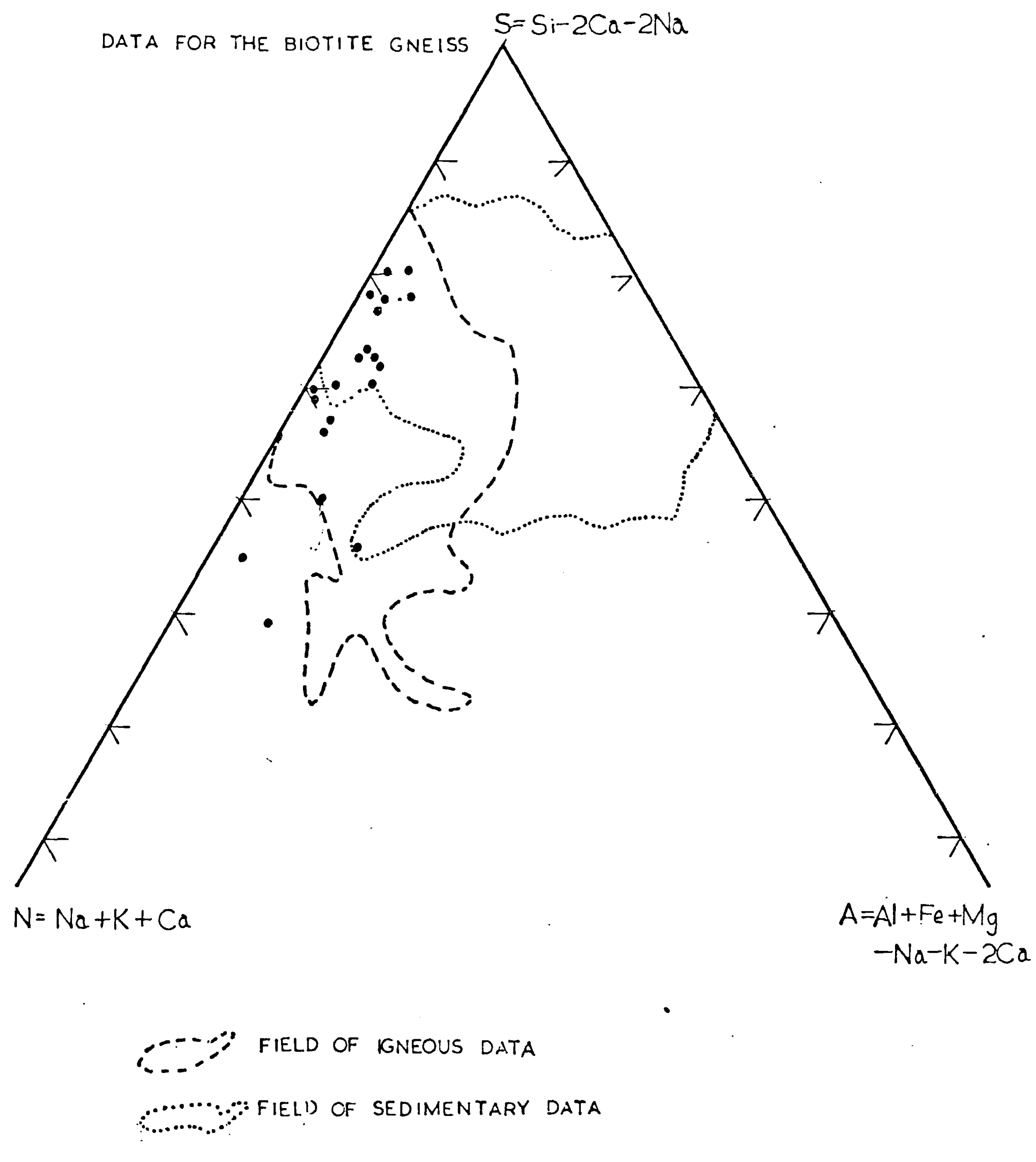
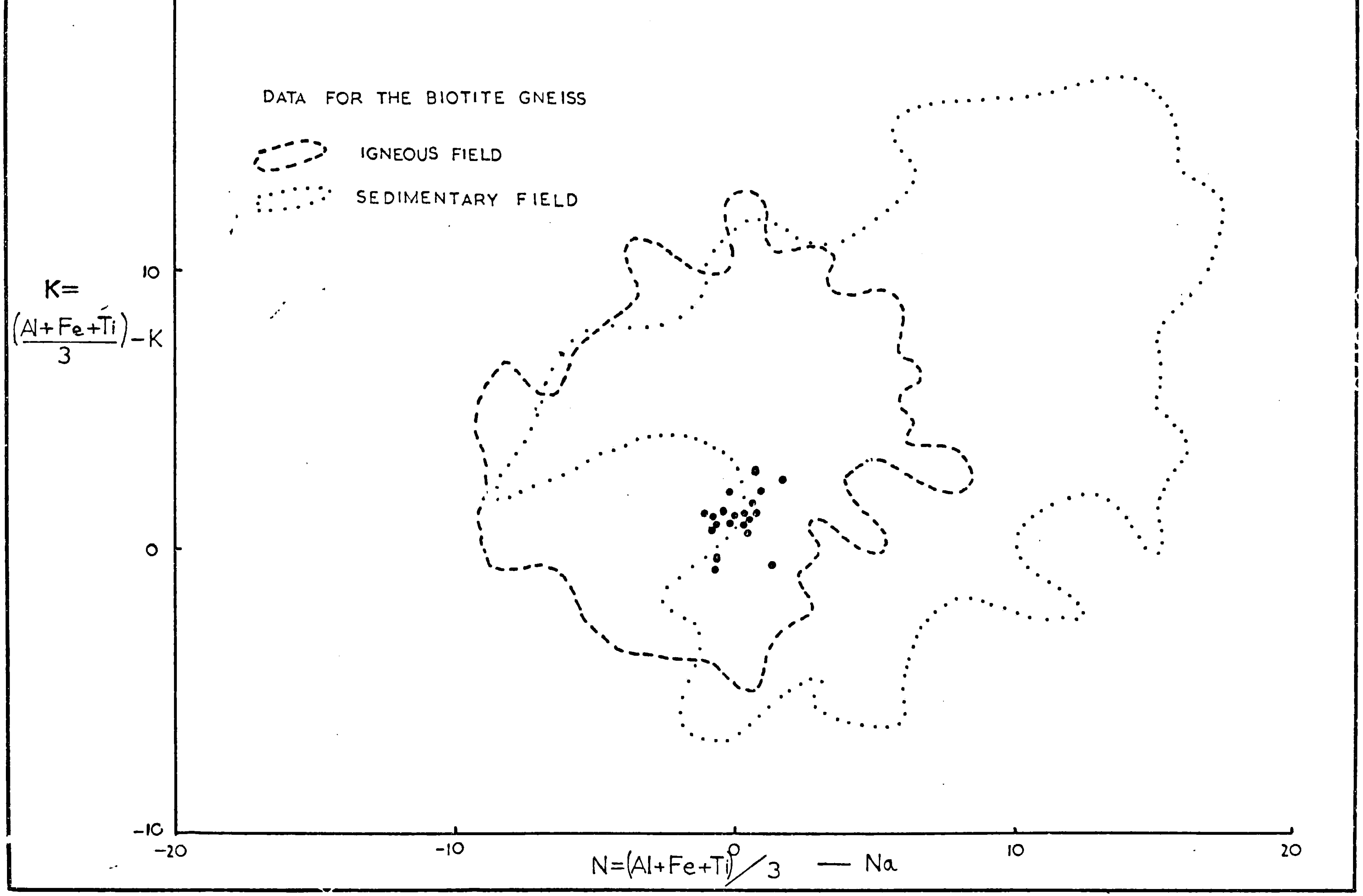


Fig. 34 Moine & de la Roche plot



function analysis. (Krumbein & Graybill 1965). This statistical method aims to distinguish between two factors; in this case, the gneisses could be either of sedimentary or igneous parentage, with equal probability for either case. Shaw (op. cit.) concluded that the following function was suitable:

$$DF = 10.44 - 0.21SiO_2 - 0.32\ Fe_2O_3(\text{total Fe}) - 0.98MgO + 0.55CaO + 1.46Na_2O + 0.54K_2O$$

Positive values for DF indicate probable igneous parentage, negative values are sedimentary. The probability of misclassification is 0.29.

This discriminatory function has been applied to the Biotite gneisses. Out of the 21 samples, only one gave a negative value (indicative of a sedimentary origin) and this sample has previously been considered of sedimentary origin from petrographic data. Thus, by discriminatory analysis, the Biotite gneisses are thought to be either orthogneisses or paragneisses retaining igneous chemical trends.

These three discrimination techniques are inadequate for dealing with rocks of intermediate or basic composition, such as the biotite-hornblende gneisses. Thus, a further test is utilised for these, which views the problem from a different angle. The question can be asked: if these gneisses were sediments, in which field would they lie, using a traditional sedimentary chemical classification system?

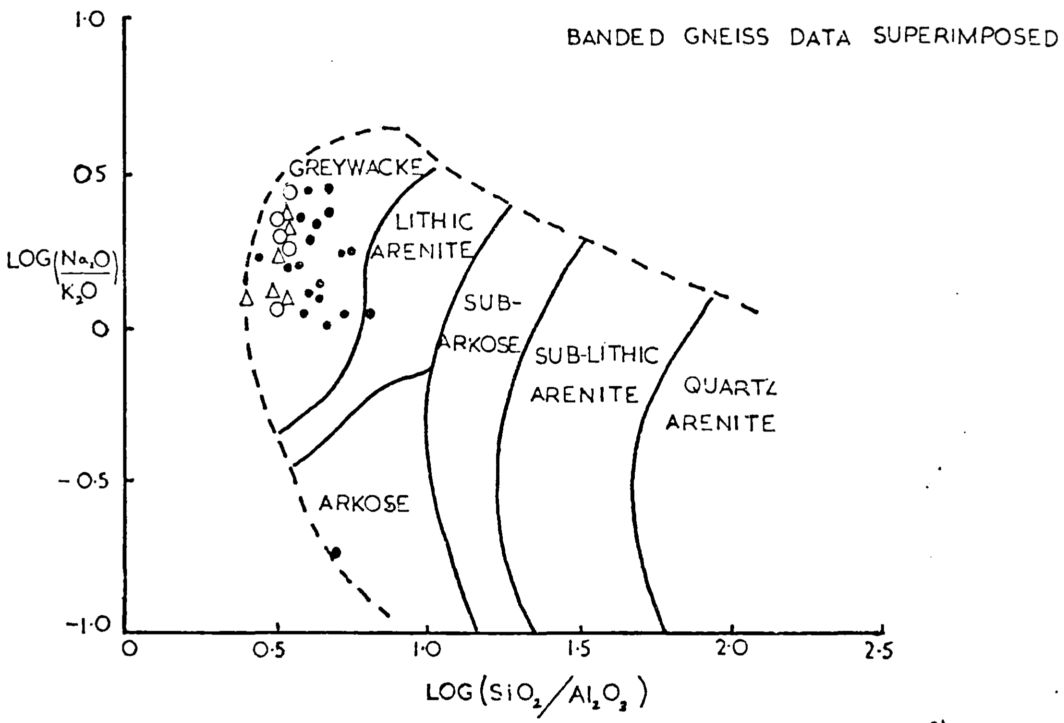
It has been shown (Blatt et al. 1972 p.317-321) that the Na/K ratio can be used to define classification fields. Greywackes are stated to differ from other sandstones by having Na/K>1. Average shales and mudstones also have Na/K<1. The data obtained for both the biotite-hornblende gneisses and the biotite gneisses displays a consistent Na/K>1 (fig 35) except for one sample, which, as previously stated, is considered to be a semi-pelite on mineralogical grounds.

In using this plot, it must be assumed that there has been no significant, preferential mobility of either element. The low range of the Na/K values suggests that mobility was either pervasive or insignificant.

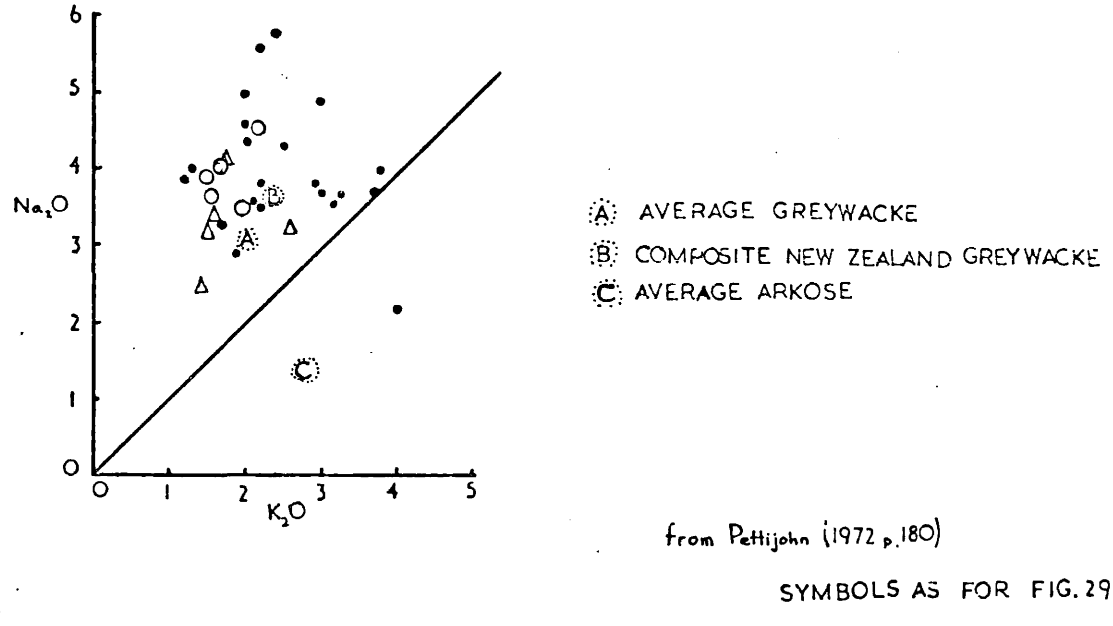
Pettijohn et al. (1972) utilise a log Na/K, against log SiO_2/Al_2O_3 plot in order to create a chemically controlled classification for sandstones (fig 35). Treated in this way, both the biotite gneiss and biotite-hornblende gneiss data plot within the field of greywackes.

From both the Na/K and log SiO_2/Al_2O_3 plots, it can be seen

Fig. 35 SEDIMENTARY CLASSIFICATION OF ARENITES



from Pettijohn (1972 p.62)



from Pettijohn (1972 p.180)

SYMBOLS AS FOR FIG. 29

that the biotite gneisses and biotite-hornblende gneisses, if sediments, would on chemical grounds, be termed greywackes. However, greywackes are the one suite of sediments that are often associated with volcanic centres, and thus could be chemically indistinguishable from the chemically similar parent igneous rocks.

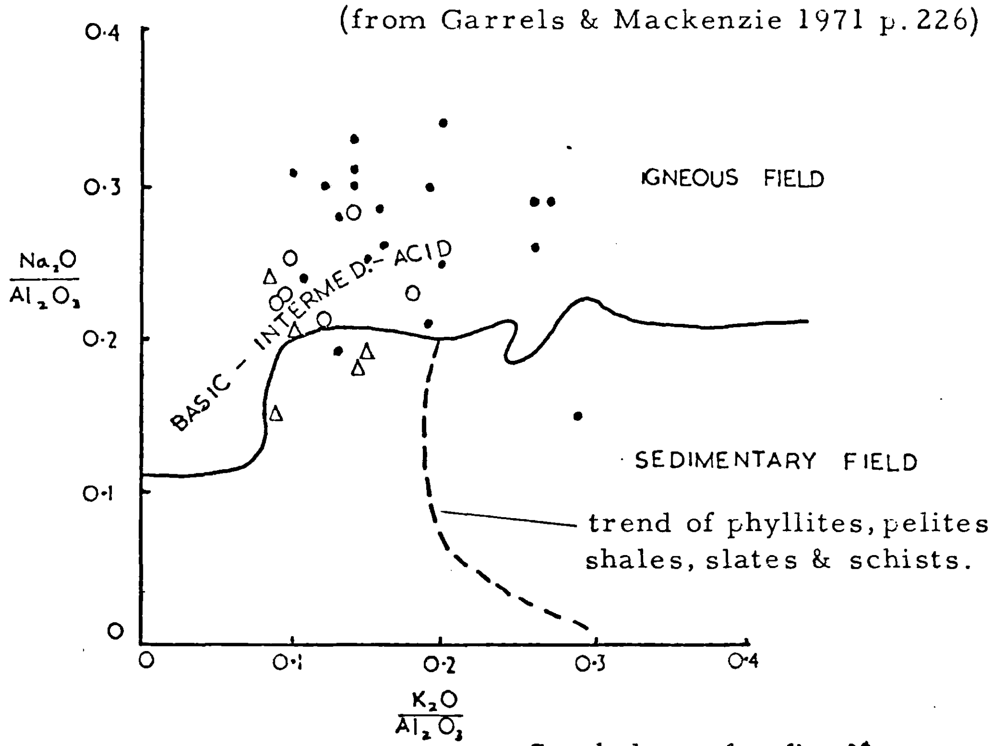
Finally, Garrels and McKenzie (1971 p.228), in studying large numbers of major element analyses for both igneous and sedimentary rocks, have concluded that, "all of the shaley rocks, regardless of age or degree of metamorphism, are distintly lower in Na_2O/Al_2O_3 compared with igneous rocks." This is reflected in figure 36, in which data for the gneisses falls predominantly within the igneous field.

Amphibolites:

Discrimination between ortho- and para-amphibolites on major element analysis alone is not considered feasible.

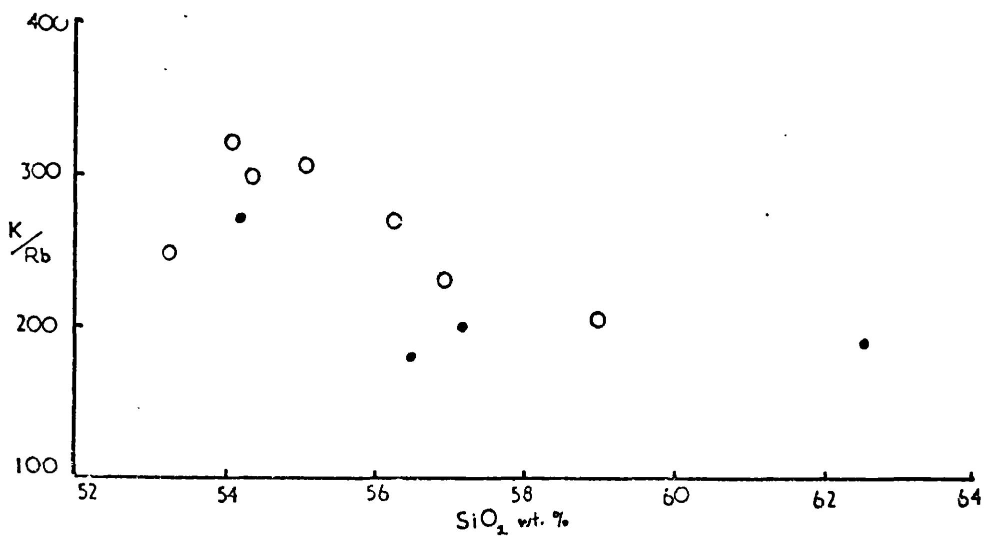
In the literature, the distinction between para- and ortho-amphibolites ia made on the basis of both field observations and chemistry. (Leake 1964, Misra 1971, Holdhus 1971, Winter 1974).. Ortho-amphibolites may retain obvious igneous textures and contact relationships, whilst para-amphibolites, being derived from calcareous sediments

FIG.36 Discrimination between igneous and sedimentary rocks.
(from Garrels & Mackenzie 1971 p. 226)



Symbols as for fig. 29

FIG. 37 K/Rb v SiO_2 for the intermediate members of the Banded Gneisses.



Symbols as for fig. 29

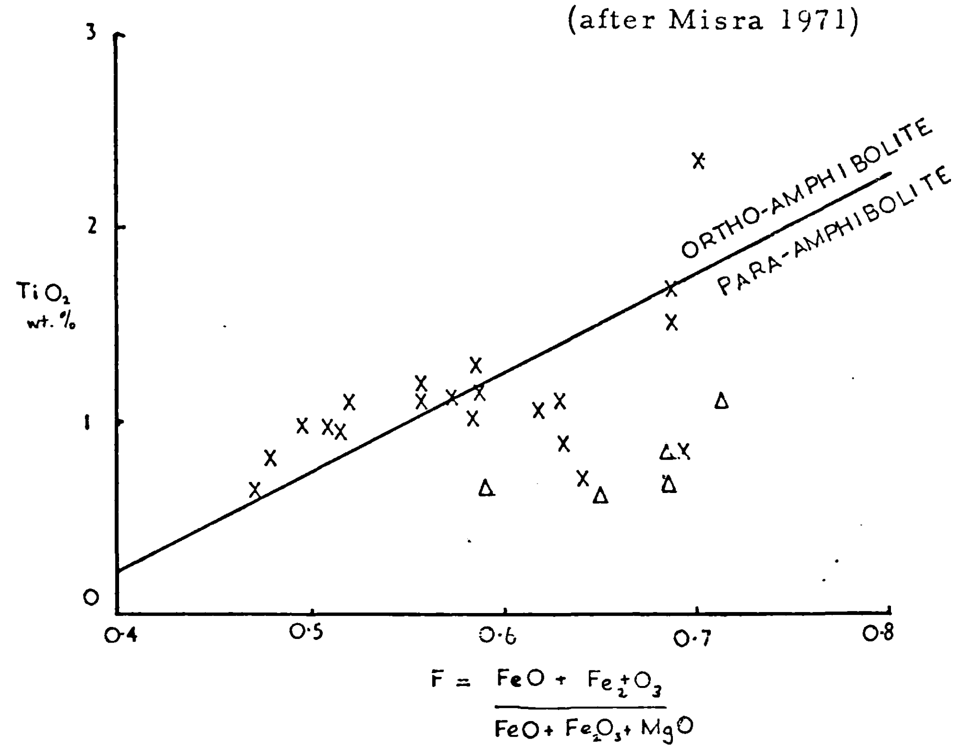
(i.e. marls), can exhibit strong banding and are commonly associated with marbles and calc-silicates.

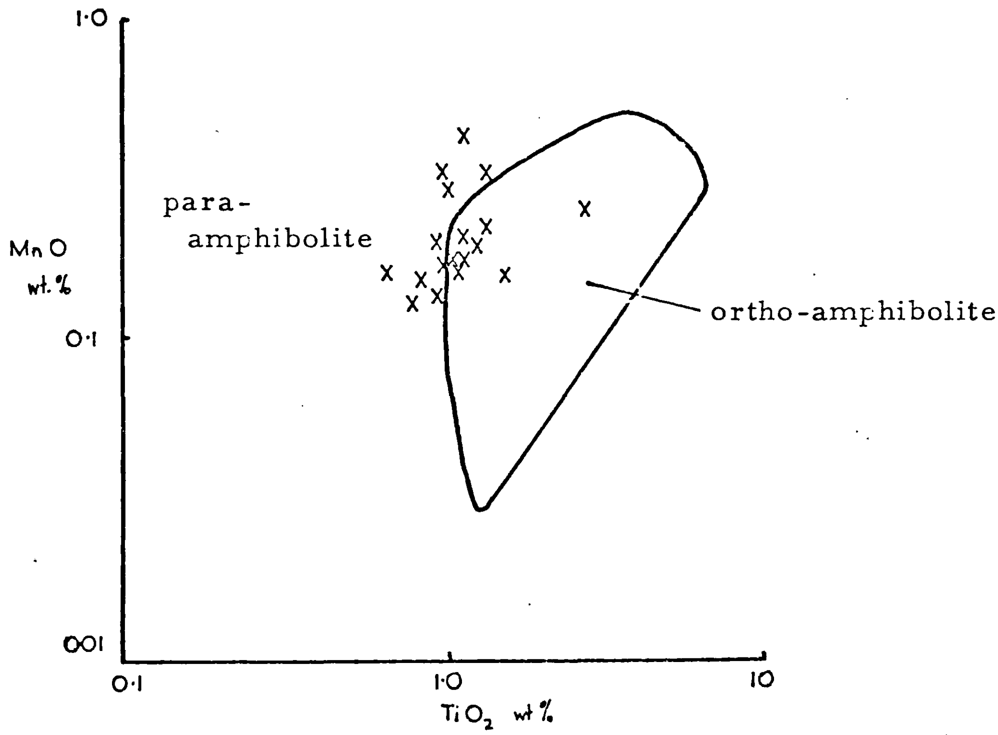
The amphibolites of this study area have been deformed and metamorphosed to a degree sufficient to mask any primary features. However, no obvious sedimentary bands are observed within them and Kvale (1946) has reported amygdaloids and epidote lenses (often a common feature in deformed basic extrusives) within other extensive amphibolite bodies of the Lower Bergsdalen Nappe. It is probable that these bodies are of similar origin to those of the mapped Bergsdalen area, as all are closely associated with the biotite, and biotite-hornblende gneisses. Kvale concluded that the Lower Bergsdalen amphibolite bodies were basalts.

Methods of chemical distinction between ortho- and para-amphibolites have been suggested by Leake (1964), Shaw and Kudo (1965), Misra (1971). Of these, Shaw and Kudo's discriminatory analysis, and many of Leake's plots, utilise trace elements which have not been analysed in this study. Analysis of the gneiss data following Misra (TiO_2 v MnO and TiO_2 v FeO + Fe_2O_3/FeO + Fe_2O_3 + MgO) is inconclusive, with the data spanning the ortho-/para-boundary in both diagrams. (fig 38)

FIG. 38 Discrimination between ortho-and para-amphibolites.

(after Misra 1971)





symbols as for fig. 29

More convincing evidence for an igneous origin for the Bergsdalen amphibolites is derived from the apparent presence of fractionation trends, which are enhanced with the addition of data from the biotite and biotite-hornblende gneisses. (fig.30). Similarly, the amphibolites display a good tholeiitic line of fractionation on an AFM diagram (fig 39) with increasing Fe at constant alkali values. On the same diagram, the biotite and biotite-hornblende gneisses display an excellent calc-alkaline line of fractionation.

Trace Elements

The discrimination between sediments and igneous rocks is difficult to make using trace elements, primarily because of the lack of published data for sediments. As with major elements, recognition of fractionation trends within trace elements distributions is considered to be a strong indicator of igneous parentage sediments having a more variable distribution of trace element concentrations. (Van de Kamp 1976).

On this basis, data for the biotite gneisses, biotite-hornblende gneisses and amphibolites appear to lie on lines of fractionation. (figs 30, 32)

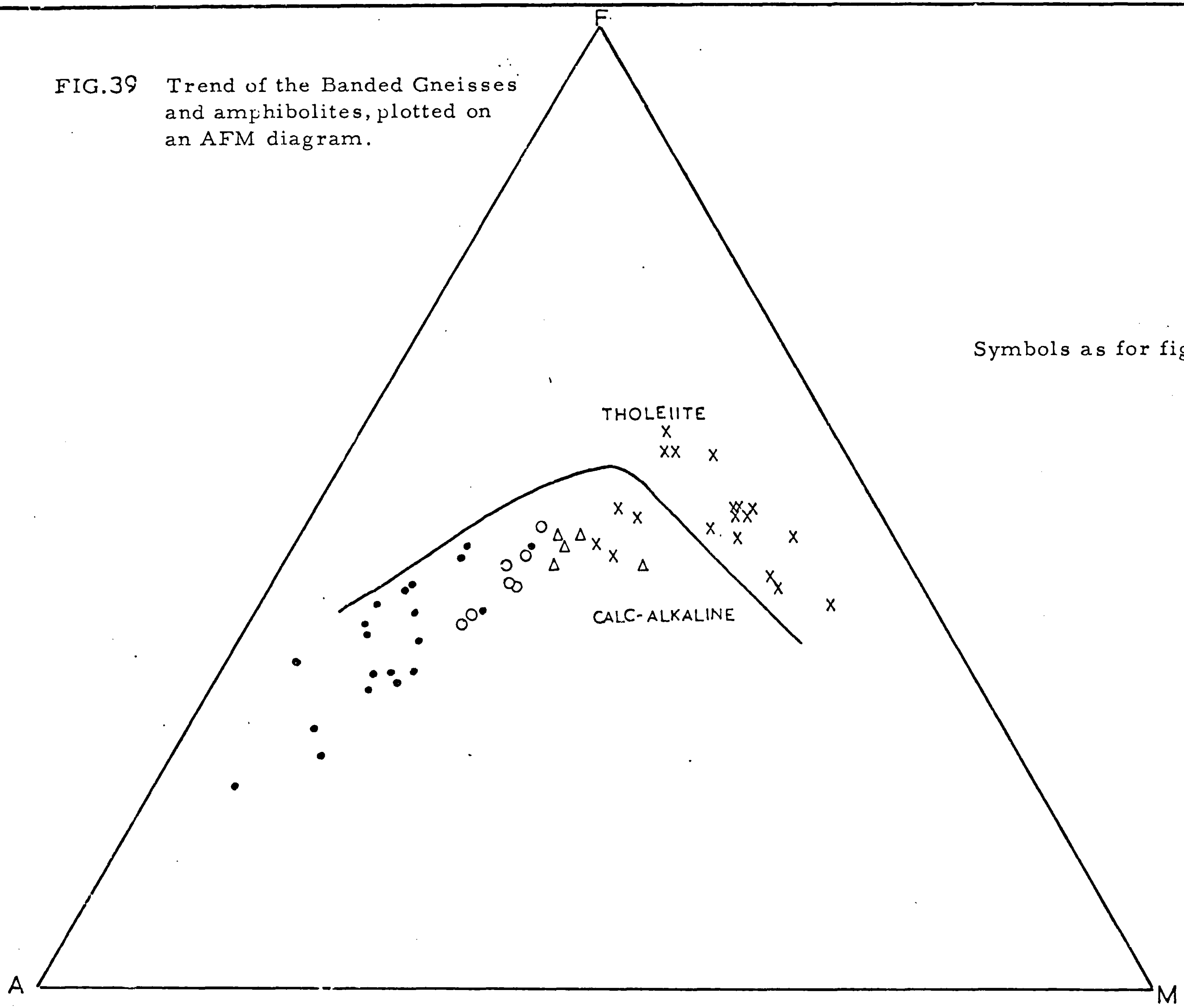


FIG.39 Trend of the Banded Gneisses and amphibolites, plotted on an AFM diagram.

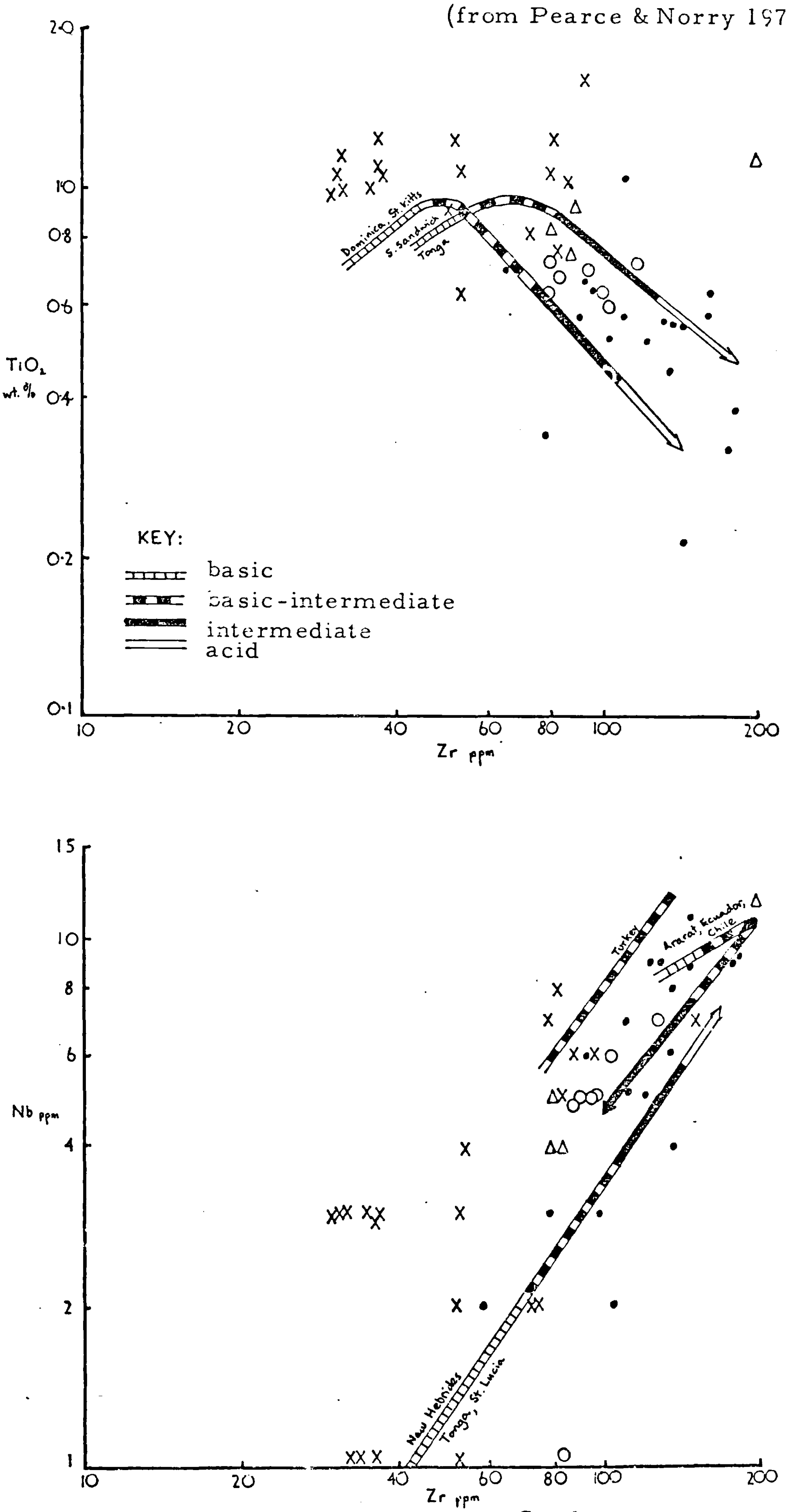
Symbols as for fig. 29

In addition, they exhibit a strong positive correlation between K and Rb , lying on the same line (K/Rb=250), as data for calc-alkaline rocks from the Antarctic peninsula (Saunders et al. 1980). Similarly, the trend lines for Ti O v Zr and NbvZr, reported by Pearce and Norry (1979) for volcanic arc series, are also closely followed. (fig 40)

More specifically, the biotite-hornblende gneiss data has been compared with the line of fractionation of K/Rb (v Si O_2) for andesites (Taylor et al. 1969). The curved line of decrease of K/Rb as fractionation persists is reflected by the biotite-hornblende gneisses. (fig 37)

Although the amount of published data is small, the Rb/Sr ratio may also be an indicator of sedimentary or igneous parentage. (Faure & Hurley 1963). There is an indication that the Rb/Sr ratio for sediments is higher than that for igneous rocks. Comparisons show that the average Rb/Sr for the biotite-hornblende gneisses is very close to that of the published averages for andesitic rocks, and is lower than the value for compositionally intermediate sediments:

FIG.40 Banded Gneiss and amphibolite data with superimposed volcanic arc variation trends.
(from Pearce & Norry 1979)



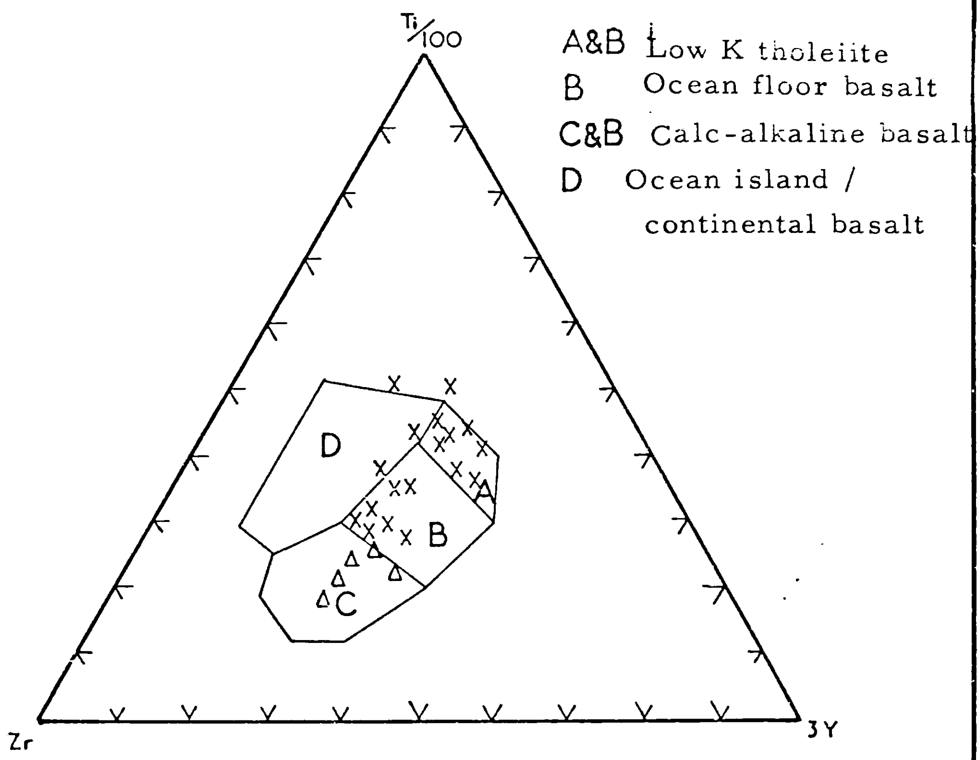
Symbols as for fig.29

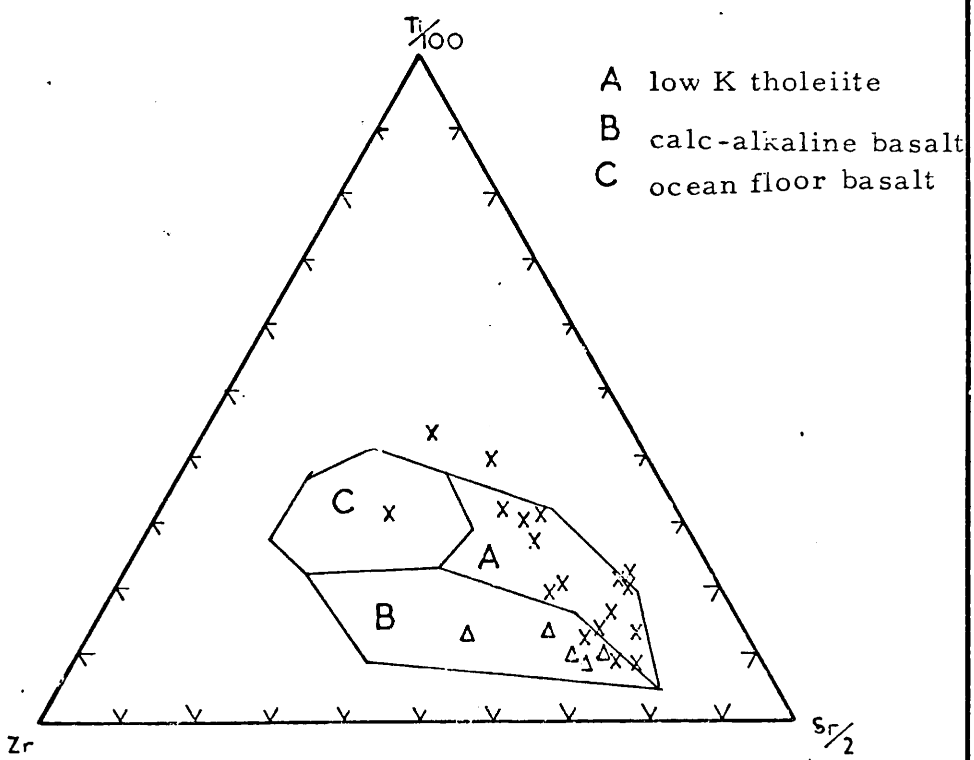
	Rb/Sr	
average intermediate biotite-hornblende gneiss	0.13	
average andesite	0.18)	
average shale	0.50)	- Van de Kamp 1970
average sandstone	3.00)	
Dalradian pelites	1.37)	
Puvington shale	1.06)	- Moore 1978

The distinction between para and ortho amphilolites, on the basis of trace element data, has been attempted, using elements such as Ni, La, Cr, V. (Leake 1964, Rivalenti & Sighinoffi 1969). Unfortunately, the analyses undertaken in this survey did not include these elements. Thus, it is much easier to compare the trace element data obtained from the amphibolites with published igneous data and thus indirectly show that the amphibolites are probably igneous. In this respect, the various plots already described, that include amphibolite data on lines of igneous fractionation are considered significant. In addition, the amphibolites lie within the fields defined by Pearce and Cann (1973) for basalts. (fig 41)

Thus, although individual plots and abundances for trace elements are difficult to interpret in terms of a sedimentary or igneous/para-igneous origin, it is thought that the consistent lines of fractionation involving all three analysed lithologies, as well as more specific indicators for the biotite-hornblende gneiss and amphibolites, suggest a direct or indirect igneous

FIG.41 Discrimination diagrams for amphibolites.
(Pearce and Cann 1973)





Symbols as for fig. 29

origin. This confirms the conclusion reached on the basis of Major element distribution.

3.5 Origin of the Banded Gneisses and Amphibolites

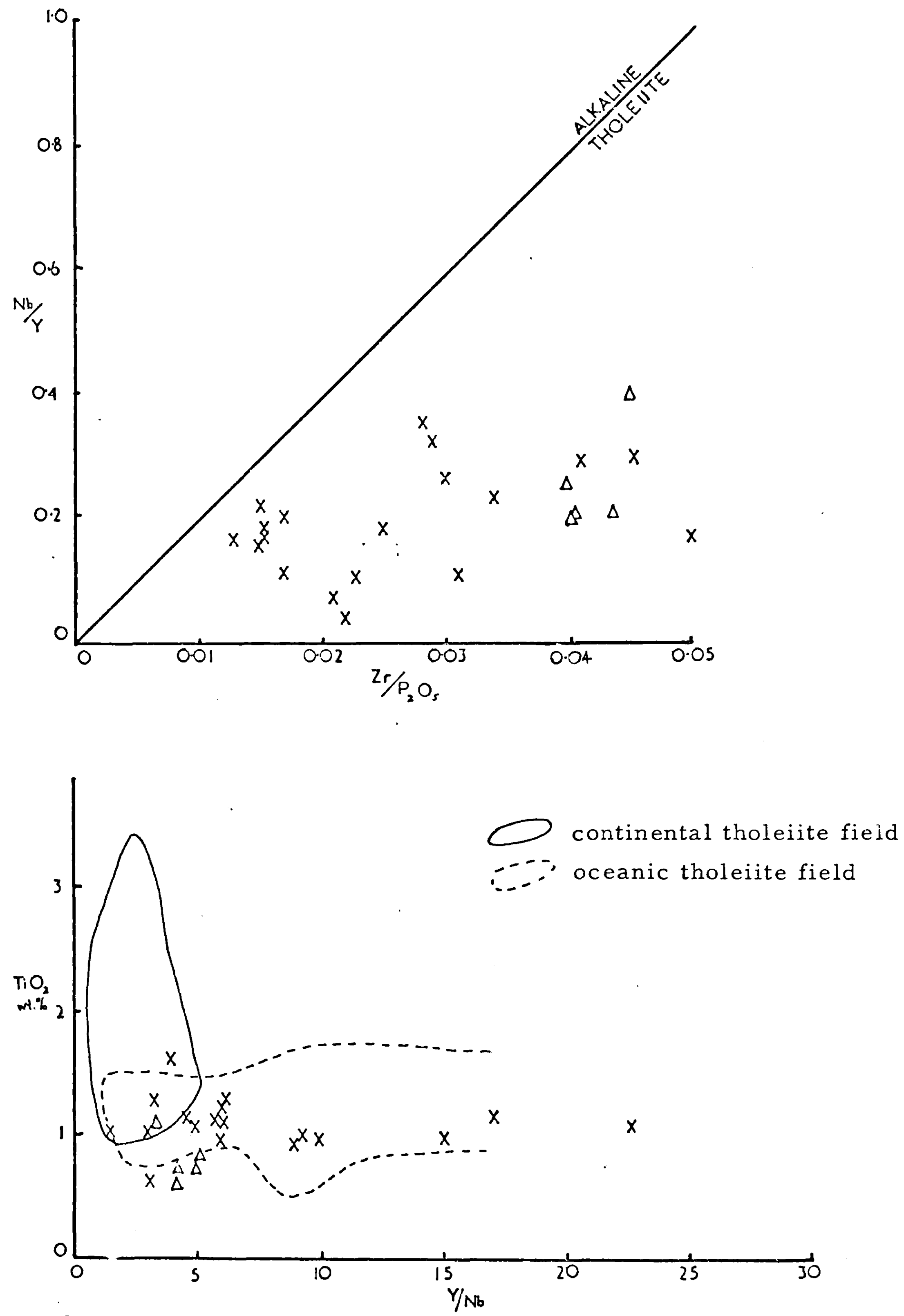
The geochemical data suggests that the Biotite gneisses, Biotite-hornblende gneisses and the amphibolites are of either igneous origin or are sediments locally derived from igneous rocks. The mineralogical series forms also a chemical series, ranging from basic-intermediate-acid. The contact relationships seen are not intrusive; the complete lack of cross cutting relations, and the large areal extent of the gneisses and amphibolites suggest a volcanic/sedimentary setting. Thus, the basic-intermediate-acid series implies the calc-alkaline basalt-andesite-rhyolite association of volcanic arcs, possibly formed at converging plate margins.

This assumed calc-alkaline origin is tested on the basis of the geochemical character of the Amphibolites and Banded Gneisses:

Amphibolites

Pronounced primary differences in the absolute ratios of the incompatible elements has allowed various authors to establish discrimination diagrams for genetically different types of basalts, on the basis of trace element combinations.

FIG.42 Classification of the Banded Gneiss Amphibolites
(from Floyd & Winchester 1975)



Discrimination between alkaline or tholeiitic parental magma composition can readily be made for the Bergsdalen amphibolites. The high Y/Nb ratio, which is consistently greater than 1 (Winchester & Floyd 1976) and the plot of Nb/Y v Zr/P_2O_5 (fig 42) locate the amphibolites in the tholeiitic field.

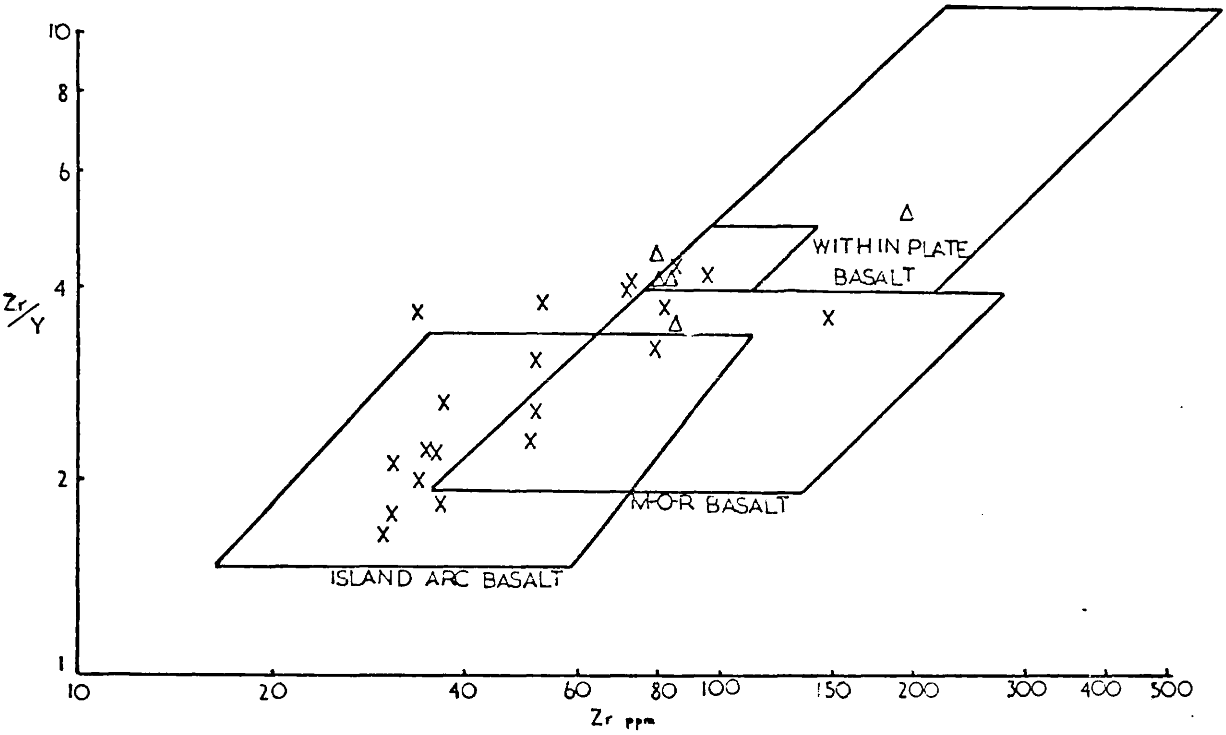
Tholeiitic basalts are generated in two distinct environments: as oceanic or continental flows. However, the constant TiO_2 value with Y/Nb enrichment shown by the Bergsdalen amphibolites (fig 42) is considered (Floyd & Winchester 1975) to be typical of oceanic tholeiites, with only a slight overlap of this trend at low Y/Nb values by continental tholeiites.

A further discrimination into mid-ocean ridge or island arc tholeiite can be made on the basis of the immobile trace elements (Pearce & Cann 1973, and Pearce & Norry 1979). (figs 40, 41, 43) The data for the Bergsdalen amphibolites plots predominantly within the field of island arc basalts in all of the diagrams - and thus they can be considered as low K tholeiites (Pearce & Cann 1973).

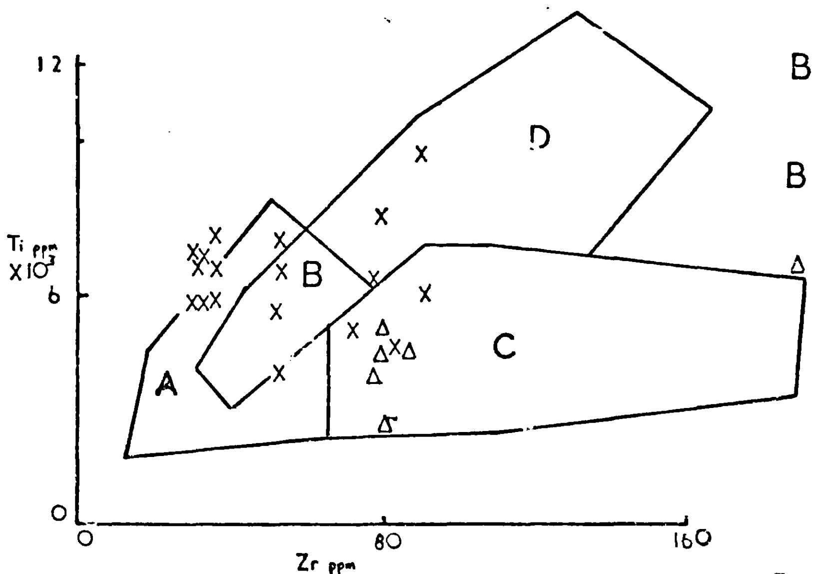
<u>Biotite Gneisses and Basic and Intermediate Biotite-Hornblende Gneisses</u>

If the gneisses and amphibolites analysed are considered as

FIG. 43 Discrimination diagrams for amphibolites.



(after Pearce & Norry 1979)



B & A Low K tholeiite

B Ocean floor basalt

B & C Calc-alkaline basalt

D Ocean floor basalt

(Pearce & Cann 1973)

Symbols as for fig. 29

representing members of the Basalt-Andesite-Rhyolite association, then the chemical characteristics of gneisses should have their analogs in recent volcanic arcs, always assuming element mobility has been insufficient to destroy the general trends.

1. AFM diagram (Irvine & Barager 1971)

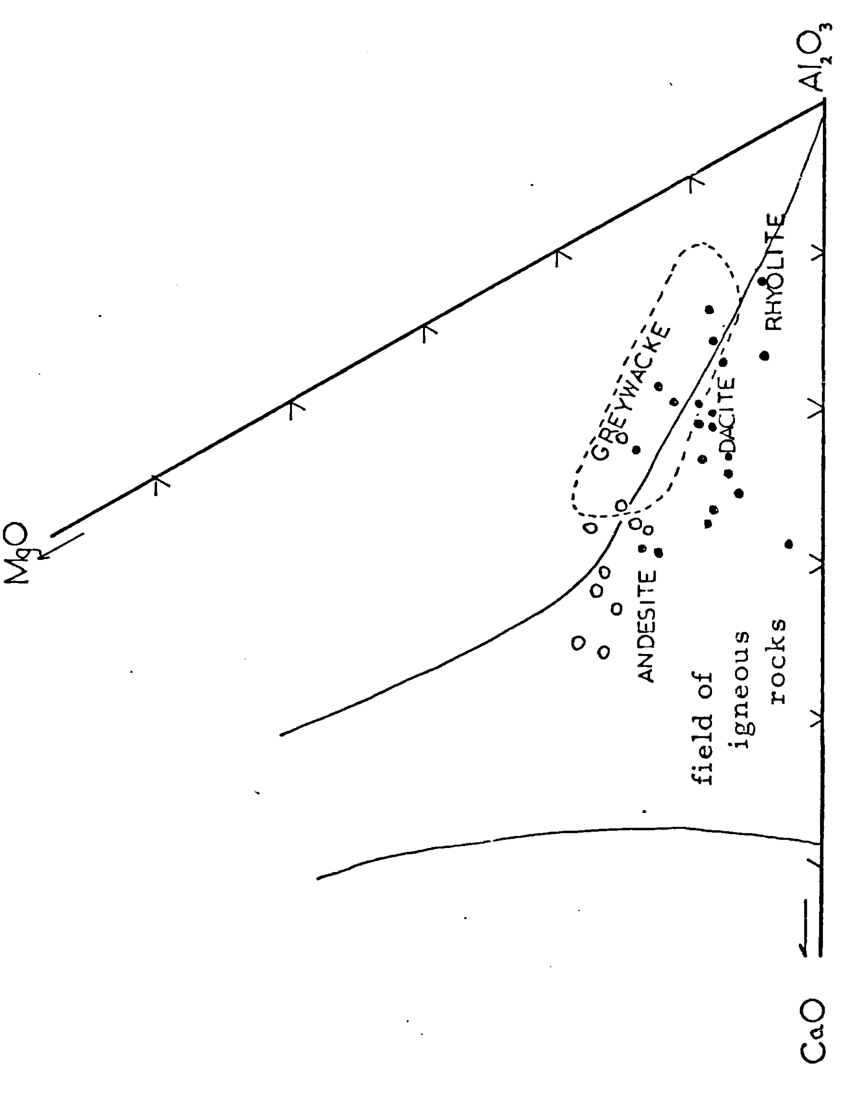
The Biotite gneisses and the Biotite-hornblende gneisses (both basic and intermediate) define an excellent calc-alkaline trend. (fig 39). The majority of the Bergsdalen amphibolites fall on thethbleiitic side, with a typical iron enrichment trend at constant alkali values. This tholeiitic composition has already been demonstrated for the amphibolites.

2. $MgO-CaO-Al_2O_3$ (from Caby et al. 1977)

The field of andesitic and dacitic rocks has been determined from the literature. (fig 44) and for comparison, the field for some greywackes has been added.

The biotite gneisses and biotite-hornblende gneisses plot very close to the idealised trends but with some scatter. This could relate to element mobility, particularly with regard to CaO. This plot suggests that the biotite gneiss lithology spans the compositional range from andesite, through dacite to rhyolite.

FIG. 44



(after Caby et al 1977)
symbols as for fig. 29

3. Major Oxides v SiO_2

Löfgren (1979) compared Swedish Precambrian Leptites (banded acidic gneisses) with modern island arc volcanics from New Zealand, by plotting Al_2O_3, MgO + CaO, FeO + Fe_2O_3 against SiO_2.

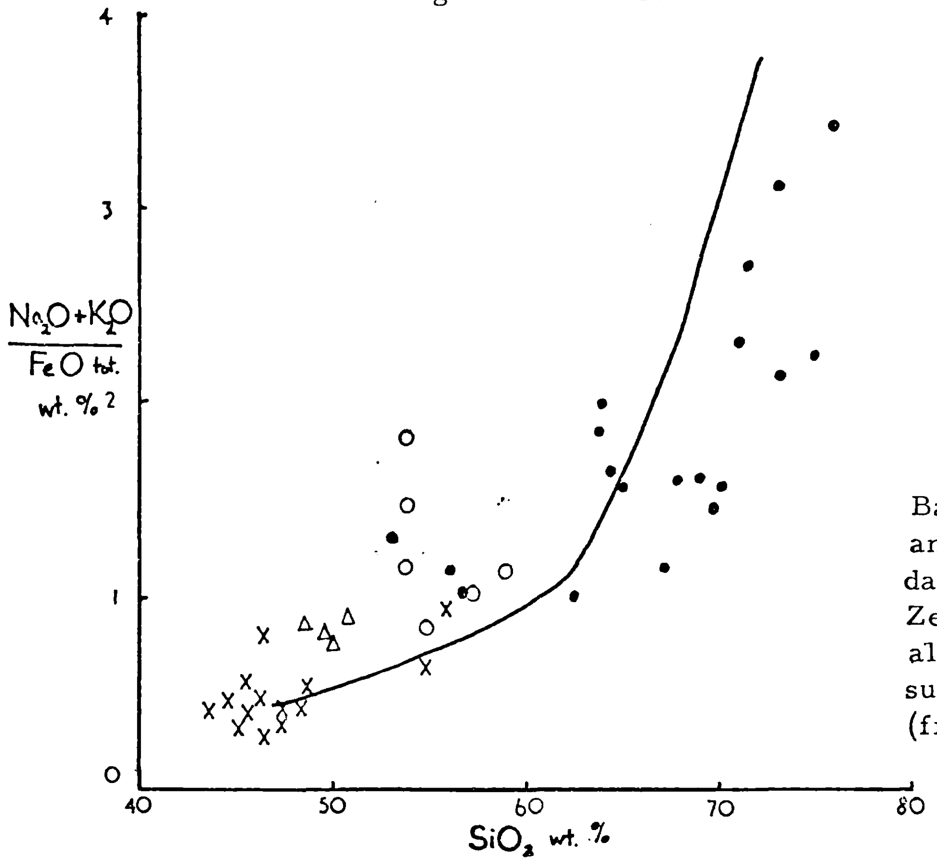
Superimposition of the Biotite gneiss and Biotite-hornblende gneiss data shows a very close similarity to the New Zealand data. (fig 29). The igneous trend for the New Zealand calc-alkaline rocks (Löfgren 1979) is closely followed by the data for both the gneisses and amphibolites, when $Na_2O + K_2O$/Fe total is plotted against SiO_2 (fig 45)

A TiO_2V SiO_2 plot (Carmichael et al. 1974 p.540) also illustrates the close similarity between the Basalt-Andesite-Rhyolite trend for the Cascade calc-alkaline province and the data from the Banded Gneiss and amphibolite (fig 45)
Again, the andesitic-rhyolitic spread of the biotite gneiss data is obvious.

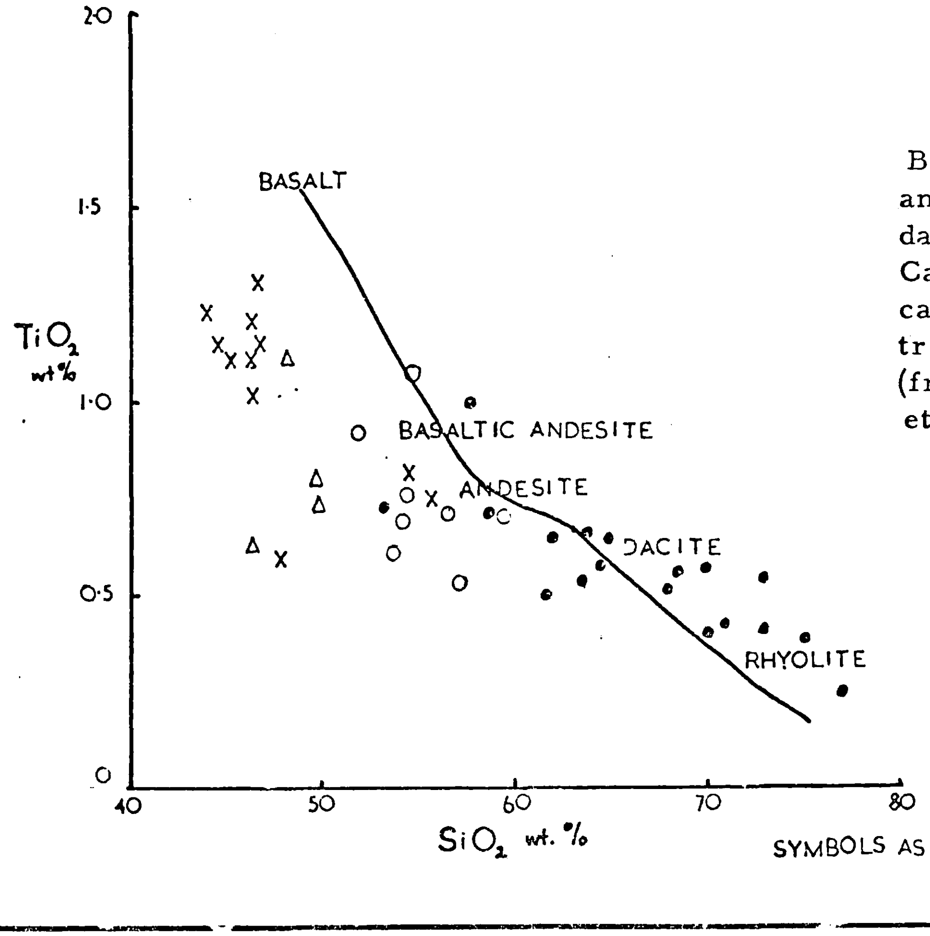
4. Pearce & Cann plots (1973)

Analytical results for the basic variety of the Biotite-hornblende gneiss is plotted on the Ti-Sr-Zr, Ti-Y-Zr and Ti-Zr diagrams and is directly compared to the amphibolite data. (fig 41, 43)

FIG.45 Comparison of oxides from the Banded Gneisses with calc-alkaline igneous trends.



Banded Gneiss and amphibolite data, with the New Zealand calc-alkaline trend superimposed. (from Löfgren 1979)



Banded Gneiss and amphibolite data, with the Cascade Province calc-alkaline trend superimposed. (from Carmichael et.al. 1974 p. 540)

SYMBOLS AS FOR FIG. 29

The basic gneisses consistently fall in the calc-alkaline field but the amphibolites lie in the low K Tholeiite field.

A similar difference is noted from the AFM diagram (fig 39) where the basic biotite hornblende gneisses lie in the calc-alkaline field, in contrast to the tholeiitic amphibolites.

Comparison of trace element distribution for the acid and intermediate gneisses, with those of rocks from volcanic arcs is made difficult because of the paucity of data. However, Taylor and White (1965) published data for common New Zealand and Japanese andesitic associations, whilst Saunders et al. (1979) provide data from the Antarctic peninsula.

Comparable patterns of concentrations are recorded (table 5) from the Banded Gneisses. Trend lines for volcanic arcs, derived from trace element data, have been published by Pearce and Norry (1979). The two plots (TiO v Zr and Nb v Zr) have trend lines for volcanic arc series from individual localities. (fig 40). When compared with these published trends, the Biotite gneiss, biotite-hornblende gneiss and amphibolite data show a close correlation, despite a certain amount of scatter.

Discussion

The geochemical data presented indicates that the analysed

Table 5. Comparison of Trace Element Data.

(Parts per Million)

	Bergsdalen Banded Gneisses				Modern Av. Tholeiites			
	amphib-olite	basic bi hb gneiss	int. bi& bi-hb gneiss	acid bi gneiss	rise	arc	calc - alkaline	Contin-ental
Sr	344	483	449	311	135	225	300	350
Rb	26	65	67	72	1	5	10	30
K/Rb	439	246	279	322	1200	700	350	300
Y	18	24	21	26	30	20	23	30
Zr	52	81	93	135	100	60	100	200
Th	2	4	3	4	-	-	-	-
Nb	4	5	5	7	-	-	-	-
Rb/Sr	0.07	0.13	0.15	0.23	0.01	0.02	0.03	0.09

	Modern Av. Andesites		Modern Av. Siliceous volcs			Av. Greywackes Composite	
	arc	calc-alkaline	arc dacite	dacite	Rhyo-lite	Archean	Phanerozoic
Sr	200	385	200	500	150	290	190
Rb	10	30	15	40	100	77	75
K/Rb	580	440	800	400	250	226	220
Y	23	20	25	30	10	15	20
Th	-	-	-	-	-	-	-
Nb	-	-	-	-	-	-	-
Rb/Sr	0.05	0.08	0.08	0.08	0.67	0.26	0.40

Data from Condie 1976

gneisses and amphibolites of the Lower Bergsdalen Nappe have a close chemical affinity to calc-alkaline rocks, within volcanic arcs. The association is complimented by the presence of intrusive bodies of quartz diorite and gabbro. However, there is no chemical method suitable for discriminating between igneous rocks, pyroclastics or locally derived sediments - volcaniclastics. Field relations and textural evidence are the only conclusive means of distinguishing these but in the Bergsdalen such evidence has been destroyed by subsequent tectono-metamorphic events.

The Bergsdalen rocks could represent a sequence of lava flows, with a generalised trend from basic - acid. However, it is not usual to find equal proportions of acids intermediate and basic flows; instead it is more common to have either abundant basic or andesitic flows, along with a small proportion of the other two compositions. A discussion involving proportionate occurrences of lava compositions must however, take into account the fact that only a small area, (in the nature of a tectonic slab) of the original deposit has been studied. On the large scale, perhaps basic compositions are dominant, although the work of Kvale (1946) and Grey (1978) suggest that there is little variation in proportions throughout the Lower Bergsdalen Nappe.

The problem of the original nature of these gneisses and amphibolites thus remains equivocal.

Section 4 STRUCTURAL HISTORY

4.1 Introduction

The first survey of the structural features of the Vaksdal-Dale-Bergsdalen area was undertaken by Kvale (1946), who recognised the tectonic nature of the contact between the formation comprising gneisses, granites, quartzites and metabasic rocks above, and the underlying gneisses of Precambrian age. Kvale consequently named the formation above the tectonic contact, the "Lower Bergsdalen Nappe". (fig 21), and he considered it to have been emplaced upon thin (less than 5 metres thick) quartz mica schists of supposed Cambro-Ordovician age.

The present work modifies, and adds to the structural knowledge obtained by Kvale, whilst continuing to use the basic framework of Basement and Nappe. Such a simple division into Basement/Nappe is, however, difficult to maintain for two reasons:

1. the high number of thrust faults recognised in the contact region.
2. the similar nature of the lithologies on either side of the Basement/ Nappe interface.

The quartz-mica schists, considered to be Cambro-Ordovician by Kvale, have been shown in this study (section 4.6b) to be tectonic schists (c.f. phyllonites of Knopf, 1931) derived from local gneisses, and thus do not have the same importance in defining the Nappe/Basement contact as when thought to be Cambro-Ordovician schists wedged between two Precambrian units. The present survey thus suggests that the boundary between the Basement autochthon, and the overlying Nappe is more complex than previously thought. It can be shown that there are 4 major tectonic units to be considered, separated from each other by thrusts:

4. Lower Bergsdalen Nappe
3. Eggjane Nappe
2. Mixed Gneiss Unit
1. Precambrian Basement

Thus, the following report will describe each major tectonic unit, and its structural history individually, to the point of structural convergence. Structures common to all tectonic units will then be described. Finally, an attempt will be made to correlate pre-convergence structures across the different units.

The deformation of the Bergsdalen area is divided into phases; each phase is erected to encompass events that are structurally related. Thus, most phases involve folding, schistosity and lineation development, often with thrusting and synchronous intrusions. Placing some events, such as superimposed flattening and post kinematic intrusions into one deformational phase or another is, however, often speculative.

4.2 The Basement Gneisses

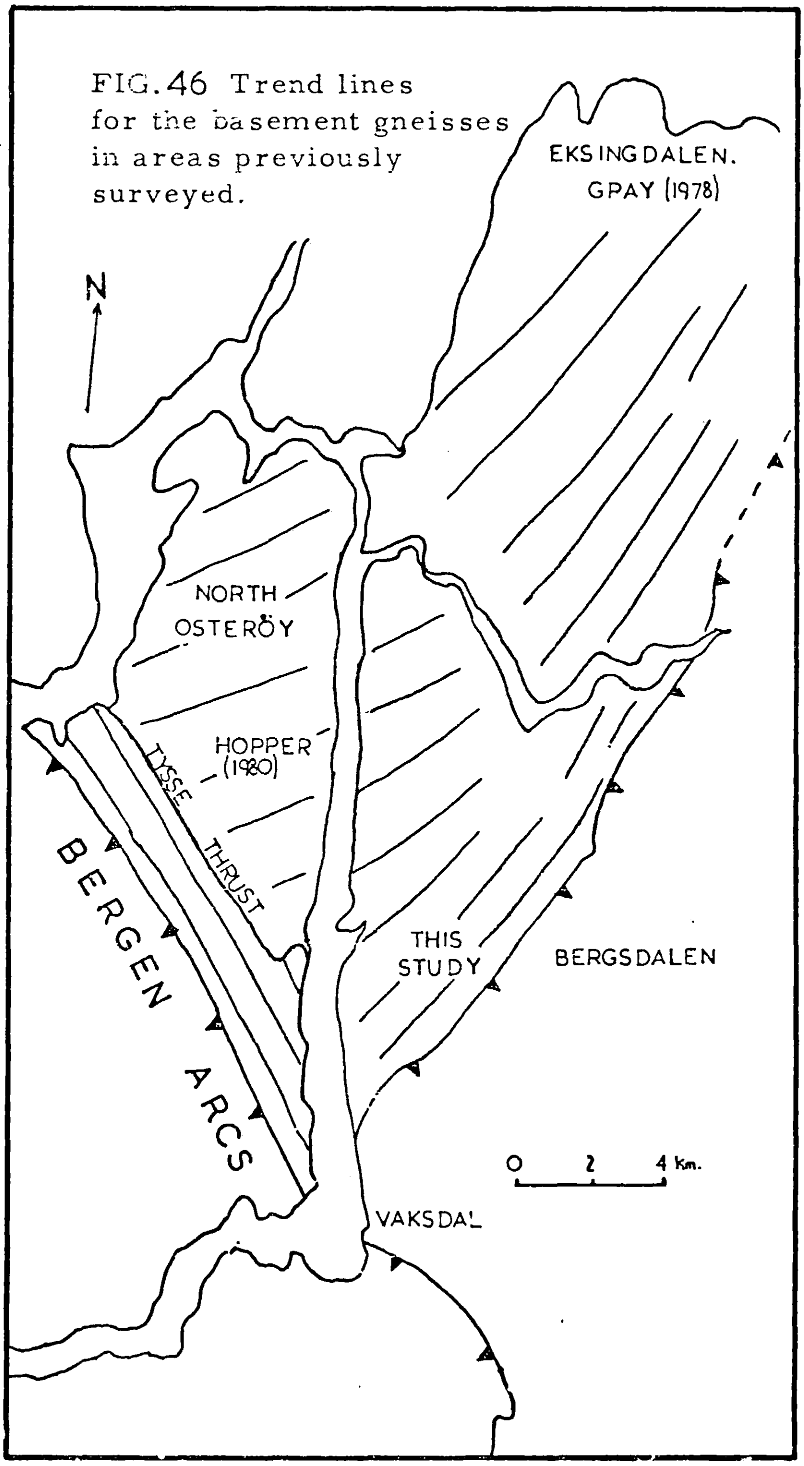
Introduction

The Dale Basement Gneisses are an extension of the Basement Gneisses mapped by Hopper (1980) on Osterøy (termed the Northern Gneisses) and the Basement Gneisses mapped by Gray (1978) in the Eksingdalen-Bolstadfjord area. (fig 46). This large tract of Precambrian Basement gneiss (Gray 1978), with a dominant north-easterly trend, forms the south-western part of the Basal Gneiss Complex of Central S.W. Norway. (Carswell 1973)(Section 1.5). Before the work of the above named authors, this southwest section of the Basal Gneiss Complex had not been studied in any significant structural detail. The Dale Basement Gneisses were briefly described by Kvale (1946).

Analysis of the structural development of the Dale Basement Gneisses has been made on the assumption that one of the phases of deformation has produced structures of characteristic style which can be recognised throughout the gneisses.

The structures associated with the D2 phase of deformation are considered to provide such a structural marker, with easily recognisable, abundant, axial planar pegmatites. Thus, structures can be placed as either pre-, or post-, the "structural marker". However, the assumption that only D2

FIG. 46 Trend lines for the basement gneisses in areas previously surveyed.



produced folds with abundant axial planar pegmatites is not conclusive. Evidence suggests that a similar style was locally produced in D1, and the possibility exists that some D1 and D2 structures can be confused. In the absence of other features, (amphibolites for example, were intruded too early in the tectonic history, and are not sufficiently abundant, to be useful markers) the D2 axial planar pegmatites provide the best, if not entirely satisfactory reference.

4.2a Deformation D "early" producing the Gneissic Banding

Structures attributable to being the oldest observed are very rare; they are observed primarily in areas of low subsequent strain, and thus are best looked for in the western portion of the Dale Basement which is structurally deeper. The early history is contained within the gneissic banding, which is enhanced by subsequent deformation. The gneissic banding (S "early") has several recognisable components:

1. granodioritic and dioritic gneiss units
2. pegmatites and aplites
3. amphibolites
4. folds

1. Granodioritic and Quartz Dioritic Gneiss. The primary rock had a composition that varied between granodioritic and quartz dioritic (section 2.2). A foliation is produced by the preferred shape and crystallographic orientation of mafic minerals, primarily

biotite and amphibole, segregated into layers. The layering is rarely coarse (less than 5cm) with only minor augening around felsic clasts. The rock thus has the appearance of a moderately homogeneous foliated gneiss.

2. Pegmatites and Aplites. Within the host gneiss are numerous pegmatitic and occasional aplitic veins. These veins can be parallel to, or cross cutting the gneissic layering, and are rarely greater than a few centimetres in thickness. If the veins were originally cross cutting, subsequent deformation has flattened them into the layering, and superimposed the regional foliation.

3. Amphibolites. The usual occurrence of amphibolites of this age, is as 1-2cm thick discontinuous, flattened, lenses, although rare larger bodies are seen (several metre pods, up to 50cm thick); they invariably parallel the gneissic banding. No primary cross cutting relationships with the gneissic banding have been observed. The amphibolites are seen to be cut by pegmatites dated as D1. (plate 19)

4. Folding is only observed on a very small scale, being defined by early thin pegmatite veins, and acid schlieren. Detached fold noses of acid schlieren (<5cm in length) can sometimes be seen (plate 20); extreme flattening of early thin pegmatite veins also produces streaked out, small scale isoclines.

Discussion of the D "early" deformation

In describing the gneissic banding, the components considered are those remaining after the subtraction of those features belonging to later structural events. The intense degree of reworking has prevented any detailed division of the banding components into a sequence of events. Thus the most comprehensive statement that can be made about the Dale Basement Gneisses is that they must have undergone a complex history, prior to that described in this section. This early history involved at least one phase of amphibolite development, and at least one of pegmatite intrusion. The isoclinally folded acid schlieren and highly flattened pegmatites are indicative of at least one early deformation phase. Thus, no evidence has been seen for the origin of the Dale Basement gneissic banding, but a tectonic control is considered to be an important factor in its development.

4.2b Deformation D1; Production of S1, F1 and ? L1

Structures of proven D1 age are rare; this is probably a combined effect of subsequent reworking, and the possibility of confusion with structures of D2 age. (section 4.1). The following tentative structural sequence of events for the first deformation has been deduced:

1. Folding; production of composite fabric and lineation.
2. Pegmatite and granite intrusion.
3. Amphibolite intrusion.
4. Flattening.

1. Folding, (F1); Composite Foliation (S1); Lineation (L1)

Folds of this generation deform the early gneissic foliation (S "early") which includes more mafic bands (plate 21) The folding F1 is always seen on a small scale, being intrafolial and tight to isoclinal. Long limbs are often sheared out (fig 47) The folding of the S "early" gneissic banding by F1 produces a new foliation (S1), which is really a composite feature involving S "early" and a new schistosity associated with F1. The S1 foliation can locally appear quite flaggy.

Being intrafolial, no confident conclusion can be drawn as to the trend of the F1 fold axes. However, in an area of low strain, where older structures are better preserved (close to the footpath from Helle, GR 03234671922) an intersection lineation between a gneissic banding and a schistosity is seen. The lineation is defined by orientated amphiboles, and is cross cut by the D2 lineation. The lineation is thus pre-D2, and will be termed L1. Occasional isoclines with axes parallel to this early lineation are seen. Lineation L1, is most strongly orientated in the quadrant

FIG 47 Schematic diagrams from field sketches, showing the relationship between S "early", S1, S2 and F1 structures.

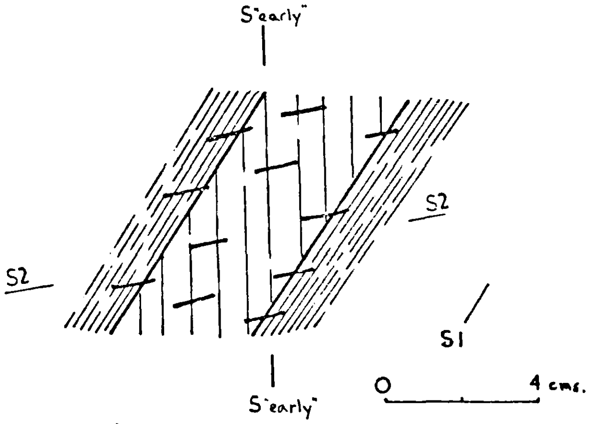
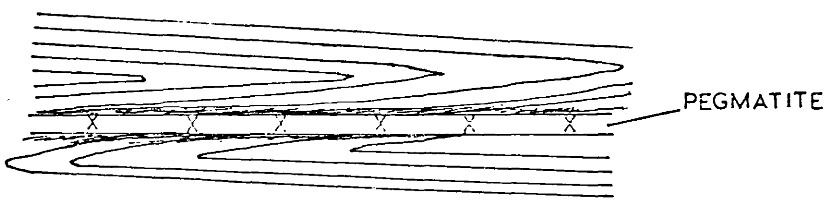


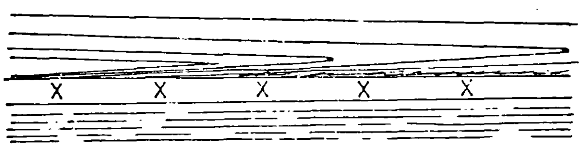
FIG. 48

Schematic diagrams to show the relationship between F2 folding, shearing and pegmatite intrusion:

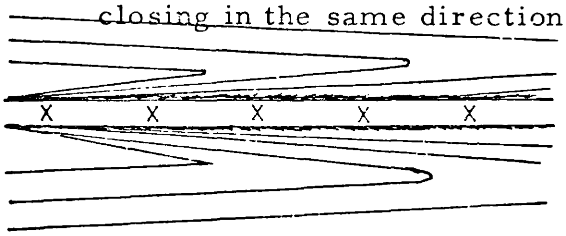
(a) The middle limb of the fold is sheared and replaced by the pegmatite.



(b) The fold limb is sheared, and replaced by the pegmatite;the complementary fold limb is absent.



(c) The pegmatite is replacing the complementary fold in the series, leaving two adjacent folds closing in the same direction.



south to south-east (fig 49), which is oblique to the subsequent north-easterly trending deformations. Other indications of an early deformational event oblique to the regional trend are seen in the form of occasional areas of pre-D2 weak intersection lineations on S1 and S2 foliation surfaces, with a present orientation in an easterly direction. (fig 50)

2. Pegmatite and granite intrusions

Pre D2 pegmatites and granitic bodies, cross cutting to the early gneissic banding (S "early") are very common in the Dale Basement Gneisses. A large (approximately $4km^2$) granite body has been mapped on Flatafjell, above Stanghelle. (fig 9). The relationship between intrusion and F1 has not been conclusively proved. However, a good example of the granite cross cutting an earlier fold (assumed to be F1) is seen in the river bed running from Fossdalsvatnet, above Fossmark (GR 0321267132) (plate 22) Here, S "early" gneissic banding, with thin pegmatites accentuating the banding, is tightly folded (F1), and cut out on both sides by thick (metre or so) granitic veins. The contacts are subsequently cut at a high angle by D2 pegmatites.

Amphibolite bodies are locally observed within the granite. Their size varies from a few centimetres, up to several metres in length. Invariably the bodies are elongate parallel to the

FIG.49 Plunge of lineation L1, Basement complex.

Area :A (basement-fig. 51)
N : 57

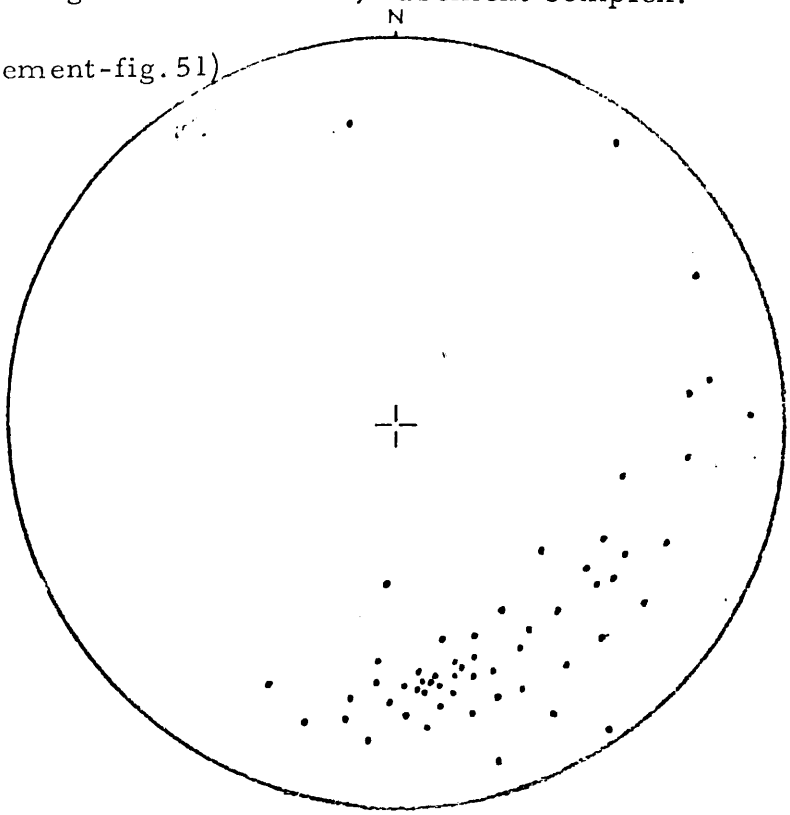
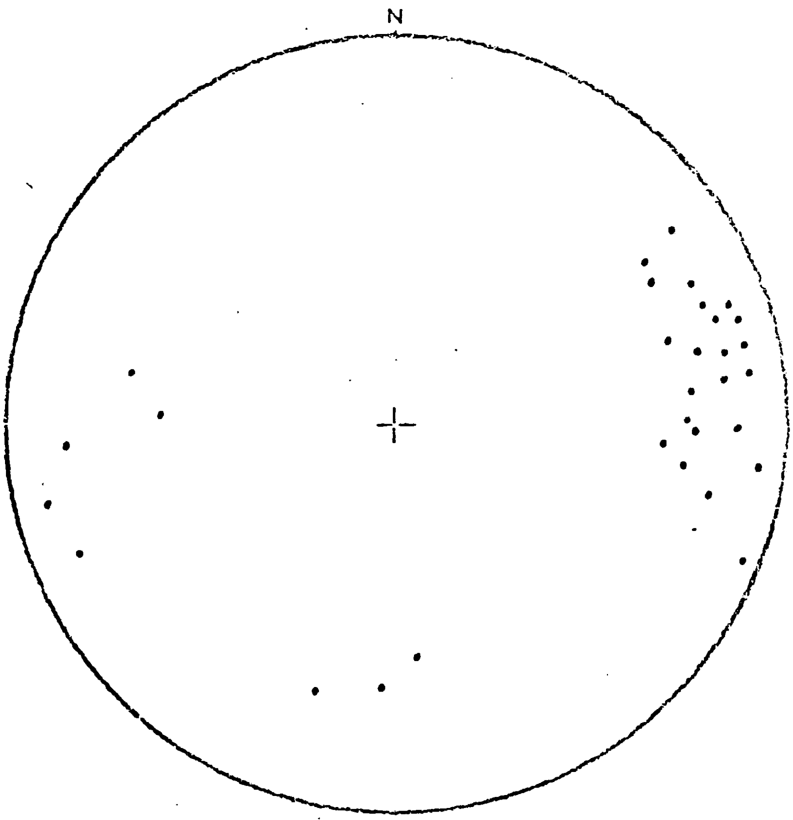
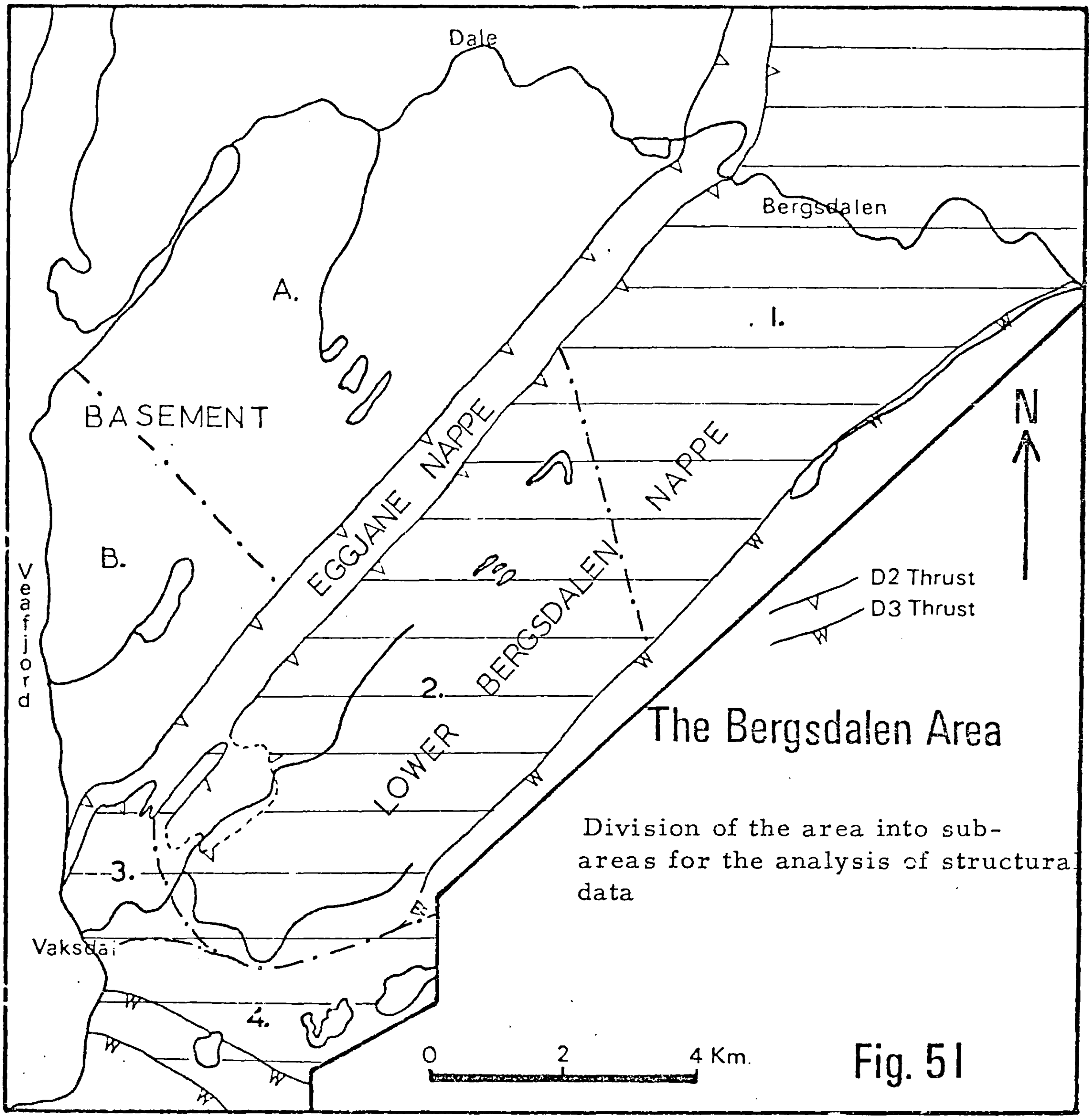


FIG. 50 Plunge of intersection lineation, ? L1, Basement Complex

Area : A&B (basement-fig. 51)
N : 31



lower hemisphere
equal area
stereographic projection



The Bergsdalen Area

Division of the area into sub-areas for the analysis of structural data

Fig. 51

regional foliation.

Pegmatites of this age are common, being intruded both parallel to, and at a high angle to the foliation. Rare occurrences of net veining have been observed and locally F1 isoclines have thin pegmatites intruded along axial planes. The abundance of intrusive pegmatites and granites would be justification for terming the Dale Basement Gneisses, injection migmatites.

3. Mafic Intrusions

Amphibolite lenses have been described as being an integral part of the S "early" gneissic banding (see section 4.2a). However, there is evidence for a second set of amphibolite intrusions. Amphibolite bodies of D1 age are relatively scarce; where observed, they are invariably flattened into the regional foliation (S1) and possess a strong shape fabric, parallel to that foliation. The most conclusive marginal relationship, indicative of a D1 age of intrusion is observed on the side of Veafjord at GR 0320467150, where a medium grained amphibolite 1.75m thick, with only rare late (D2) pegmatite intrusions, cross cuts the regional gneissic banding (S1) at a low angle (plate 23) The margin shows no sign of having been sheared. The S1 foliation cut by the amphibolite contains intrafolial F1 folding, which is cut by axial planar pegmatites.

Other than amphibolite bodies, some coarse amphibole and plagioclase units have been mapped, and are termed metagabbros. The units are never greater than 15m in thickness, but can often be traced for several kilometres. (fig 16). The age of intrusion is problematical. An indication of the youngest possible age of intrusion is seen in figure 52 where a body is seen to cross cut, at a low angle, the regional foliation S1, yet has a fabric that is parallel to that foliation.

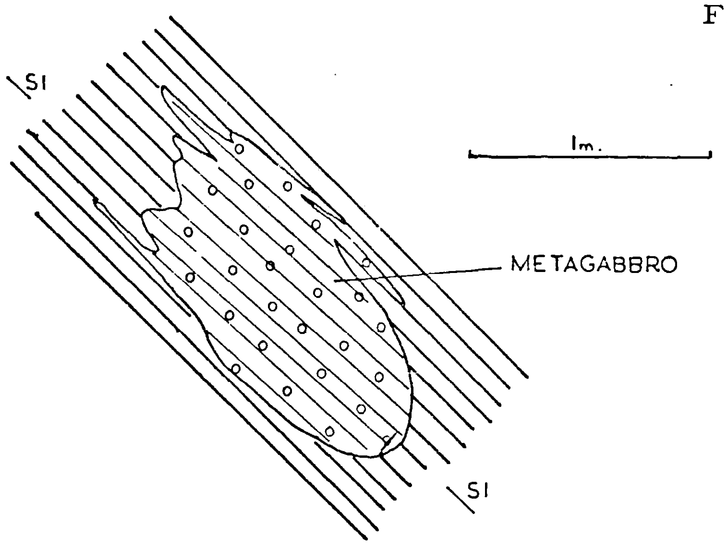
This fabric is subsequently folded by D2. Similarly, a stringer of metagabbro has been seen passing into the country gneiss, disrupting a gneissic block. A strong fabric is cross cutting from the gneiss into the metagabbro. (fig 52)

In conclusion, it would appear only possible to be certain that the metagabbro was intruded prior to the flattening which preceded D2.

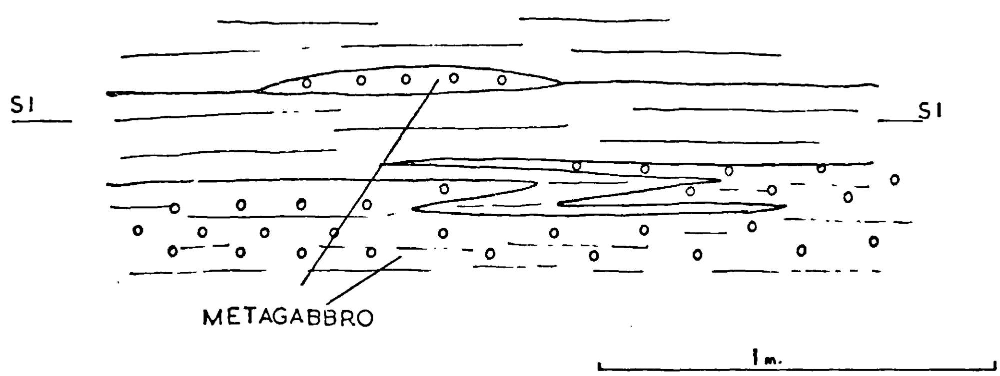
4. Flattening

Both the granite and amphibolite bodies possess a strong fabric, which parallels the regional composite foliation (S1). The flattening also enhanced the S1 foliation; depending upon their orientation relative to D1 strain axes pegmatites were either boudinaged, or flattened into isoclinal folds.

FIG. 52



Field sketch of a metagabbro body intruded into the basement quartzofeldspathic gneiss;the S1 foliation is developed in both.



Field sketch of a metagabbro body intruded/infolded into basement quartzofeldspathic gneiss;subsequent flattening has generated the composite foliation , S1.

Discussion of Deformation, D1

In describing the deformation D1, the problem is recognised that a sequence of events is built up on limited exposure evidence; where evidence from one exposure is obtained, it can be practically impossible to relate conclusively to that seen elsewhere. Thus, D1 should really be considered as an amalgamation of structures of possibly different ages. A pre D2 age is the common link for the described D1 structures.

Thus, two pre D2 intersection lineations are observed (L1) (figs. 49, 50) in separate areas, but have at present a similar trend, falling in the quadrant between south and east. Whether or not they belong to the same or different deformation phases is open to question, but the important fact arising is the indication that an early deformation (or deformations) existed, and was probably derived in a stress field different from that which produced the ubiquitous north-easterly trends of subsequent deformations.

The relationship between amphibolites, metagabbros and granites is also problematical. No attempt has been made to separate the amphibolites and metagabbro due to insufficient evidence. However, chronologically, they would both appear to fall in the same basic structural framework. The granite/amphibolite relationship is indicated: locally; the D1 granite contains bodies of amphibolite. These could be either xenoliths, included by the granite on intrusion, or dykes intruded into the granite, and subsequently disrupted by deformation. Either possibility could be true, although the Basement Gneisses into which the granite was intruded are typically acidic, and there is no evidence for a mafic host rock from which amphibolite xenoliths could be plucked. It would be simpler to consider the amphibolites to have been intruded into the granite. A similar conclusion for the age relationship between D1 pegmatites and amphibolites can be drawn from the described (section 4.2b) amphibolite intrusion on the side of Veafjord. The lack of D1 pegmatites within the amphibolite which cuts a D1 fold with associated axial planar pegmatite, suggests that the amphibolite post dates the pegmatite phase.

The chronological sequence of granite and pegmatite predating dyke intrusion is thus made.

4.2c Deformation D2 Production of S2, F2, L2

The deformation, D2 that succeeds the flattening of the D1 structures, produces the most obvious structures in the Dale Basement Gneisses. No large scale structures are recognised.

The following sequence of events has been deduced:

1. Folding, schistosity and intersection lineation.
2. Pegmatite intrusion
3. Granite intrusion
4. Pegmatite intrusion
5. Flattening
6. Thrusting

1. Folding (F2), Schistosity (S2) Lineation (L2)

The gneissic foliation (S1) produced by the flattening of D1 structures is seen to be deformed by structures of D2 age.(fig 47) (plate 24). Folds (F2) produced during the second deformation are of variable style, ranging from open/closed through to isoclinal in areas of high subsequent strain. The fold profile shapes fall into class 1C (Ramsay 1967) and are modified only slightly by flattening.

F2 folds have a very consistent NE/SW trend, and plunge to the NE at very low angles. (fig 53). The axial surfaces tend to strike to the NE and dip to the SE at approximately 30^{o}. Coaxial D3 folds have locally influenced the distribution of the F2 axial surfaces. Despite this, F2 folds invariably verge towards the NW. Undoubtedly, folds of this generation occur on a large scale - as recorded by Hopper (1980) on the island of

FIG. 53 Poles to F2 axial surfaces(•) and plunge of F2 fold axes (x), in the Basement Complex

Area : A&B (basement-fig 51)
N : • 31
x 16

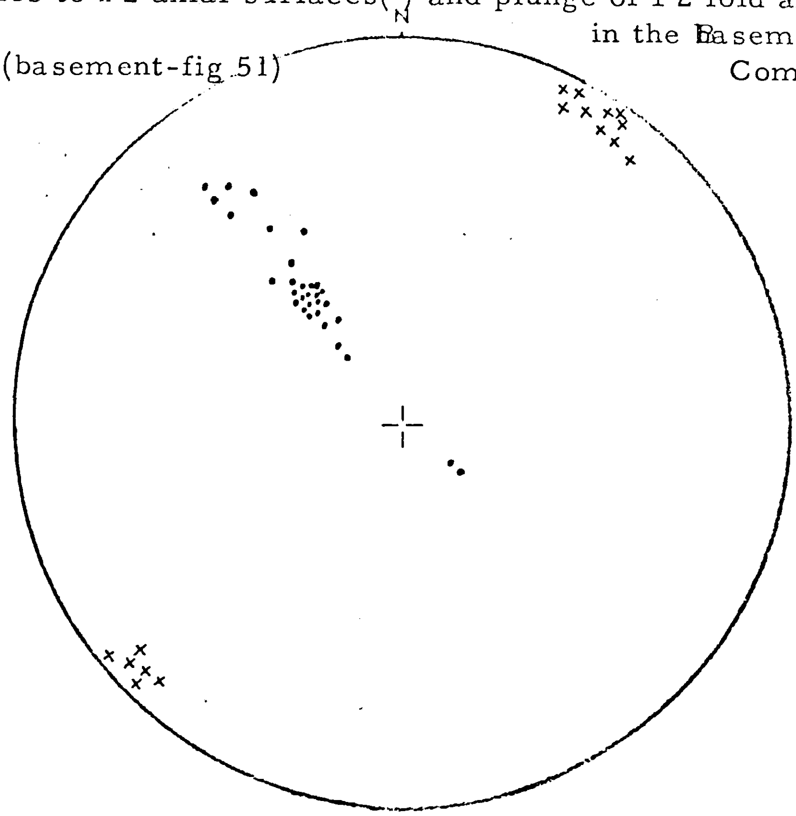
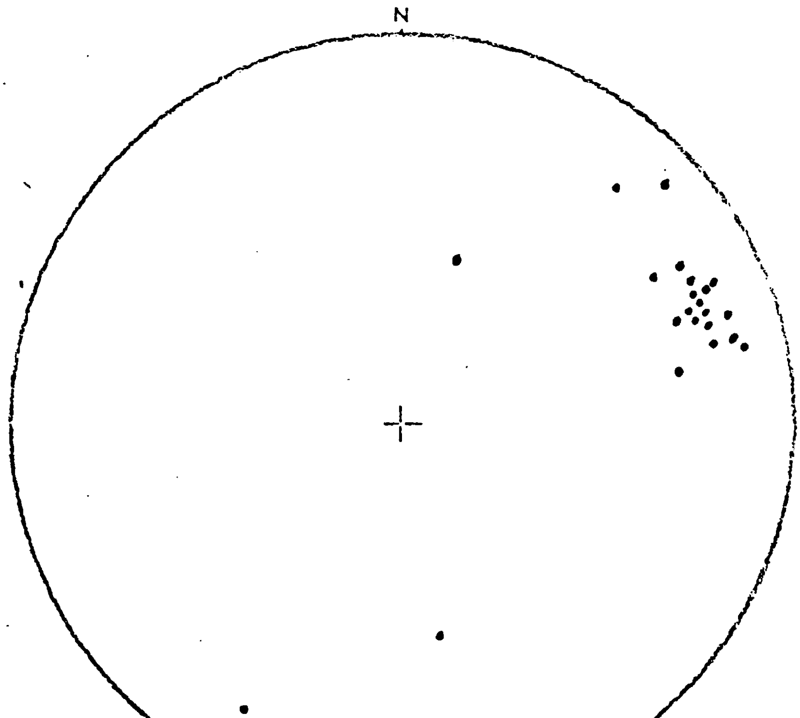


FIG. 54 Plunge of lineation L1, Eggjane Nappe

Area : Eggjane Nappe
N : 27



lower hemisphere
equal area
stereographic projection

FIG. 55 Poles to schistosity (S2) in the Basement Complex

Area :B (basement -fig 51)
N :40

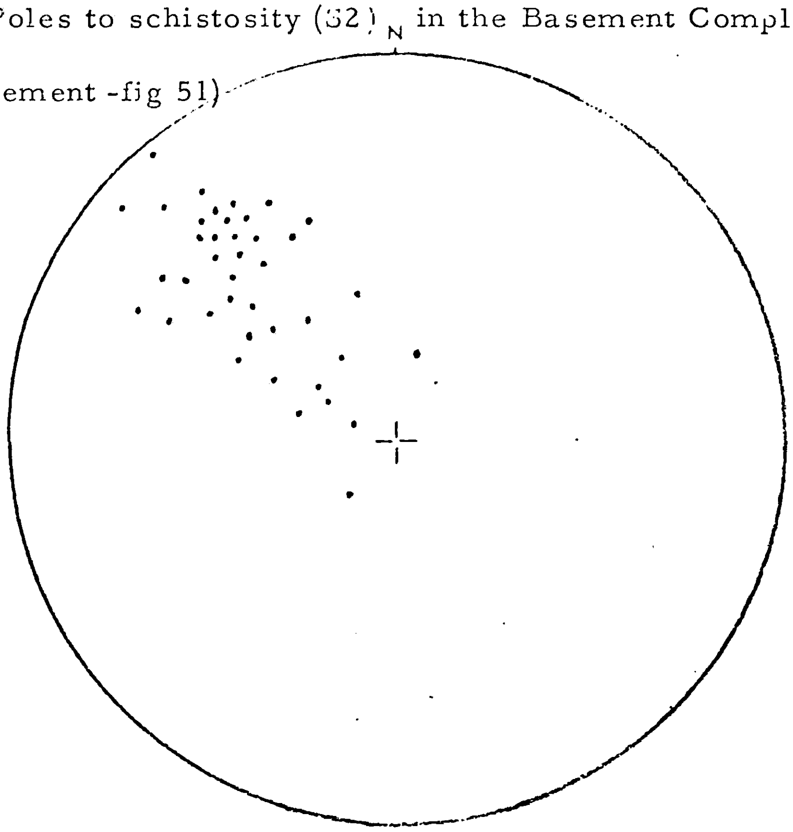
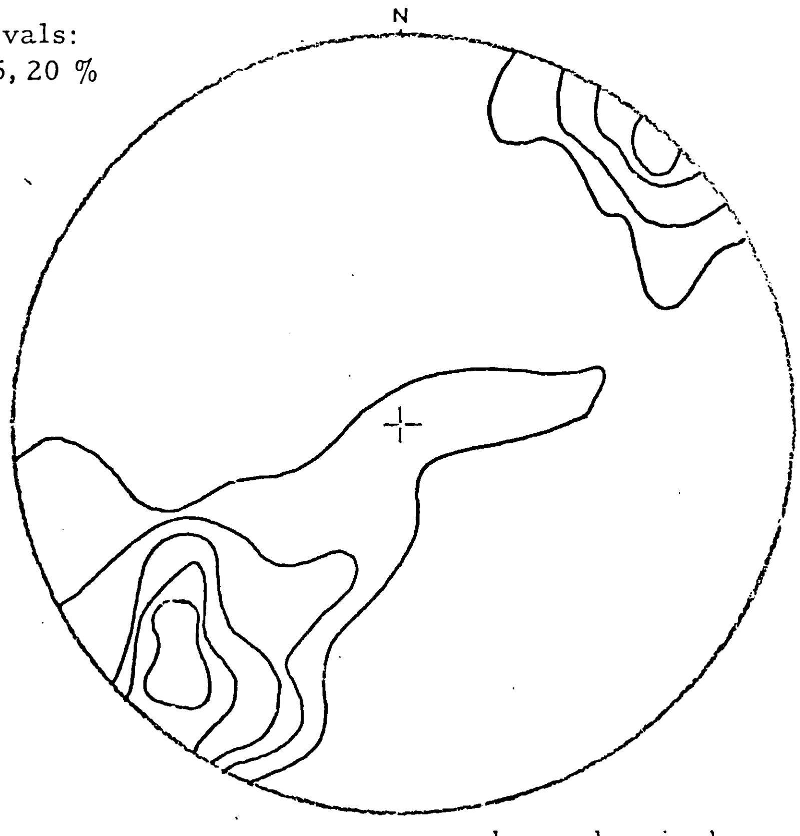


FIG. 56 Plunge of lineation, L2 in the Basement Complex

Area : B (basement-fig 51)
N : 143
contour intervals:
1, 3, 6, 15, 20 %



lower hemisphere
equal area
stereographic projection

FIG. 57 Plunge of lineation, L2 in the Basement Complex

Area : A (basement-fig51)
N : 319
contour intervals:
1, 5, 10, 20, 25%

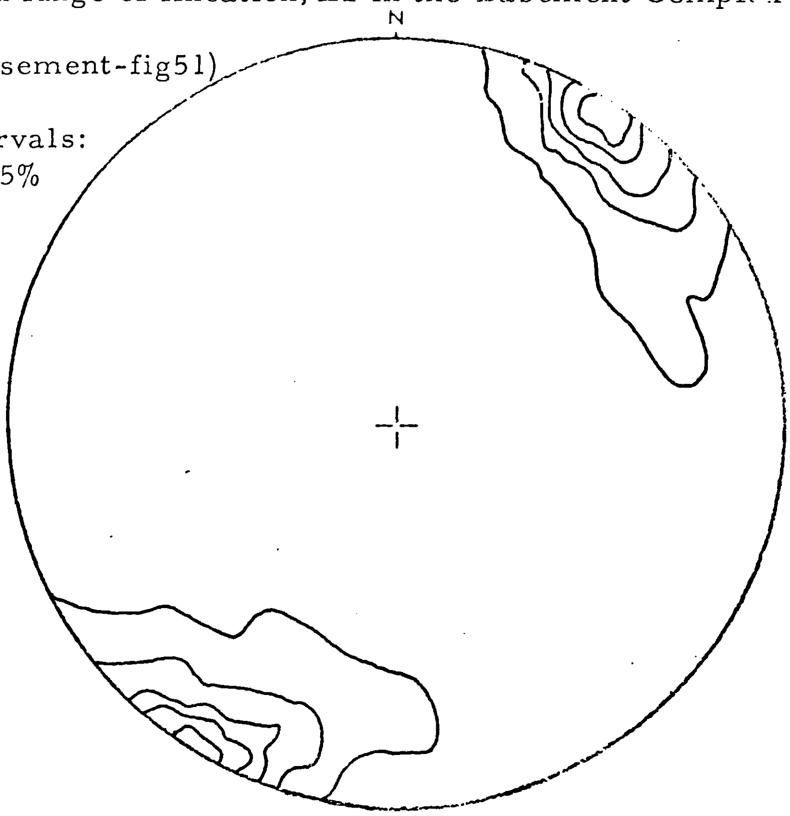
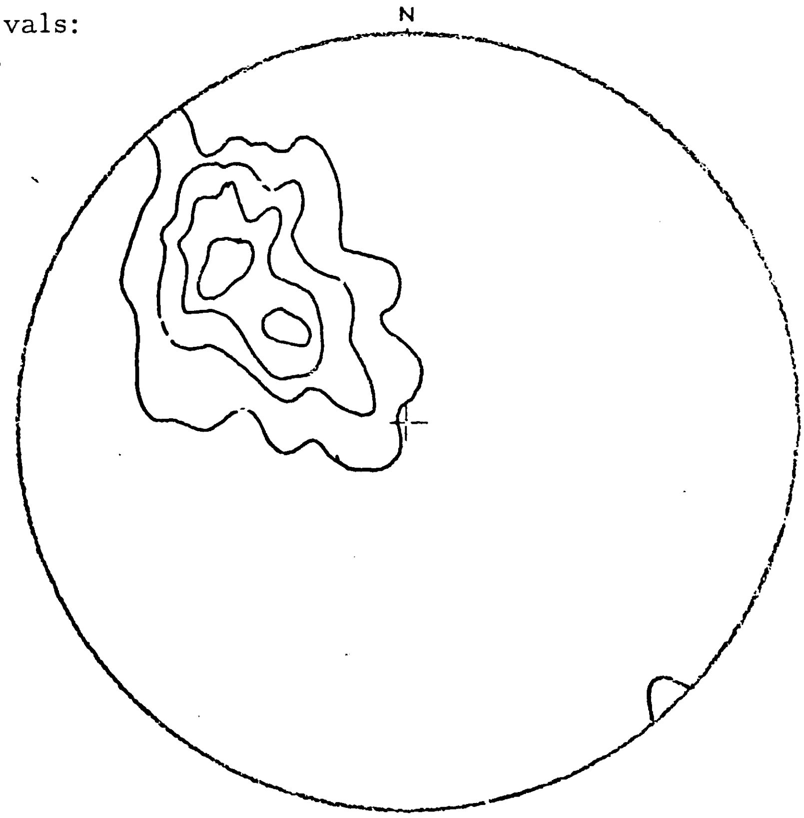


FIG. 58 Poles to schistosity (S2) in the Basement Complex

Area : A (basement-fig 51)
N : 153
contour intervals:
1, 5, 10, 15%



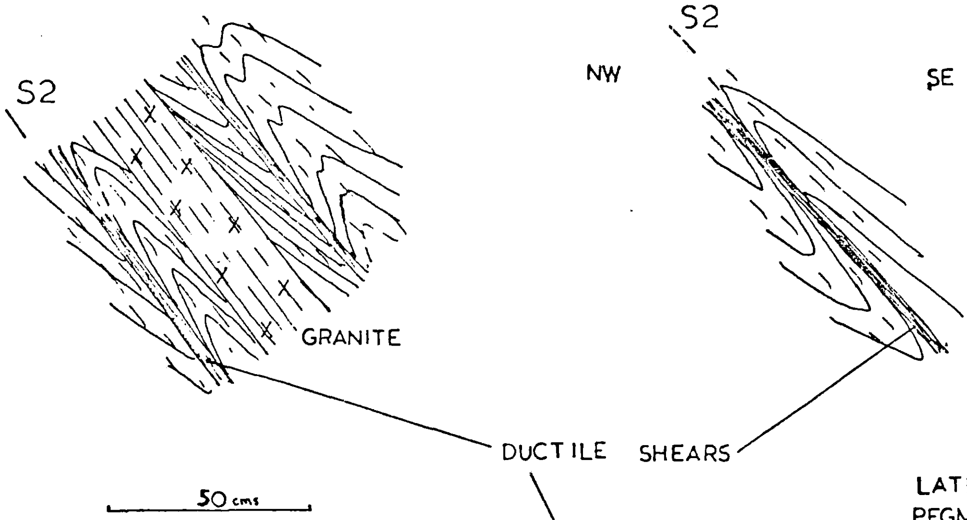
lower hemisphere
equal area
stereographic projection

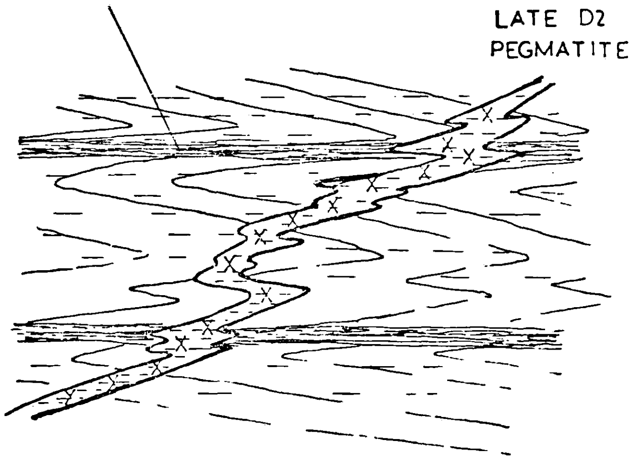
Osterøy, immediately to the west of the area studied. However, a combination of lack of mappable units within the Basement and subsequent deformation, prevented the mapping of any major axial traces of this deformation event. Folds of outcrop scale, and smaller, are very common over the whole area, suggesting that deformation has been widespread.

An axial planar schistosity is developed, producing a new fabric (S2) (fig 55, 58.) This fabric, defined by biotites and amphiboles with both shape and crystallographic orientation is best developed in the hinge regions of the F2 folds, and only variably developed on the fold limbs. The S2 fabric is thus inhomogeneous, and is unsuited for use in the deduction of large scale structures. Where present, the cross cutting S2 fabric confirms the presence of D1 structures. (plate 24)

The intersection of S2 with the S1 foliation, results in a strong intersection lineation. This lineation (L2) has an ubiquitous NE/SW trend (fig56, 57) and is defined by elongate lenses of quartz and feldspar, along with biotite, epidote, amphibole and occasionally garnet. Locally, a true L tectonite rodding lineation is produced but the usual appearance is as an L-S tectonite.

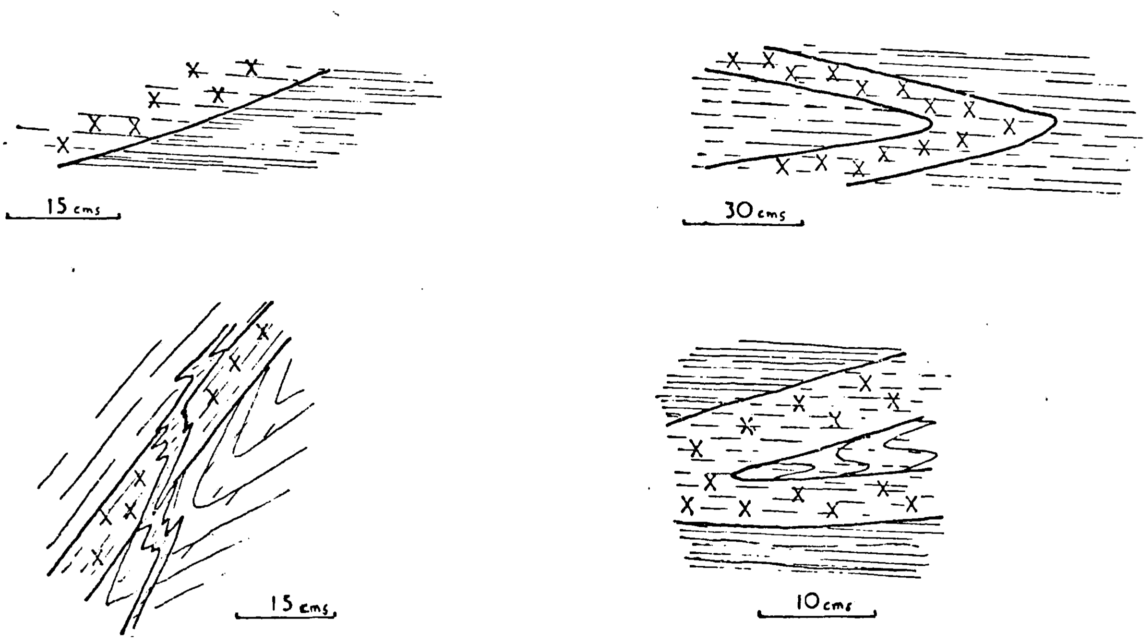
FIG.59 Field sketches of F2 folds in basement gneisses, with limbs replaced by ductile shears.





note that the late D2 pegmatite is cross-cutting to the ductile shears yet also contains the S2 fabric.

FIG..60 Field sketches of intrusive granite contacts with the basement gneisses.



A common feature of F2 folding, is the presence of narrow, small scale ductile shear zones (ranging in thickness from under a centimetre, up to about 15cm). Shearing is most often associated with the hinge regions of the folding, and can result in the drastic reduction in thickness of fold limbs. Where observed, the shear sense of these zones is directed towards the NW. (fig 59)

2. Pegmatite Intrusion

A regional pegmatite suite was intruded along the axial planes of the F2 folds, often replacing sheared out limbs. The pegmatites (quartz, pink and white feldspar and biotite) mostly range from 2-25cm in thickness, although pegmatites up to 3m have been observed. Two main styles of intrusion along axial planes are seen:

the pegmatite passes along the axial plane of an F2 fold with no associated shear

or

the pegmatite is associated with a plane of shear, parallel to the axial plane of the fold; (plate 25), this latter style produces a variation in fold/shear/pegmatite associations. (fig 48)

3. Granite Intrusion

Large granitic bodies (with a gneissic fabric) have been mapped in the hillsides above Storfossen (0328367202), and together have been termed Dystingen granite. (section 2.2a). Samples from a freshly cut road exposure within the granite (0328667202) were collected and analysed for Rb/Sr dating purposes.

Granitic veins up to 30cm thick, marginal to the main Dystingen body exhibit the most informative intrusive relationships with the Basement gneisses. The veins are cross cutting, with an axial planar attitude to F2 folds (plate 21). The fold limbs are often replaced by the granite veins, in a manner very similar to the pegmatites described above. Intrusive relationships are also locally observed at the margins of granite sheets; the contact cross cutting at a low angle the S1 foliation. Occasional xenoliths of granodioritic gneiss are also observed. The various intrusive relationships are shown in fig 60

More evidence for the intrusive nature of the granitic bodies can be seen (from a boat) on the side of Veafjord (GR 0320367162). A thick (several metres) granitic body, containing a folded granodioritic xenolith, cross cuts the regional foliation at a low angle (plates 26, 27) No granite margin ever exhibits chilling features or alters the wall rock.

The D2 (Dystingen) granites are distinguished from D1 granites by their structural relationship to D2 folds, and by their very homogeneous appearance, with only rare pegmatites. D2 axial planar pegmatites are never seen to cut the granites. In contrast, Dl granites are folded by D2 and contain abundant D2 pegmatites.

4. Pegmatite Intrusion

A late set of D2 pegmatites, rarely thicker than 20cm, cross cut the early D2 pegmatites and granite. Typically, these are intruded both parallel to, and at a high angle to the foliation, yet they are always cut by it. Pegmatites of this age locally cross cut the early D2 shears, associated with fold hinges (fig 59)

5. Flattening; enhancement of S2

Within the eastern part of the Dale Basement, partially underlying the Nappe complex, is a zone of well flattened gneisses of a minimum 500m thickness. (fig 9)
A maximum figure has not been obtained due to subsequent tectonic disruption. The gneisses have a flaggy parting (plate 28) (breaking along regular planes 5-10cm in thickness) and are characterised by the occurrence of intrafolial isoclines of F2 age (plate 29)in association with the axial planar pegmatites and granites. Compositionally, these flaggy gneisses are in part identical to the granodioritic gneisses, with the additional element of more epidote rich zones. (section 2.2b). Dystingen granite forms part of these flaggy gneisses.

The isoclinal folds possess a very strong axial planar fabric (S2) which is only obvious in the hinges; fold limbs combine with the fabric to define a composite foliation (S1/S2). Thus, the S2 fabric, which is only partially developed within the less flattened basement, has been enhanced in conjunction with the rotation of the S1 fabric, forming a well developed composite (S1/S2) fabric.

The lineation associated with F2 is also enhanced, resulting in a well defined NE-SW shape fabric.

There is no apparent rotation of D2, or earlier, structures into this zone of flattening - all the deformation appears to be coaxial.

The granite veins and bodies have been shown to cross cut D2 structures. That the intrusion predates this phase of flattening is obvious, with all intrusives possessing the S2 fabric. The acid veins are often boudinaged or isoclinally folded into S2, depending upon their original orientation. Xenoliths within the granite bodies are invariably orientated with their longest axes parallel to the foliation. The fabric does not augen around the xenoliths, instead passing into them. (plate 26). Smaller granite bodies of D2 age are locally observed within the unflattened basement gneisses. These also possess a strong fabric, which has the same orientation as the S2 fabric.

6. Thrusting

Zones of intense shearing, almost invariably confined to bodies of mafic material, have been interpreted as thrusts. (plate 30) Disruption and discontinuities across the planes are common.

These mafic zones have sharp margins with the surrounding gneisses and range in thickness from 20cm - 2cm. The thrusts are orientated parallel to the axial planes of the F2 folds. A very strong planar fabric of biotite and chlorite develops parallel to the margins of the thrusts, which tend to be parallel or sub-parallel to the gneissic foliation. Small blocks and fragments of gneiss and pegmatite (including D2 pegmatites) are common, embedded within the mafic zones.

Movement along the thrusts would not appear to be great, with very similar lithologies and structures remaining on either side. No conclusive evidence has been observed as to the direction of movement along the thrusts, but rarely observed rotation of the biotite fabric from the core to the margin of the mafic bodies, along with the very occasional rotation of structures into the thrust, suggest a north westerly directed movement of the upper blocks. However, in contrast, apparent matching of pegmatites and gneissic bands across small thrusts, indicates a down dip (south-easterly) movement.

Few thrusts of this age have been mapped. The easily weathered nature of the mafic units makes observation in the field difficult. The thrusting is considered to post date the flattening, as well flattened gneiss is seen to be disrupted by the mafic zones.

Discussion

Age of the flattening

Information about the relative age of the flattening with respect to the D2 phase of deformation is of great importance in understanding the evolution of the Dale gneisses. The granite intrusion and development of the associated fabric, which is considered to be the equivalent of the composite S1/S2 foliation in the gneisses, offers a chance to place an absolute age on the development of the D2 structures. Radiometric Rb/Sr whole rock analysis (section 2.2a) has given a date of 1050ma for the age of intrusion of the granite. The question to be answered is: can the S1/S2 fabric be considered as a late stage in the D2 phase, and thus be thought of as closely linked temporarily with deformation and intrusion, or has there been a long time interval between D2 folding/intrusion, and a subsequent deformation, whose only manifestation is in flattening and thrusting?

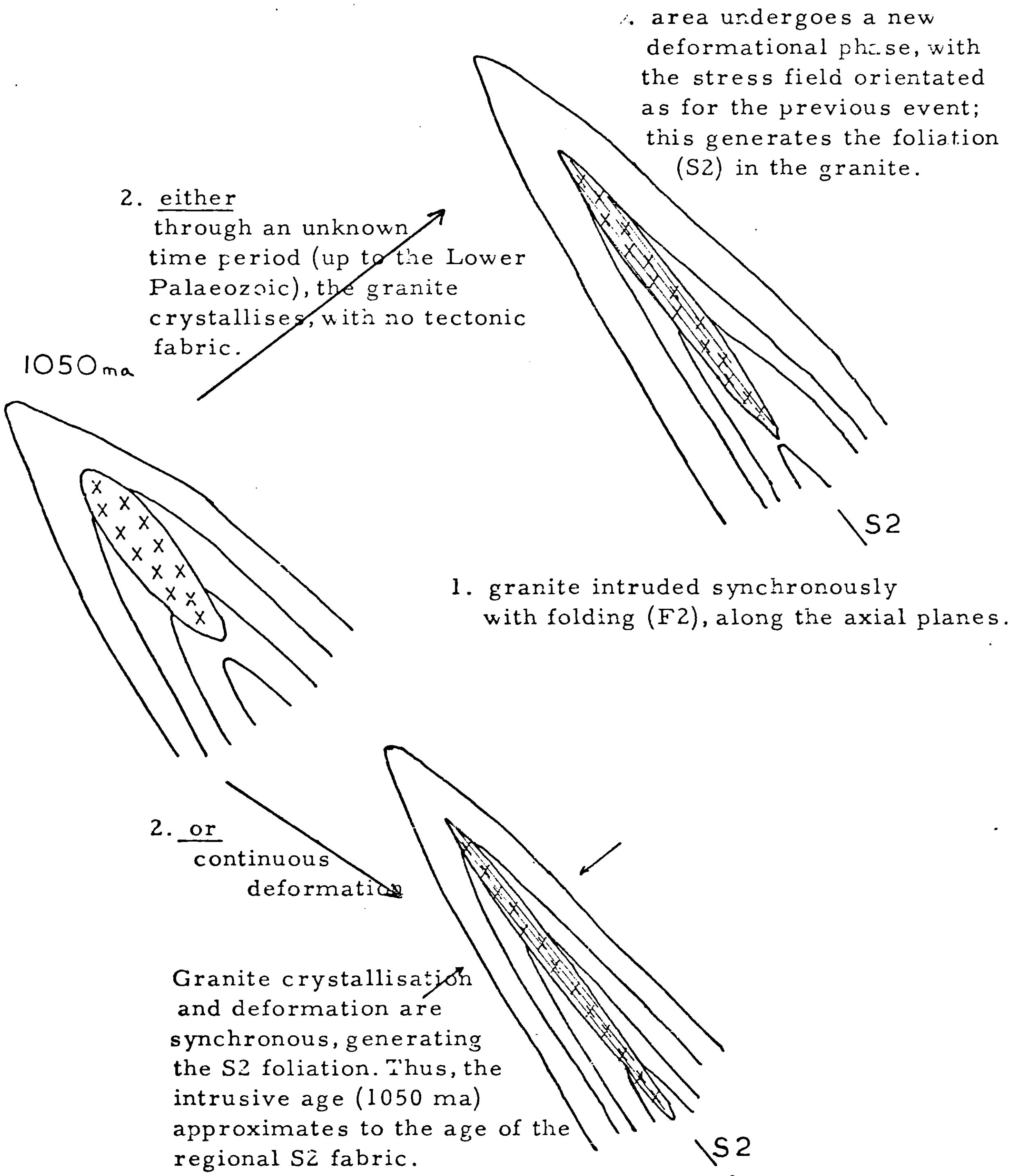
The coincidence of the fabric in the granite with its setting suggests that its emplacement was syntectonic. The lack of any marginal features, such as chilled margins or wall rock alteration, along with the mineralogy (section 2.2a) suggests emplacement at moderately deep levels. That the fabric in the granite is invariably parallel to the S2 schistosity (developed in response to F2 folding) and the S1/S2 composite foliation, suggests that all three were developed under a stress field of the same orientation.

There are thus two possibilities: (fig 62)

1. The development of the D2 stress system resulted in F2 folding and associated schistosity with the granite intruded at a late stage. The stress system was then relaxed - possibly representing the end of an orogeny. After an unknown period of time, a new stress system is set up, with a very similar orientation to D2, this is represented by ductile deformation at a minimum of Lower Amphibolite facies (section 5.1c) resulting in the production of flattened gneisses and granites with a composite S1/S2 fabric.

If this occurred, then the age of intrusion of the granite would bear no relationship to the age of the development of the composite fabric.

FIG.62 Possible sequence of events for the intrusion of the D2 granite, and the generation of the S2 fabric.



2. The development of the D2 stress system resulted in F2 folding and associated schistosity, with syntectonic granite intrusion. Continued deformation flattens the F2 structures and produces the composite fabric (S1/S2); the granite recrystallises in the D2 stress system with a fabric that is equivalent to S1/S2.

In this case, the age of intrusion of the granite will closely approximate the age of fabric generation.

Of these two proposals, the second is favoured for the following reasons:

1. There is no evidence for any relic igneous texture, which might be expected if the granite was allowed to crystallise during an early orogeny, and was subsequently deformed. Everywhere the texture is metamorphic.

2. Small granite bodies intruded within the less flattened gneisses also possess the S1/S2 fabric. It is unlikely that a subsequent, rather than coeval, fabric genesis would have preferentially developed such strong fabrics in the granites, whilst leaving the enveloping gneisses virtually unflattened, with only the local development of a weak S2 schistosity.

3. The coincidence of the S2 schistosity, the S1/S2 composite fabric and the granite fabric, is considered to be relevant. It would appear less likely for a stress system with the same orientation to be developed, relaxed and then redeveloped, rather than the continuation of one stress system.

Model for sequential intrusion and flattening of granite

The available evidence suggests that the S1/S2 composite foliation developed in the D2 granite under the same stress system as the D2 folding. Hopper (1980) has prepared a model that combines folding, intrusion and flattening into one deformational episode. Folds have been shown to develop serially (Price 1975)

with the first formed locking up, prior to the development of the second, and so on. A fold locks up due to the change in maximum principal stress - the change is from the horizontal to the vertical axis. The switch occurs when the amplitude of the fold is sufficient for the gravity vector to become σ_1. When this happens, the fold stops growing, and fracturing can occur along a plane parallel to σ_1, and perpendicular to σ_3. Thus, fracturing develops parallel to the axial plane. Any fluids such as a granitic magma, will rise up the fracture, under its magmatic pressure, thus being intruded along the axial planes of the fold. If this happens at sufficient depth, there will be no chilling or aureole features, and slow crystallisation will start. At the same time as the granite is crystallising, further folds in the train develop, until the layer is completely folded. If the stress regime continues, then the fold train starts to be flattened, and the individual folds become tightened. Any intrusions will also be flattened, and a tectonic fabric will be superimposed, breaking down the initially coarsely crystalline grains. Thus, it can be considered that the flattening event is an integral part of the deformation series, following on from folding and intrusion. Thus, it is suggested that any Rb/Sr date obtained for the intrusion of the granite can also approximate to the age of the flattening and production of the composite foliation S1/S2.

4.2d Deformation D3; Production of F3

Structures associated with D3 are described from throughout the Dale Basement Gneisses. However, the effects are more pronounced in the east of the area where folding and thrusting combine to produce a complex structural pattern. The D3 event is the last major structural event affecting the Basement Gneisses, and as such, has an important control on outcrop patterns. Local, subsequent modification of these patterns occurs in the SW of the area, associated with the development of the Bergen Arcs.

The following sequence of events has been deduced:

1. Folding, Lineation
2. Pegmatite intrusion
3. Thrusting

1. <u>Folding (F3)</u>

The variably flattened composite foliation (S2) produced by the second deformation, along with associated D2 structures (i.e. boudinaged pegmatites, F2 folds + axial planar pegmatites, shear zones and the S2 schistosity) are seen to be deformed by the regional F3 folding. The effect of the coaxial refolding is to produce occasional small scale complex interference patterns (plate 31). However, no large scale interference patterns purely attributable to the interplay of F2 and F3 have been mapped. The D2 granite bodies, and their gneissic foliation (= regional S2) are also folded by F3, this being the first deformation to affect the granite fabric.

F3 folding is recognised on all scales from the local production of microfolds up to a regional scale, with wavelengths of the order of 1km, (plate 32) and mappable axial traces (fig 63) The large scale folding is asymmetrical, overturned towards the northwest. The overturned limbs fold the gneissic foliation into steep belts, which commonly exhibit F3 parasitic

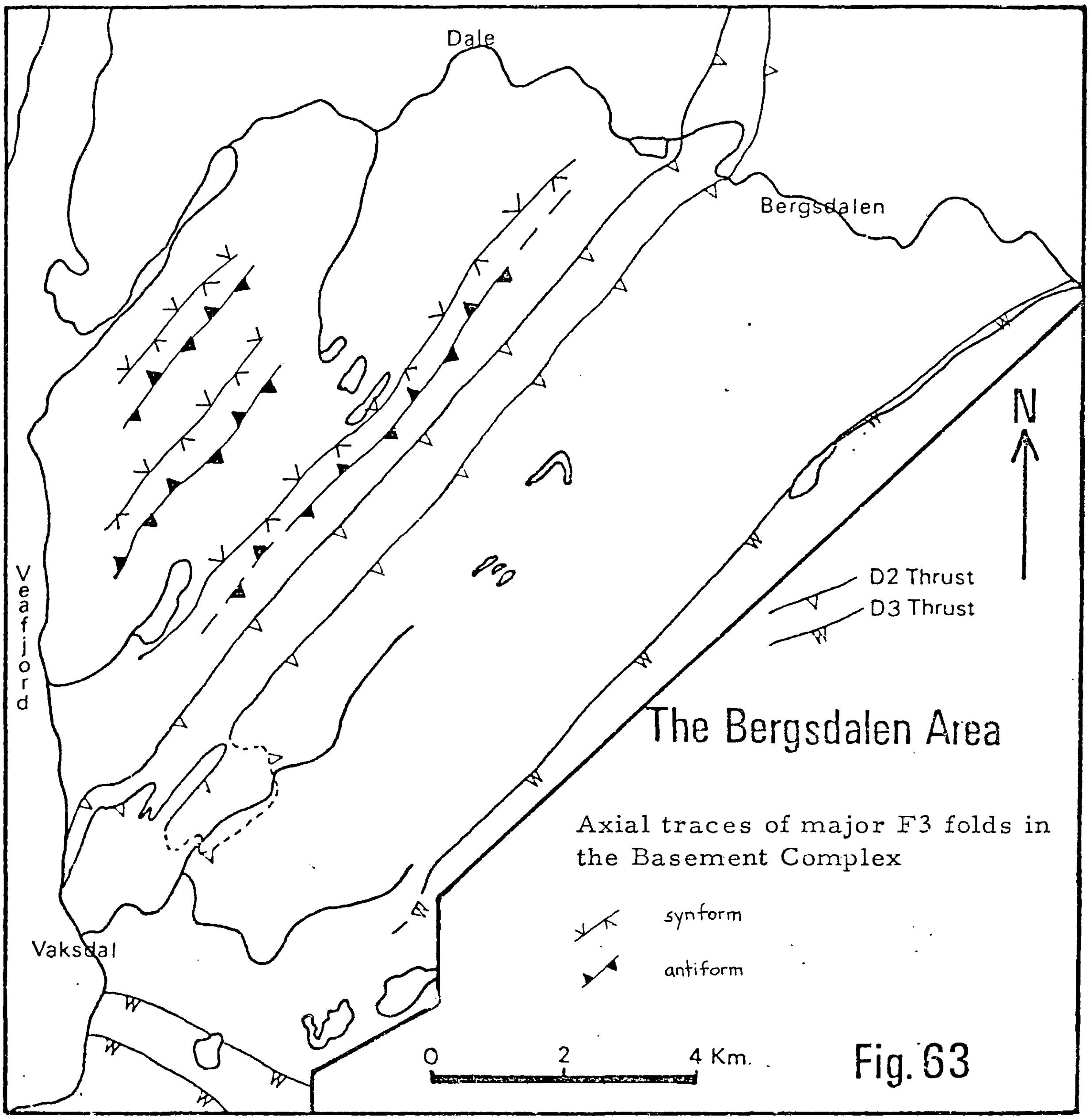

Dale
Bergsdalen
Veafjord
Vaksdal
N
D2 Thrust
D3 Thrust
The Bergsdalen Area
Axial traces of major F3 folds in the Basement Complex
synform
antiform
0 2 4 Km.

Fig. 63

folds. These small scale folds are variable in profile, between open and closed, and approximate to class 1B (parallel folds) in style where the gneissic banding is flaggy; folds in more massive gneissose banding approximate to class 3 (plates 33, 56). Shallow limbs of the large scale folds rarely show parasitic folds. Surfaces of biotite and chlorite are common on S2 foliation planes, and are subsequently folded by F3. F3 folding is coaxial with F2, consequently, the strong shape lineation (L2) is enhanced. The lineation (L2) is defined by elongate lenses of quartzofeldspathic rich, and mafic rich aggregates up to 5cm in length, that consistently have roughly ellipsoidal shapes with $X>Y>Z$; the Z/Y axes lie within the plane of the gneissic foliation, thus producing an L-S tectonite. It is assumed that the X Y Z axes of the ellipsoidal aggregates are parallel to XYZ of the strain ellipsoid.

L2 lineations are plunge parallel to F3 fold axes and are developed ubiquitously. Thus, both the folds and lineation trend consistently to the north-east-south-west, and plunge in either direction at a very low angle. The axial surfaces to F3 folds dip to the southeast at 40^{o}-50^{o} (figs 64, 65)

The F3 folds, combined with the coaxial F2 folding, control the strike of the gneissic foliation throughout the Basement.

FIG. 64 Plunge of F3(basement) fold axes(x) and poles to F3 axial surfaces(•)

Area : B (basement-fig 51)
N : x 58
• 30

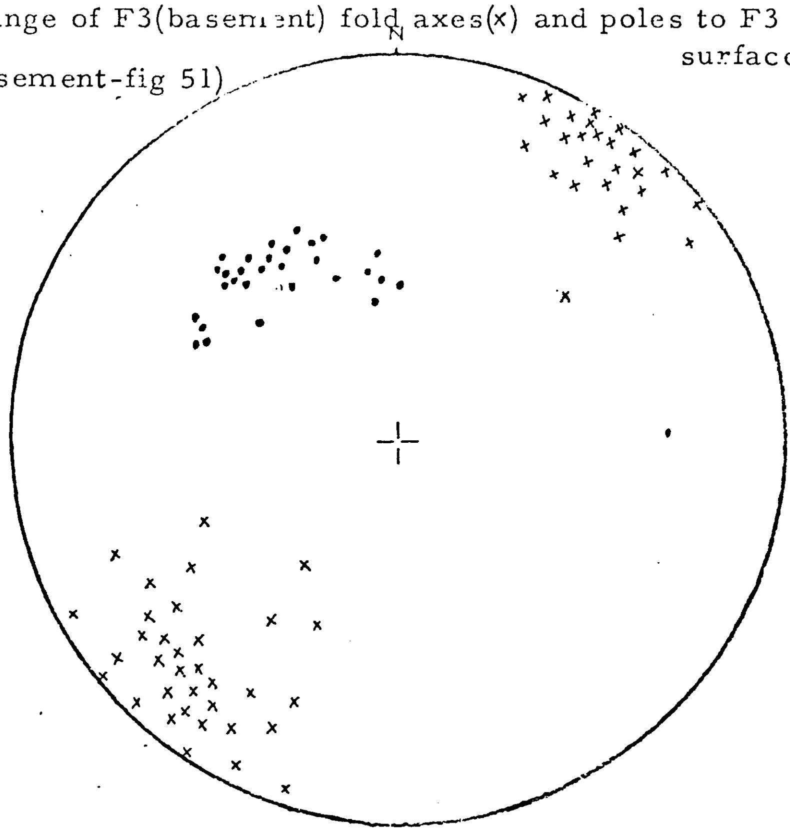
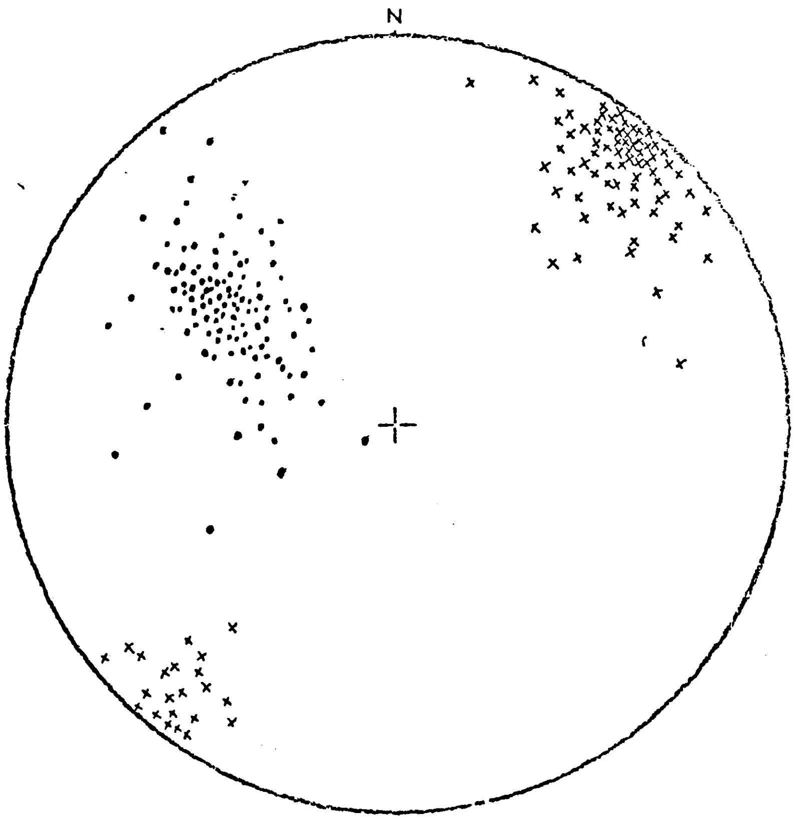


FIG.65 Plunge of F3 (basement)fold axes (x) and poles to F3 axial surfaces (•)

Area : A (basement-fig 51)
N : x 113
• 102



lower hemisphere
equal area
stereographic projection

2. Pegmatite Intrusion

Rare thin pegmatites are intruded parallel to the axial planes of F3 folds. They do not contain a deformation fabric.

3. Thrusting

D3 thrusting controls the distribution of the major Tectonic Units discussed (Basement, Mixed Gneiss Unit, Eggjane Nappe, Lower Bergsdalen Nappe) and is consequently of major importance in the structural chronology of the region. Thus, the regional D3 thrusting will be described in a separate section.

4.3 Mixed Gneiss Tectonic Unit

Introduction

The Mixed Gneiss unit outcrops immediately beneath the Eggjane Nappe (fig 18) and has nearly everywhere D3 thrust contacts with it, and the underlying Basement Gneiss. Vegetation covers much of the Mixed Gneisses (compared with the excellent exposure of the surrounding gneisses), and so forms a very obvious feature, both from the air and the ground (plate . 5) The outcrop of the unit is never greater than 400m wide, but it runs parallel to the regional linear features for most of the length of the area mapped. (fig 18)

The Mixed Gneisses can be studied in detail in the new road cuttings near Skreii (03206 67117).

The Mixed Gneisses are considered here as a separate tectonic unit for two reasons:

1. Diverse lithologies - the unit contains elements of Basement, Bergsdalen Nappe and Eggjane Nappe character. (section 2.5).
2. The Mixed Gneisses are tectonically juxtaposed against Basement Gneisses by an early (D1) slide. (section 4.3b)

Structural History

The precise age and nature of the "mixing" of the various gneiss units within this tectonic unit is unknown; the age can be tied down no further than being prior to D1, as the first recognisable major deformation is considered to affect the Mixed Gneisses pervasively. This is suggested, despite the extreme flattening suffered by the variable lithologies, because of the close similarity in style and orientation of the structures observed in all 3 of the major lithologic units, the biotite-epidote-hornblende gneisses, Banded Gneisses and Quartzofeldspathic gneisses. The end products of this D1 deformation is the generation of a highly flattened composite fabric, which contains intrafolial folds cut by axial planar pegmatites and granites (plate 34)
Locally, small areas of lower strain allow some knowledge of

the earlier structural histories for individual lithologies to be deduced:

4.3a <u>Deformation, D "early"; Production of S "early"</u>

No detailed structural history can be described due to the patchy nature of the evidence and the difficulties involved in correlation from one area to another. Evidence for these early structures has only been obtained from the Banded Gneisses and Basement gneisses within the Mixed Gneiss tectonic unit.

The elements that together are considered as D "early", and define S "early" were observed in differing intensities within both lithologies and will thus be described as one:

1. thin amphibolite and biotitic lenses
2. aplitic, pegmatitic and granitic veins
3. calcitic, calc-silicate and dioritic bands (only in (Banded Gneisses)
4. isoclinal folding and flattening

The S "early" fabric is well developed, with a strong gneissic texture defined by biotite and hornblende in variable proportions, depending upon the lithology. The fabric, especially in the Banded Gneisses is accentuated by small (several cm), very thin biotite and hornblende lenses, that are invariably concordant to the other elements of the fabric, such as the narrow calcitic, calc-silicate and dioritic bands (section 6) and the aplitic,

pegmatitic and granitic bodies and veins (plate 34)
The granitic bodies are similar in appearance to the D2 granites seen within the Basement gneisses (section 2.2a): however, in detail there are differences, as the D "early" granites of the Mixed Gneisses are not seen to exceed 15 cm in thickness, and contain a fabric defined by thin stringers and "ghosts" of biotite rich lenses. These early granites are deformed by D1 structures, which themselves have associated granites that are considered to be equivalent to the D2 (Basement) granites.

The aplitic and pegmatitic veins, which are rarely thicker than 2cm, are the best indicators of the S "early" fabric, recording some of the earlier complex tectono-metamorphic history that these gneisses must have undergone. The veins were intruded both concordant and oblique to, the S "early" foliation, and were flattened into it, due to subsequent pre D1 strain, with the development of both boudin and fold structures

Isoclinal folding is rare, and always on a very small scale. Rootless hinges defined by aplitic veins also occur. No orientation data was obtained for the folding.

The final stages of the D "early" deformation is characterised by a period of high strain, with the development of small scale shear zones that juxtapose the various elements that together form S "early". The shears are invariably concordant to S "early".

4.3b <u>Deformation, D1; Production of F1, L1 and S1</u>

This first pervasive deformation is thought to generate the regional fabric of the Mixed Gneisses tectonic unit, which is subsequently modified but does not lose its inherent character, i.e. that of being flaggy, commonly splitting along planes no thicker than 5cm.

D1 structures are invariably observed on only a small scale, although one important structure, a D1 slide zone has been mapped for a short distance.

The following sequence of events has been recorded:

1. Folding, lineation
2. Pegmatites and granite bodies intruded
3. Flattening and generation of the slide

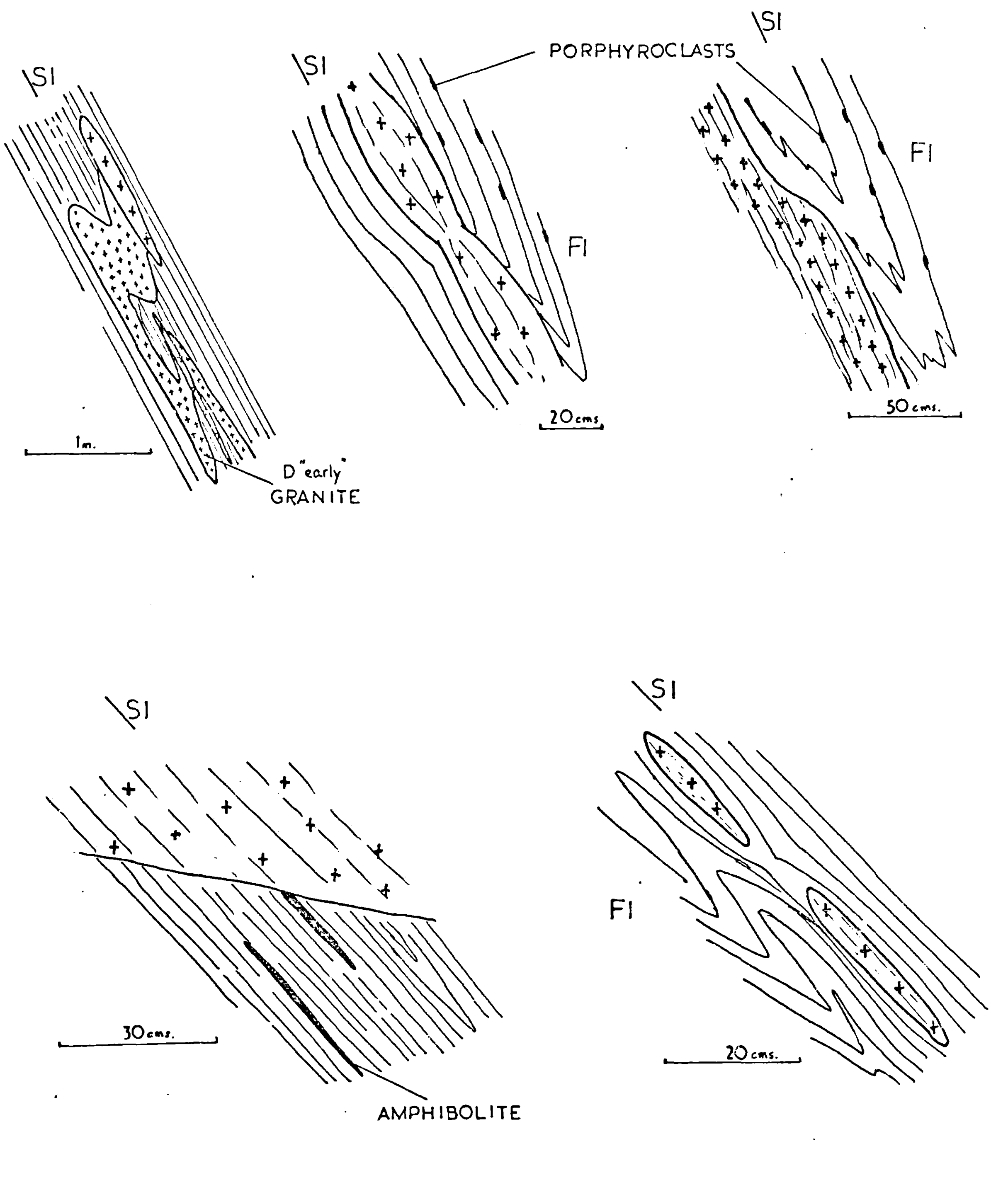
1. <u>Folding (F1), lineation (L1) and schistosity, S1</u>

F1 deforms the S "early" fabric into folds of variable profile depending on lithology and subsequent deformation (plates 34, 35) Most commonly, F1 is tight to isoclinal, although rarely it is more open. An axial planar schistosity (S1) is developed, defined by biotites and hornblendes; however, the intrafolial nature of the folding results in the schistosity only being obvious in the hinge regions of the F1 folds. Consequently, the new fabric generated is derived from the transposition of S "early" in conjunction with recrystallisation parallel to the S1 schistosity. Everywhere, the intersection of this schistosity with S "early" produces a north easterly trending shape fabric lineation defined by ellipsoidal quartzofeldspathic aggregates (L1). Similarly, F1 plunges at a very low angle towards either the north east or south west. Axial planes dip towards the south east at low angles, unless modified by subsequent folding.

2. Pegmatites and Granite Bodies

Axial planar pegmatites are very common associates of F1 (plates 35, 38) in all of the lithologies, cutting out fold limbs and hinges (fig 66). Pegmatites vary from being thin strings up to bodies 1 metre thick. The style of intrusion is very similar to that seen within the Basement during D2. (section 4.2c). Pegmatites oblique to the axial surface occur only rarely. Granite bodies, of homogeneous appearance, up to 2m in thickness are seen throughout the Mixed Gneiss tectonic unit. They are intruded into all lithologies indiscriminately. Discordant margins are not common, but when seen often exhibit an axial planar attitude to the D1 structures. (fig 66)

FIG. 66 The relationship between granite intrusions, S1 and F1 in the Mixed Gneiss tectonic unit.



However, more irregular intrusions, and rare inclusions are also seen (plates 36, 37) Several bodies may be traced for many kilometres locally defining tight subsequent folding.

3. Flattening

As inferred above, F1 folds, and the associated pegmatitic and granitic intrusions suffered a phase of flattening that imparted a strong fabric upon the intrusives and left the folds intrafolial. The fabric generated within the intrusives (S1) is concordant to that of the gneisses, and is defined by orientated biotite. In addition, the pegmatites are locally boudinaged.

Where the gneisses have remained limb regions for both D "early" and D1, the superimposed flattening has generated a true mylonitic foliation, which locally includes porphyroclasts of white feldspar (plate 39)

A D1 age is also given for the generation of a slide that juxtaposes the Mixed Gneisses against the underlying Basement Gneisses. The age of the slide is deduced from the involvement of D1 structures which may or may not be flattened, and its subsequent D2 folding.

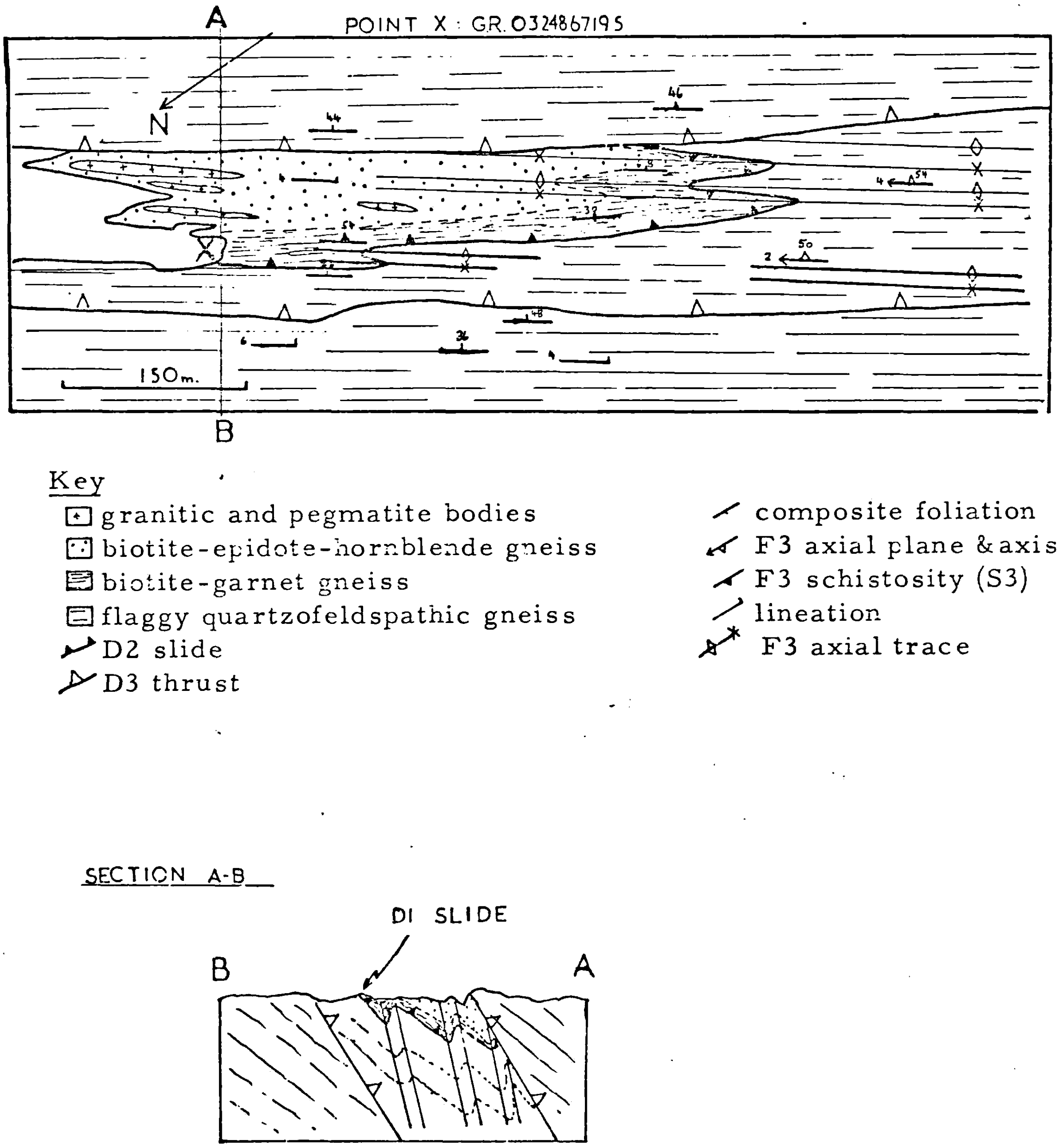
The tectonic contact between Basement gneiss and Biotite gneiss (part of the Banded Gneiss lithology) of the Mixed Gneiss tectonic unit has been followed for 600m, (1km NW of Eggjane, 0324667153).

The Basement Gneiss has suffered D2 (basement) flattening, as indicated by the presence of isoclinal folding with axial planar granites and pegmatites; it is separated from the main body of the flattened Basement gneiss by a D3 basement thrust. The unit of Basement Gneiss under consideration is progressively more intensely flattened through a thickness of 2-3 metres, until finally it takes on the appearance of a flaggy acid gneiss (1m thick) with a rusty brown weathering colour. (plates 40, 41). The flaggy partings (2.5cm thick) dip uniformly at $34^{o}/132$. The flaggy acid gneiss is overlain, with a slight discordance (6^{o}) by a more massive Banded Gneiss, rich in biotite, and with occasional garnet. The banding is isoclinally folded with occasional axial planar pegmatites, and a strong axial planar schistosity, which dips at $40^{o}/126^{o}$.

Thus an isoclinally folded Banded Gneiss discordantly overlies a very flaggy unfolded unit of Basement gneiss. The contact is deformed on a large scale by D3 (basement) folds, which are themselves involved in subsequent thrusting. (fig 67)

The contact is interpreted as a slide, the sense of movement relative to the structure is unknown; it carries Banded Gneisses and the other lithologies of the Mixed Gneisses over the relatively homogeneous Basement gneisses. There is no variation in structural trends across the slide.

FIG.67 The D1 slide between the basement gneisses and the Mixed gneisses.



4.3c Deformation D2; Production of F2, L2 and S2

The second pervasive deformation accounts for the present strike and distribution of lithologies. Structures are found on a medium to large scale, and are closely linked with the introduction of the Eggjane Nappe. (section 4.6a). This association with thrusting is reflected in the variable style of the structures, according to their position relative to the thrusts. Thus, the following structural sequence has been recognised:

1. folding, lineation and schistosity
2. pegmatite intrusion
3. thrusting

1. Folding (F2), Lineation (L2) and Schistosity (S2)

The small scale elements that define S1, along with the slide, are seen to be deformed by folds of variable profile on all scales. The slide is traced around an F2 synform (fig 67), while D1 granites can similarly be traced around fold noses. Axial traces of closed to tight F2 folds have been mapped (fig 67) within the Mixed Gneisses. The rounded hinges are perfectly cylindrical, with a parallel, well developed fold mullion (plate 42) and intersection lineation (L2); this is defined by orientated biotites and hornblendes, which have recrystallised to form a schistosity (S2) that is recognised primarily in hinge zones. Axial surfaces to the folds dip consistently at moderate angles towards the southeast . These structures are very similar to D3 folds within the Basement; the correlation is confirmed where Basement gneisses directly underlie the Mixed Gneisses, in the southwest of the area - both are deformed by the same fold structure.

F2 folds are modified in the vicinity of thrusts by a reduction in the interlimb angle, in association with the development of a more angular hinge zone . The effect of this flattening is to generate a transposed fabric, which, along with the schistosity, produces a well defined S2 foliation.

Where granite or pegmatite bodies are involved in the folding, two features are noted; a) boudinage of the body is common, resulting in the deformation of the S1 fabric (especially within the granites (plate 43) b) the S2 schistosity is readily generated in the granite; this can be of variable intensity - either an almost total overprint of S1, or as discrete planar mylonitic bands, slightly oblique to S1.

The granite and pegmatite bodies have well defined shape fabric lineations generated by the superimposition of the schistosities. The lineation has an identical orientation to L2 in the gneisses.

2. Pegmatite Intrusion

Thin pegmatites locally (especially in the southwest of the area) lie along the axial planes of some D2 folds; in one instance, this was cross cutting to both a folded D1 granite and pegmatite.

3. Thrusting

The outcrop pattern of the Mixed Gneiss tectonic unit is largely controlled by thrusts of D2 age; these thrusts are associated with the emplacement of the Nappes, and so will be discussed elsewhere in more detail. (section 4.6a)

Discussion

The Mixed Gneiss tectonic unit provides a dilemma, with its "mèlange" of Basement Gneiss, Eggjane Gneisses and Banded gneiss. These three lithologies are derived from 3 distinct tectonic units, that regionally are termed; autochthonous basement, Eggjane Nappe, and Lower Bergsdalen Nappe. Therefore, if an understanding of the relationships between these units within the Mixed gneisses can be obtained, it could shed light on the large scale relationships.

A correlation may be made between the Basement Gneisses within the Mixed Gneisses, and that of the autochthon. An important structural "marker" is represented by the characteristic intrusion of the granite and pegmatite bodies, and the generation of their internal fabric. This occurred during D2 in the Basement and D1 in the Mixed Gneisses. The correlation is assisted by the consistent orientation of structural data within the two units. Similarly, it has been shown that D2 in the Mixed Gneisses correlates undoubtedly with D3 in the Basement. (fig 92)

Evidence from the Mixed Gneisses points to the following facts:

1. Banded Gneisses and Basement Gneisses have similar styles of early structures, with no obvious differences.
2. Banded Gneisses, Eggjane Gneisses and Basement Gneisses have been deformed in the same environment during both D1 and D2.
3. A tectonic restacking of the units occurred at the end of D1.

Therefore, it can be assumed that the individual units within the Mixed Gneisses were juxtaposed prior to D2 in the Basement, which has been dated as a Sveconorwegian deformation (section 4.2c). Correlation between older structures is much more difficult, although there is little doubt that D "early" in the Mixed Gneiss Basement gneisses is equivalent to D1 and possibly D "early" in the autochthonous Basement; correlation with the D "early" structures of the Mixed Gneiss, Banded Gneisses is debatable, but not to be ignored, especially with the similarity of structures.

4.4 The Eggjane Nappe

The Eggjane Nappe, which is composed of hornblende gneisses and biotite-epidote gneisses, along with subordinate Banded Gneisses, quartz-diorites gneissose and Basement gneisses, forms a continuous unit that runs from Bjørnfjell in the southwest, to the limit of the mapped area on the flank of Dystingen in the northeast. The outcrop is approximately 15km in length, and has a consistent map width of 0.75km (fig 18). Exposure is excellent, forming a prominent feature for the whole length of outcrop.

The Eggjane Nappe has a lower thrust contact with the Mixed Gneiss tectonic unit, and is structurally overlain by tectonic schists (phyllonites). The nappe is approximately 300 metres thick. A sequence of structural events has been deduced for the hornblende and biotite-epidote gneisses that form the main body of the nappe. The outcrop of the subordinate units is limited, and no early history has been recorded. All of the units have been deformed by both structures generated during the first deformational phase, and subsequent deformation.

4.4a <u>Deformation, D "early"</u>

The first pervasive fabric recorded is that which incorporates features ascribed to D "early". The following elements together form D "early"; they are described in a tentative order of events:

1. Intrusion of a quartz-diorite (?) body into Basal Gneisses, precursor to the biotite-epidote gneiss and the hornblende gneiss. (Section 2.8)

2. Intrusion of amphibolites
3. Isoclinal folding and mineral lineation
4. Intrusion of pegmatites, aplites, quartz veins and dioritic segregations.
5. Flattening, development of a foliation.

1. It is postulated that a body of quartz-diorite was intruded into a sequence of basal gneisses. This is suspected from the presence of minor horizons of quartzofeldspathic gneiss within the body that are invariably concordant to the foliation. In addition, epidote quartzofeldspathic gneiss bands within the quartzofeldspathic gneisses in the basement immediately below the Eggjane Nappe are superficially very similar in appearance to the Eggjane gneisses.

2. Intrusion of amphibolites: thin amphibolitic lenses are a common feature within the banding that defines the foliation of the Eggjane gneisses. At one location, (plate 44) a D "early" amphibolite occurs as small elongate pods (<10cm) that are strung out defining S1. These early amphibolites are invariably parallel to an early foliation and are never seen to be cut by the D "early" aplites.

There is no evidence as to whether the quartz-diorite body had suffered any deformation prior to the intrusion of the amphibolites.

3. Isoclinal folding, and lineation (L "early")

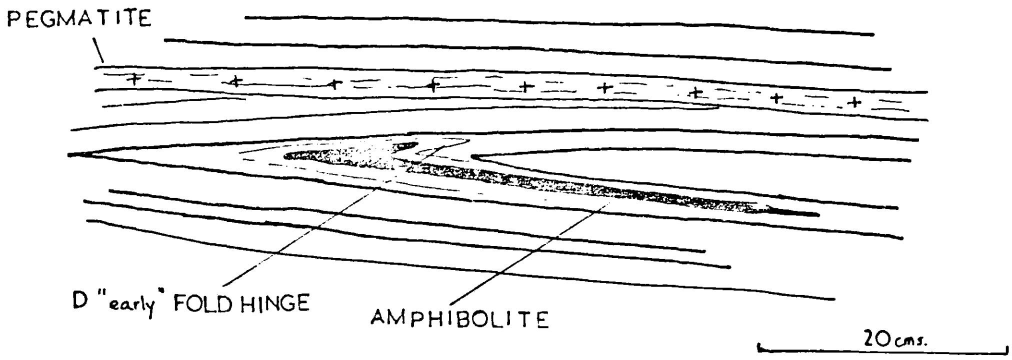
Evidence for D "early" isoclinal folding is restricted to one exposure within the new road cuttings immediately to the north of Skreii (0320667115). A small scale F1 intrafolial isocline is defined by the aplite veins of D "early"; in the hinge region, there is a type 2 (Ramsay 1967) interference pattern, defined by an amphibolite unit. The D "early" aplites are not involved in the interference pattern, suggesting that they post date the early isocline. (fig 68).

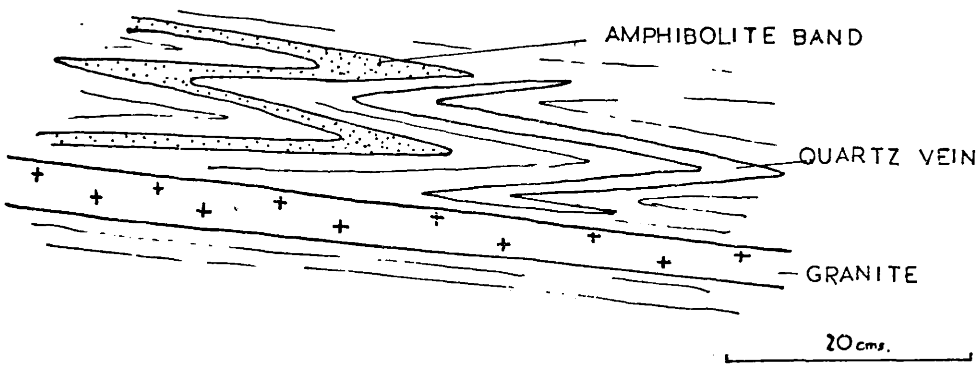
A lineation, defined by the intersection of biotites, hornblendes and epidotes with the S1 foliation is sporadically observed throughout the gneisses of the nappe. The dominant trend of this D "early" lineation is towards the eastern and southern quadrant (fig 69) Invariably, it is overprinted by the subsequent northeasterly trending lineations.

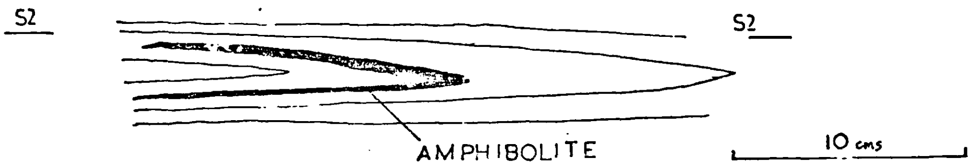
4. Intrusion of pegmatites, aplites, quartz veins and dioritic bands

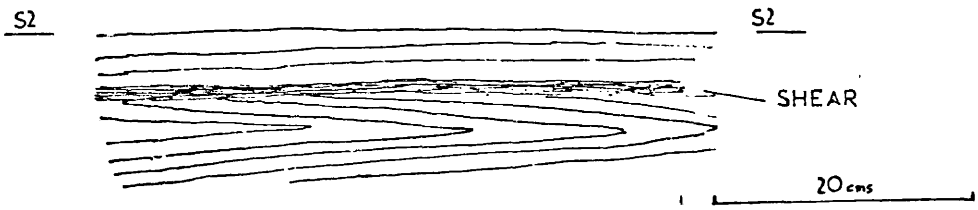
Thin pegmatites (<10cm thick), aplites (<1cm thick) and quartz veins (<1cm thick) form an integral part of the D "early" history. They are invariably parallel to the later foliation, and act as important markers within the moderately homogeneous hornblende and biotite-epidote gneisses. Thin veins of dioritic segregation are also seen; they have a zone (<5mm thick) entirely of plagioclase

FIG. 58 Field sketches of F1 folds from the Eggjane Nappe









and minor quartz either in the centre or at the margin of the vein. (fig 73). Hornblende and plagioclase make up the remainder of the veins, which are rarely thicker than 3cm. The veins are rarely extensive on outcrop scale.

5. Flattening, generation of S "early"

All of the structures ascribed to D "early" have been flattened into a foliation, termed S "early". The flattening appears to have been pervasive and intense.

It is difficult to locate the general trend of structures within the D "early" deformational phase, although the sporadic early (fig 69) lineations (L1) suggest that there was, in part, an east-west axis involved, in contrast to all of the subsequent northeasterly trending structures.

4.4b Deformation D1, Production of F1, S1 and L1

Only small scale structures of this age are recognised; however, they are developed throughout the Nappe, in all of the lithologies. The following sequence of events has been deduced:

1. (amphibolite intrusion)
2. isoclinal folding, lineation, schistosity
3. intrusion of axial planar pegmatites and granites
4. flattening and boudinage-generation of foliation S2

FIG. 69 Plunge of the D "early" lineation in the Eggjane Gneiss

Area : Eggjane Nappe (fig 51)
N : 27

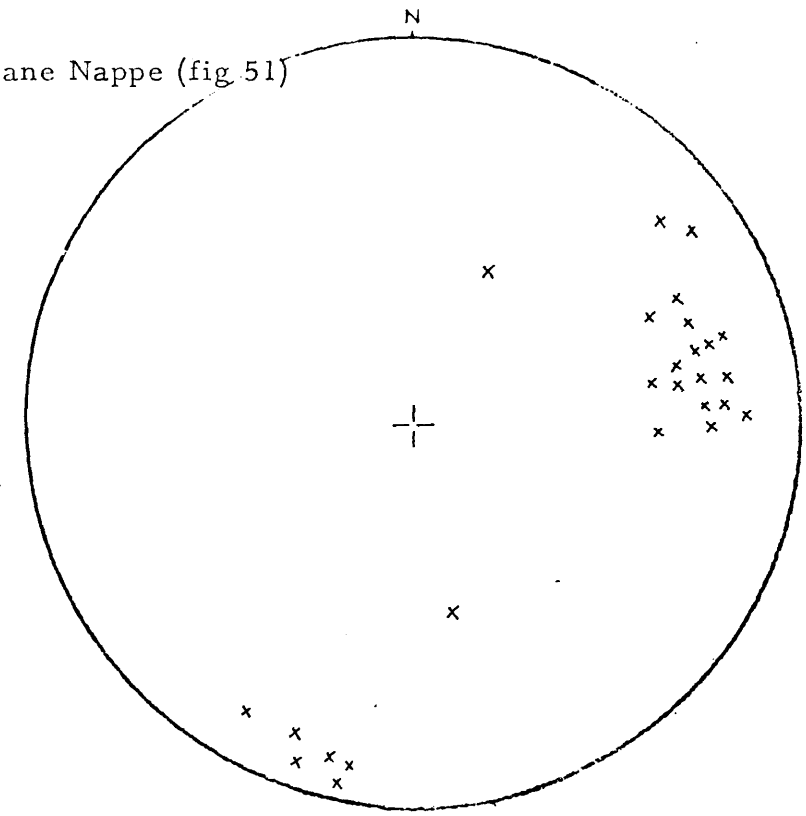
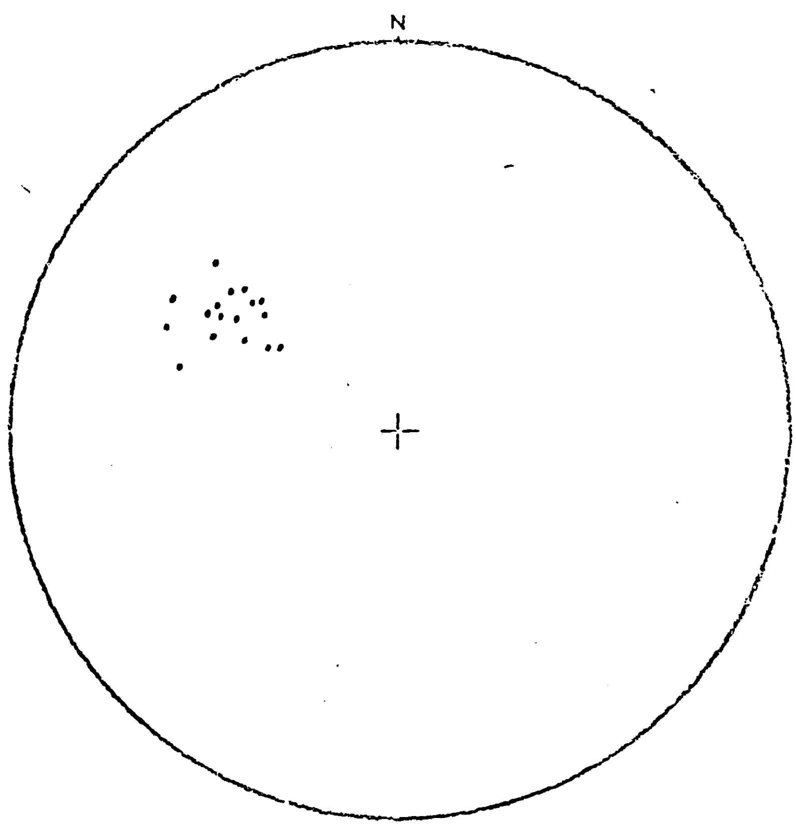


FIG. 70 Poles to D3 thrust planes in the Basement Complex

Area A& B (basement-fig 51)
N : 17



lower hemisphere
equal area
stereographic projection

1. Amphibolite Intrusion

Small amphibolite bodies are fairly common within the gneisses of the Eggjane Nappe, and are often on a scale suitable for mapping; invariably they are parallel to the composite foliation.
Deformation subsequent to the intrusion of the amphibolites has masked nearly everywhere, the original nature of the contact with the gneisses. The only evidence for the timing of the intrusion has been observed along the new road section to the north of Skreii (0320667115). At this exposure (plate 45) a low angle discordance between the S1 gneissic foliation containing D "early" aplites, and the amphibolite contact can be seen; the contact is not sheared. The margin of the amphibolite is typified by thin stringers passing into the gneiss, both parallel and sub-parallel to the foliation.

2. Isoclinal folding (F1), schistosity (S1), Lineation (L1)

Folding (F1) of the second deformation is everywhere observed on a small scale; nowhere has an axial trace of a large F1 fold been mapped. F1 deforms the S1 foliation, along with the early D1 amphibolites. (fig 68). The folding is intrafolial, tight to isoclinal, with the limbs forming part of the composite S1 fabric. An axial planar schistosity (S1) is developed in the hinge region of the folds, defined by biotite and hornblende.

A minimal amount of data has been collected for the orientation of F1 folds, although locally an intersection lineation between the S1 schistosity and the foliation trends to the northeast. This, however, has subsequently been intensified by the production of a coaxial fold set (D2), and extreme difficulties arise in identifying a uniquely D1 lineation.

3. <u>Intrusion of pegmatites and granites</u>

Axial planar pegmatites, and locally, granites are common associates of the F1 folds. The granites are very homogeneous texturally, and are very similar in appearance to the D2 granites within the Basement.

The pegmatites and granites show the same style of intrusion, so will be described together (plate 46)

Typically, the pegmatites are under 30cm in thickness, although some may be up to 2m. They are intruded along the axial planes of the folds, and are thus cross cutting to the D "early" structures and the D1 amphibolites, in the nose regions of the F1 folds. Away from the fold hinges, it is difficult to distinguish D "early" and D1 pegmatites, as both sets are conformable to the composite foliation. (fig 68)

Locally, D1 pegmatites are seen to have been intruded at an angle to the F1 axial plane; subsequently they are flattened into the composite foliation.

<u>Flattening, production of the regional composite foliation (S1)</u>

Evidence for flattening of the D2 structures is very common; all of the

D2 granites and pegmatites exhibit a strong LS fabric parallel to their margins. On the basis of shape fabric, it is estimated that the nature of the strain was oblate. This fabric is parallel to the enveloping composite foliation, and is homogeneous across the thickness of the intrusive bodies, with marginal shearing. The acid bodies are often boudinaged in a chocolate tablet form.

The effect of the flattening is to produce a very flaggy foliation within the gneisses of the Eggjane Nappe (plate 47) that is developed ubiquitously, apart from occasional small areas that have preserved earlier structures.

4.4c Deformation, D2; Production of F2, S2 and L2

Structures associated with the third deformation are ubiquitous, and can be seen on all scales in all of the gneissic units of the Eggjane Nappe.

The following sequence of events has been deduced:

1. folding, production of a lineation and schistosity
2. thrusting

1. Folding (F2), Lineation (L2), Schistosity (S2)

From the mapping it can be seen that the Eggjane Nappe is a large scale F2 antiformal fold that has had its lower limb, and part of the hinge zone removed by thrusting (map 3)

The D2 flaggy composite foliation (S2) with the typical intrafolial folds accompanied by axial planar pegmatites, is deformed by closed to tight overturned folds (F2) with axes that plunge at a low angle consistently towards 040^{o}, and axial planes that strike to the north east (fig 71) with a moderate dip (40^{o}- 50^{o}). The folds verge everywhere towards the northwest. Individual axial traces can be mapped for many kilometres (map 2) demonstrating the cylindricity of the folding.

Fold hinges exhibit a weak axial planar schistocity defined by the shape orientated growth of biotite and hornblende. However, a very strong lineation (L2) occurs on S2 foliation surfaces, defined by crystallographically orientated biotites, epidotes and hornblendes, along with elongate lensoidal aggregates of quartz and feldspar. This is everywhere plunge parallel to the F2 folding, but is the product of two sets of coaxial folding (F1 and F2). (fig 72)
A fold mullion lineation is also produced by the parallel orientation of small scale tight F2 hinges.

Occasional thin pegmatites and quartz veins lie axial planar to F2 structures.

2. Thrusting

The Eggjane Nappe is bounded below and above by thrusts that cut out F2 folds. (map 2). The nature of associated mylonites differs,

FIG.71 Plunge of F2 fold axes (x) and poles to F2 axial surfaces (•) in the Eggjane Gneisses

Area : Eggjane Nappe (fig 51)
N : x 75
• 94

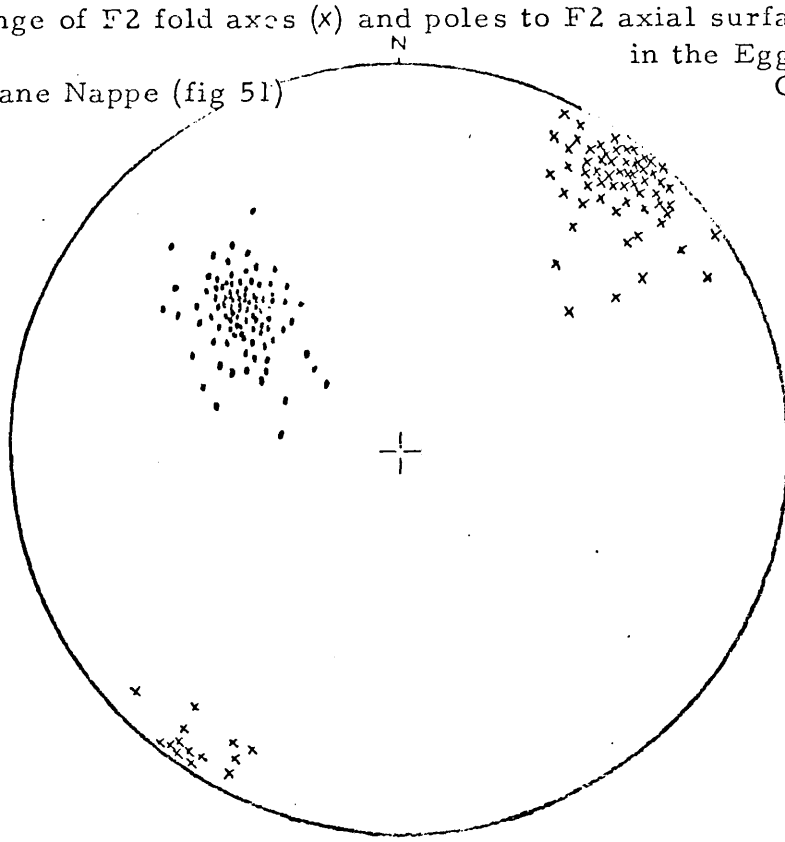
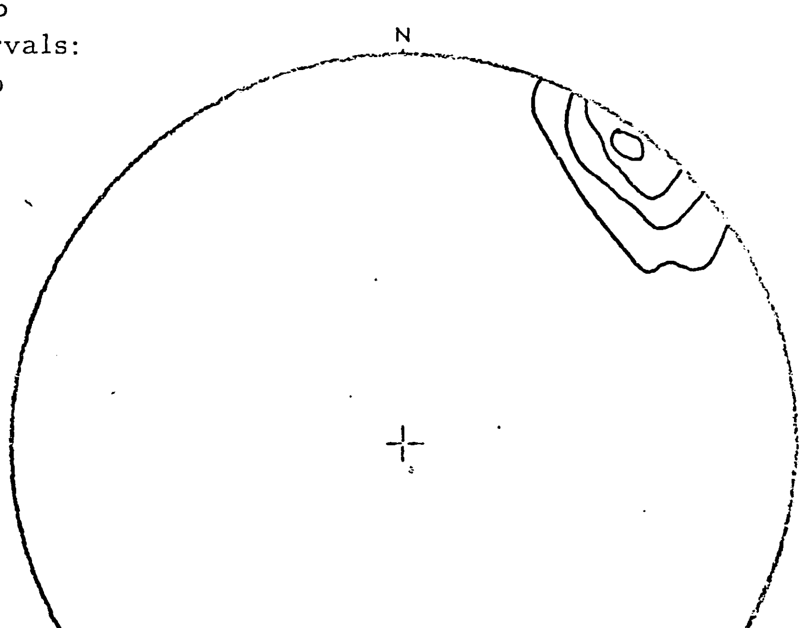


FIG.72 Plunge of the L2 lineation in the Eggjane Gneisses

Area : Eggjane Nappe (fig 51)
N : 135
contour intervals:
1, 5, 20, 60 %



lower hemisphere
equal area
stereographic projection

with a ductile, highly flattened mylonite gneiss below the nappe and a tectonic schist (phyllonite) above. The thrusting and its features are discussed in detail elsewhere (section 4.6).

4.5 The Lower Bergsdalen Nappe

The Lower Bergsdalen Nappe is one tectonic unit stacked within a pile of nappes; (fig 7) throughout it has a similar structural sequence, the various deformation phases being correlated using intrusive granite bodies as relative time markers. The most obvious variation through the nappe is an increase in the degree of development of D3 structures as one progresses to structurally higher levels (i.e. from northwest to southeast).

The Lower Bergsdalen Nappe is itself restacked by a minor phase of thrusting, with the result that a unit comprising mainly quartzite and granite is carried over the predominantly Banded Gneiss lithologies (map 3); thus the structures of the quartzites and granites have been studied in the southwest of the area, and can be compared with those structures seen in the large tract of Banded Gneisses.

The structural history is described in two parts:

1. Pre-nappe emplacement structures
2. Post-nappe emplacement structures.

1. Pre-nappe Emplacement Structures

Most of the lithologies of the Lower Bergsdalen Nappe have suffered intensive deformation and recrystallisation (section 5.4) so that early structures are rarely seen. The Banded Gneisses, amphibolites and gneissose quartz diorites are, in this context, the most problematic rocks, while the quartzites and granites, having undergone less deformation, are more simple.

4.5a Deformation, D "early"

The earliest history involving the Banded Gneisses, amphibolites and gneissose quartz diorites is described:

introduction of the gneissose quartz diorite { 1. colour banding in the Banded Gneisses, with interbanding of amphibolites
2. isoclinal folding
3. intrusion of dioritic, calc-silicate and quartz veining
4. ? quartzite deposition

Colour Banding (S "early")

A banding between predominantly fine grained grey biotite gneiss, a fine to medium grained biotite schist, fine to medium grained greenish biotite-hornblende gneiss and a dark green fine grained amphibolite occurs on all scales from centimetres to metres (plate 11). The large scale interbanding of the mapped amphibolite bodies and the Banded Gneisses is also a primary feature.

No structures that may be interpreted as either depositional or volcanological have been recorded, and the nature of the banding is thus unknown.

Isoclinal folding

Evidence from only 2 exposures along the Voss road in Bergsdalen, suggests that the colour banding underwent an early phase of isoclinal folding (fig 73), making the banding a composite feature. The very early age for the small scale isoclines is suggested because they are cross cut, by axial planar calc-silicate veins that represent the end stage of the D "early" phase. (section 6.1). Elsewhere, the calc-silicate veins are isoclinally folded, forming part of the regional Banded Gneiss foliation. (plates 48, 49)

At one location, a lineation is associated with these early folds, plunging towards the east north east, and overprinted by a north easterly trending lineation.

Intrusion of the gneissose quartz diorite

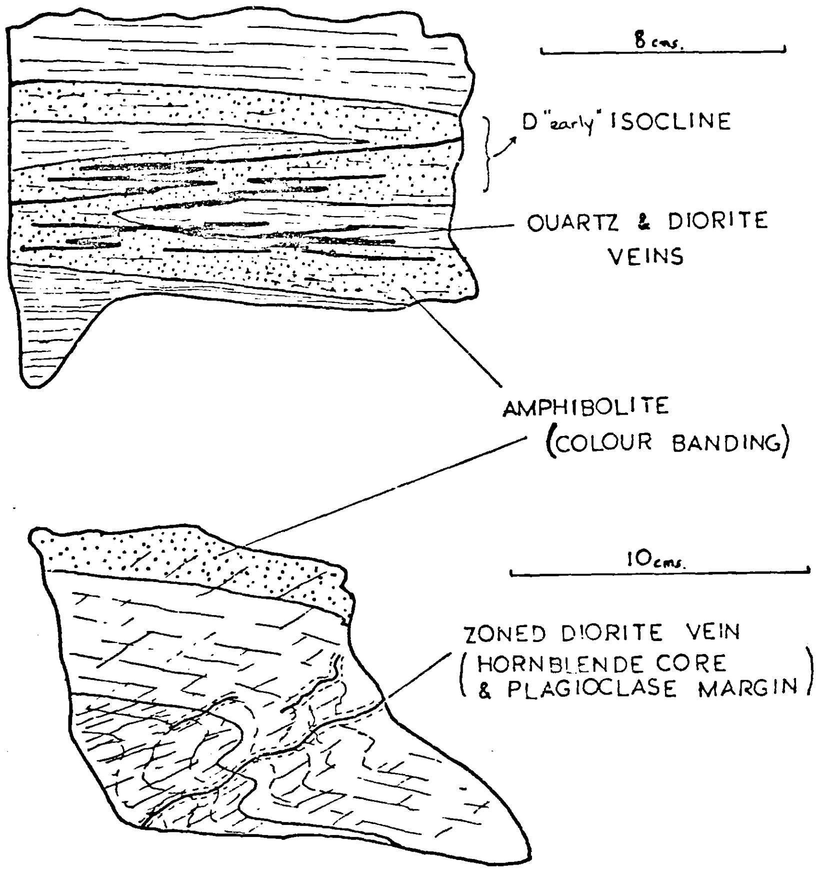
The age of intrusion of the quartz- diorite is problematical; it is itself intruded by the late D "early" dioritic and calc-silicate veins, yet has a concordant contact with the Banded Gneisses. It appears that the quartz diorites were intruded into the stack of Banded Gneisses either during, or before, the isoclinal folding.

Dioritic, calc-silicate and quartz veining

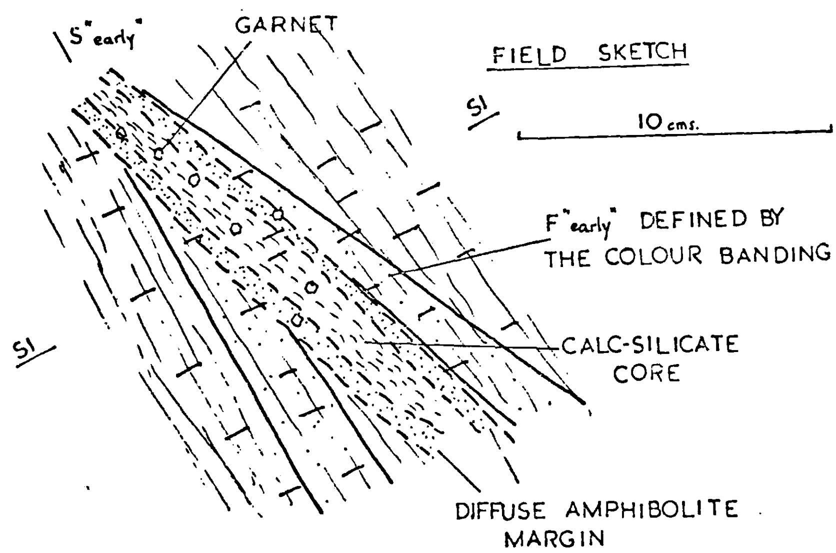
The Banded Gneisses, gneissose quartz-diorites and amphibolites are all intruded by dioritic, calc-silicate (section 6) and quartz

FIG. 73 Relationship of calc-alkaline and dioritic veins to D "early" structures.

Drawn from hand specimens:



Segregated calc-silicate vein :



veins. These veins are absent from the quartzites, granites and gabbros. None of the veins exceed a few centimetres in thickness, and are now seen as discontinuous lenses parallel to the colour banding fabric.

The dioritic veins are axial planar to the early folds (fig 73) and are locally zoned on a small scale, with hornblende cores and plagioclase margins.

? Quartzite deposition

Evidence for the age of deposition of the Bergsdalen quartzites, in relation to the deformational phases undergone by the Banded Gneisses is inconclusive. The extensive quartzite bodies within the Lower Bergsdalen Nappe have not been investigated during this study, but deductions are based on evidence from smaller bodies of limited outcrop.

Comparison with the evidence given by other workers (Gray 1978), (Evans & Winter pers. comm 1978) suggests that the structural history of the quartzites is the same throughout the nappe. There is no evidence for any D "early" events within the quartzites; instead they have a relatively simple history that is initiated by synchronous isoclinal folding and granite intrusion.

It is therefore postulated that the quartzites lie unconformably on the

Banded Gneisses, with deposition or tectonic introduction (section 7) post dating the D "early" phase, but pre-dating D1 in the history of the Nappe.

4.5b Deformation, D1; Production of F1, S1

Evidence for this deformation is pervasive, although always observed on a small scale. Similar structures are recorded throughout all of the lithologies (including the quartzites) of the Lower Bergsdalen Nappe, excepting the granite plutons.

The following sequence of events has been recorded:

1. isoclinal folding (F1), production of S1 } gabbro and
2. shearing } amphibolite intrusion
3. pegmatite and granite intrusion
4. flattening

The position of the basic intrusives in this sequence is problematical. Kvale (1946) describes the metagabbros as intrusive into a banding in the quartzites, yet they are, on field evidence clearly older than the D1 granites. Field evidence further suggests that F1 isoclines deform the sedimentary banding of the quartzites; therefore the gabbros must be intruded into either a sedimentary banding or a tectonic banding, i.e. either pre- or syn-F1, but pre-granite.

Rare basic units in the Banded Gneisses, other than the amphibolites of the banding, including some small metagabbro units, do not contain the D "early" veining, despite its presence in adjacent lithologies. However, these bodies share the regional foliation with the enveloping gneisses, implying that they were intruded after the D "early" phase, yet prior to the main fabric forming event and granite intrusion of D1.

1. Isoclinal folding (F1) and production of S1

In the Banded Gneisses and associated lithologies, the S "early" fabrics containing the elements: colour banding, dioritic, calc-silicate and quartz veining, is seen to be isoclinally folded on a small scale (F1) (plates 48, 49). In the quartzites, the compositional sedimentary banding (with rare cross bedding (Kvale 1946)) is also isoclinally folded on a small scale.

A new schistosity (S1) is developed parallel to the axial planes of the F1 structures, and is observed in hinge zones. In limb regions, the S1 foliation is composite with S "early".

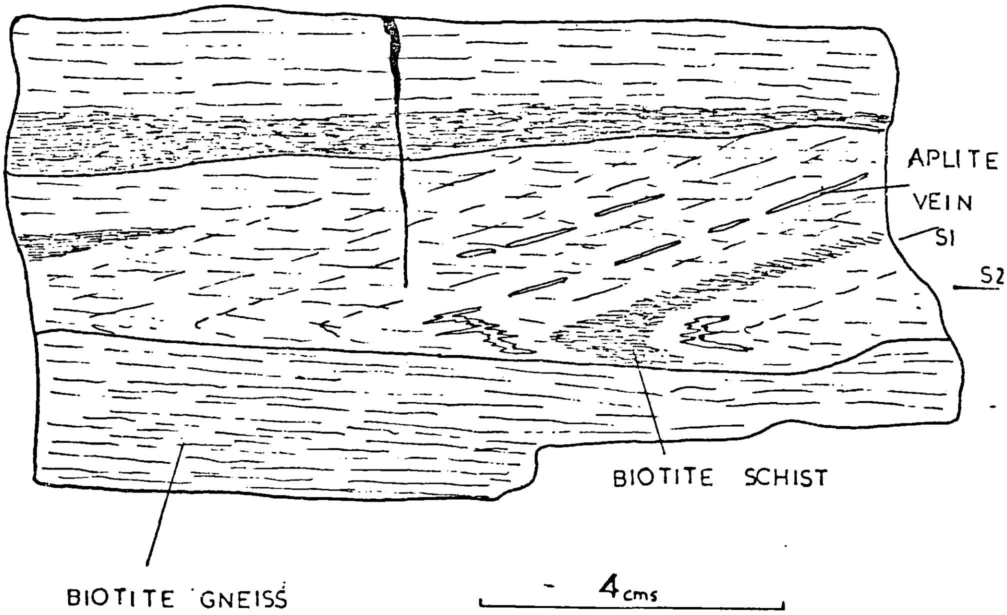
2. Shearing

The long limbs of F1 folds are locally (in all lithologies) replaced by very narrow (less than 1cm) small scale shear planes. This feature is most common in the quartzites, resulting in complete or partial preservation of relic F1 hinges between the planar elements (fig 74). In quartzites this may locally be mistaken for cross bedding.

FIG 74

F1 sheared out fold in biotite gneiss (Banded Gneisses), Lower Bergsdalen Nappe.

(drawn from hand specimen)



3. Pegmatites and granite intrusion

Thin (<10cm) veins occur in all of the lithologies, although they are less common in the gneissose quartz diorites and quartzites. The pegmatite veins are most commonly cross cutting, but axial planar to F1 folds, occurring often along shear zones.

Granite bodies form structural markers within the Lower Bergsdalen Nappe, and outcrop over extensive areas. In the area mapped, the granite bodies are intrusive into the Banded Gneisses and the quartzites. The relative age of intrusion is readily observed in the quartzites (Gray 1978, Evans and Winter 1978 pers. comm.) where they cross cut F1 structures (fig 25). However, evidence for their age relative to the Banded Gneisses is less obvious. Nearly everywhere the granite/Banded Gneiss contact is concordant (fig 25) with strings of granite localised adjacent to the margins of the main granite bodies. Most outcrops provide evidence that the granite was intruded prior to the development of the regional foliation. However, at one location (GR 0333767178) an isoclinal fold (F1) can be seen cross cut by a thick granite body. Similarly, in the new road section in Bergsdalen, about 1km northwest from Bergevatnet (GR 0334467183), the granite net veins (plate 50) altered Banded Gneisses (section 6.3). Granite stringers running from the main body cross cut isoclinally folded D "early" calc-silicate veins. (plate 101)

The pegmatites and granites intrude the early D1 basic bodies.

4. Flattening and the enhancement of S1

The S1 schistosity that developed in hinge regions of F1 is enhanced by S "early" colour banding and the S1 shearing. However, it is even further enhanced by a flattening that generated a gneissose fabric in the granite and pegmatite bodies. All of the elements together form the composite S1 foliation, which lay parallel or sub parallel to the XY plane of the D1 strain ellipsoid. Thus a composite foliation involving gneisses and flattened granites is generated and constitutes the regional fabric throughout the Lower Bergsdalen Nappe.

Discussion of deformation, D1

The orientation of the F1 folding is problematical. Despite the association of a strong schistosity, as recorded in hinge zones, nowhere is a lineation seen that can be ascribed uniquely to F1. There are three possible explanations:

1. no lineation was produced
2. the lineation associated with F1 had an orientation oblique to subsequent folding, but was entirely destroyed by that subsequent folding.
3. the lineation is coaxial with subsequent folding; thus a composite or enhanced lineation is seen, but is always ascribed to a younger fold phase.

Total destruction of the lineation, if it were oblique to subsequent deformational trends would be unusual, rather evidence for refolding and local preservation of the lineation would be expected. It is therefore concluded that a D1 lineation was coaxial with L1 (section 4.5c). Thus, F1 probably had an axial trend similar to F2, i.e. north-east/south-west.

4.5c Deformation, D2; Production of F2, S2 and L1

Second phase deformation structures form an important element in the development of the Lower Bergsdalen Nappe. In the Banded Gneisses, the D2 structures are the most common feature observed, and have an important control on the present distribution of lithologies. Similarly, the granites and quartzites of the higher structural units, seen in the southwest of the area above a D3 thrust (map 3) have also suffered considerable D2 deformation. However, cross correlation of deformation structures of the structurally higher granites and quartzites with D2 in the Banded Gneisses is not immediately obvious although structural styles are superficially similar.

As a consequence the structural history of the central and northern portions of the Lower Bergsdalen Nappe will be discussed separately, where necessary, from that of the granites and quartzites of the southwest margin.

The elements that together form S1 are ubiquitously deformed by D2 on both the large and small scale.

The following sequence of events is recorded:

1. folding, schistosity and lineation production
2. quartz vein intrusions (local)
3. thrusting

1. Folding (F2), schistosity (S2) and lineation (L1)

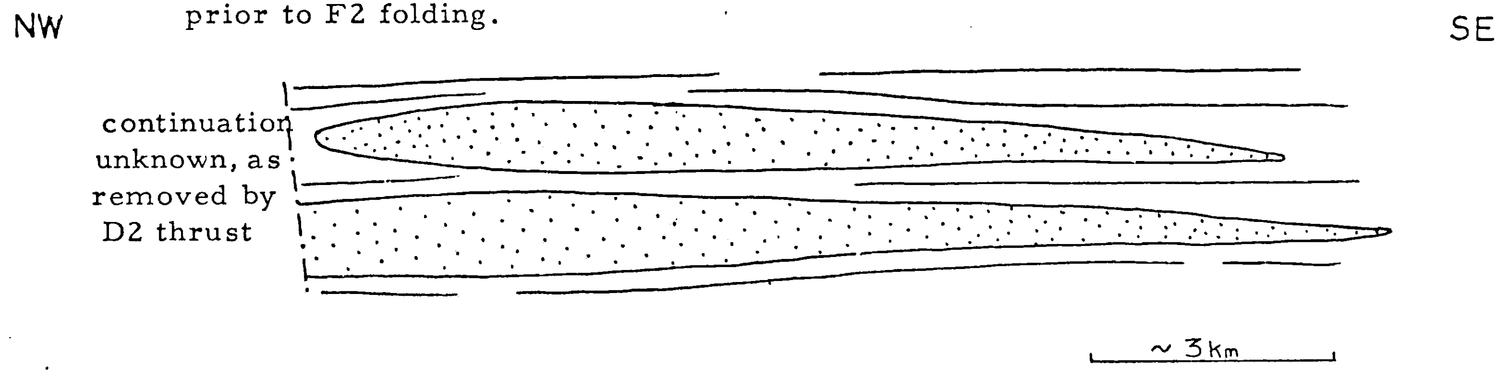
A regional, tight, F2 antiformal and synformal structure involves the large tract of Banded Gneisses and amphibolites that crop out in the central portion of the Lower Bergsdalen Nappe. This, together with subsequent large scale folding in the Bergsdalen area, has produced a complex outcrop pattern (fig 23 and map 1)

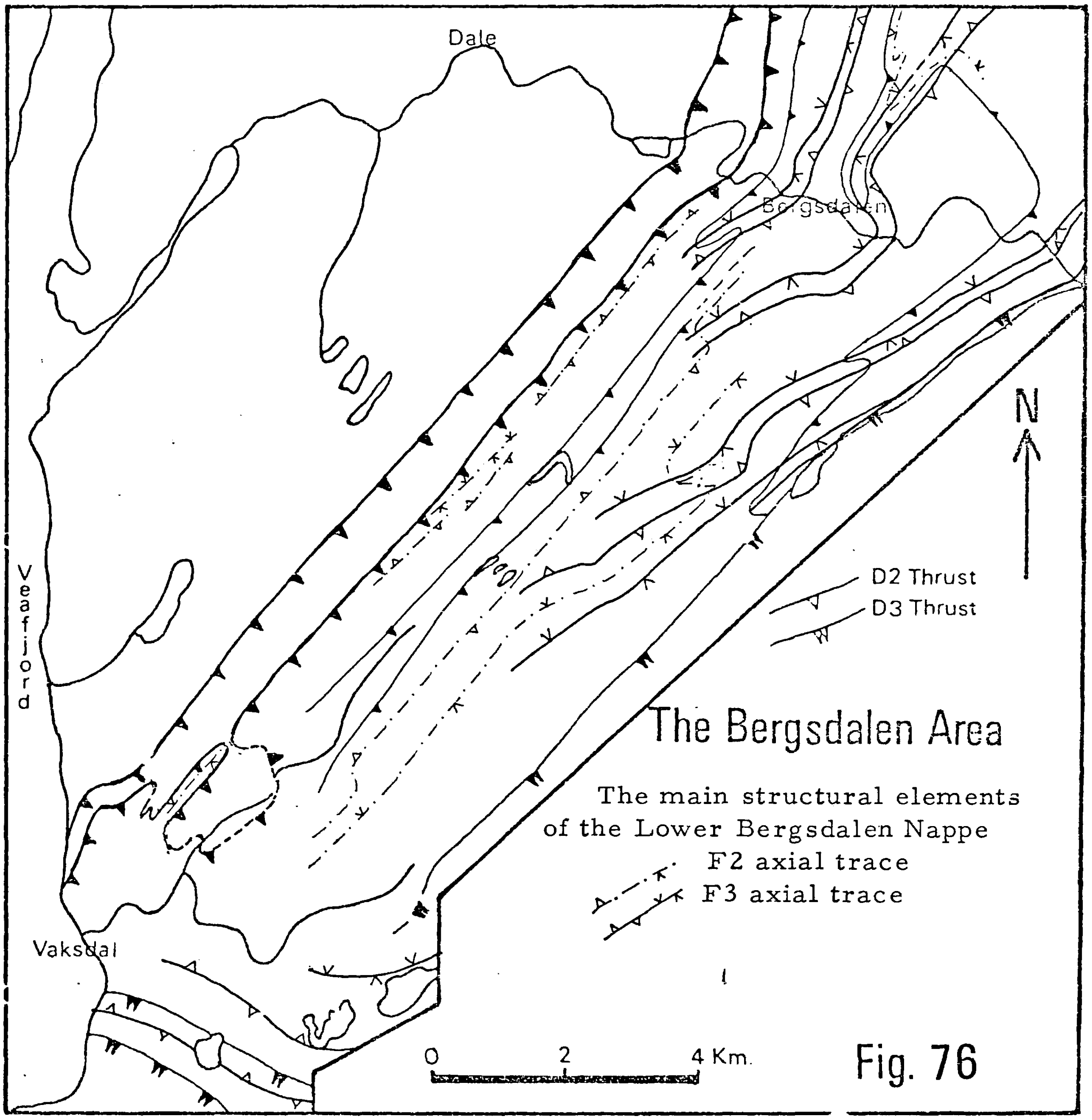
The fold pair is defined by the outcrop of the large amphibolite bodies; (fig 23) removal of the effects of this folding reveals the two amphibolite bodies as separated, stacked one above the other, with a slight offset (fig 75). The recognition of two amphibolite bodies could either be a primary feature, perhaps representing two lava flows, or separate intrusive bodies, or more likely the effects of tectonic restacking during earlier deformational phases.

In addition to the antiform and synform, other large scale D2 fold hinges are preserved, tectonically disrupted within the highly tectonised lower part of the Lower Bergsdalen Nappe. (fig 76)

FIG.75

Diagrammatic section of the Amphibolite bodies in the Lower Bergsdalen Nappe, prior to F2 folding.





Dale
Bergsdalen
Veafjord
Vaksdal
N
D2 Thrust
D3 Thrust
The Bergsdalen Area
The main structural elements
of the Lower Bergsdalen Nappe
F2 axial trace
F3 axial trace
0
2
4 Km.

Fig. 76

The large scale structures with a wavelength of about 2km are overturned towards the northwest, and plunge at a low angle to the northeast. The long limb common to the antiform and synform dips at 12^o-20^o to the southeast whilst the overturned limb dips at 40^o - 50^o also to the southeast.

Parasitic small scale folds are very common in the hinge regions of the large structures, but are rare on the shallow long limbs. The small scale harmonic F2 folding is tight (plate 51) with an average interlimb angle of 30^o, and a profile geometry approximately to class 111 (Ramsay 1967 p.367). The axes of the small scale folds plunge at a low angle towards both the northeast and southwest, and have axial surfaces dipping to the southeast at 30^o. (figs 77,79,81)These attitudes are modified by subsequent deformation in both the northeast and southwest of the area.

An axial planar schistosity (S2) is associated with the folding, being most pronounced in hinge regions; it is defined by the shape orientation of recrystallised biotites, hornblendes and quartzo-feldspathic aggregates. This, however, is much more poorly developed in limb regions. Associated pervasive linear structures (L1) always plunge parallel to the axes of the F2 folds. (fig 78, 80, 82)

FIG. 77 Poles to F2 axial surfaces (•) and plunge of fold axes (×) in the Lower Bergsdalen Nappe

Area : 1 (fig 51)
N : •79
×40

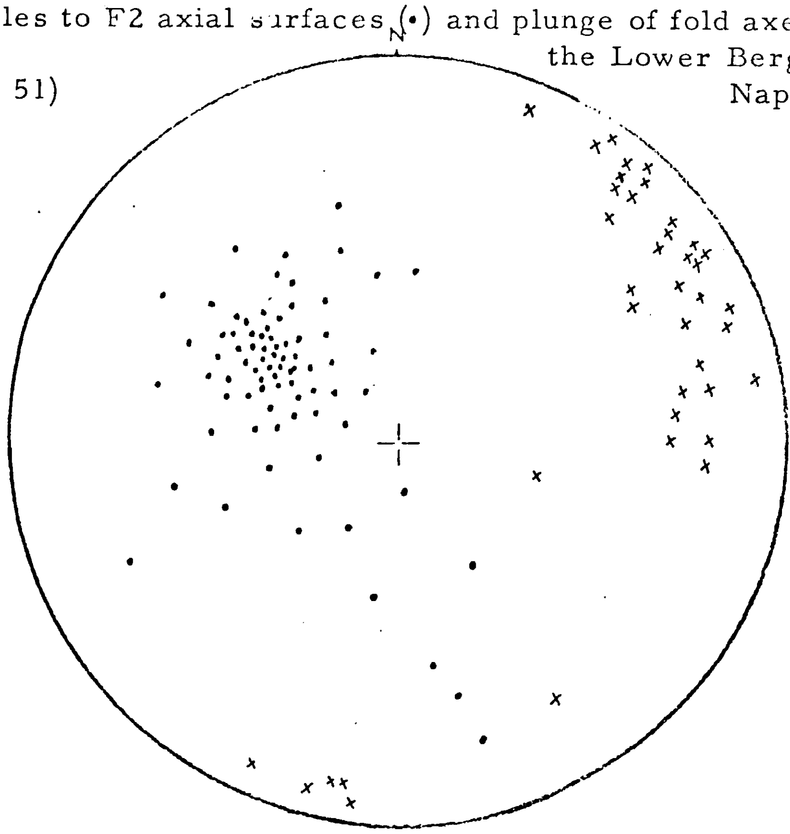
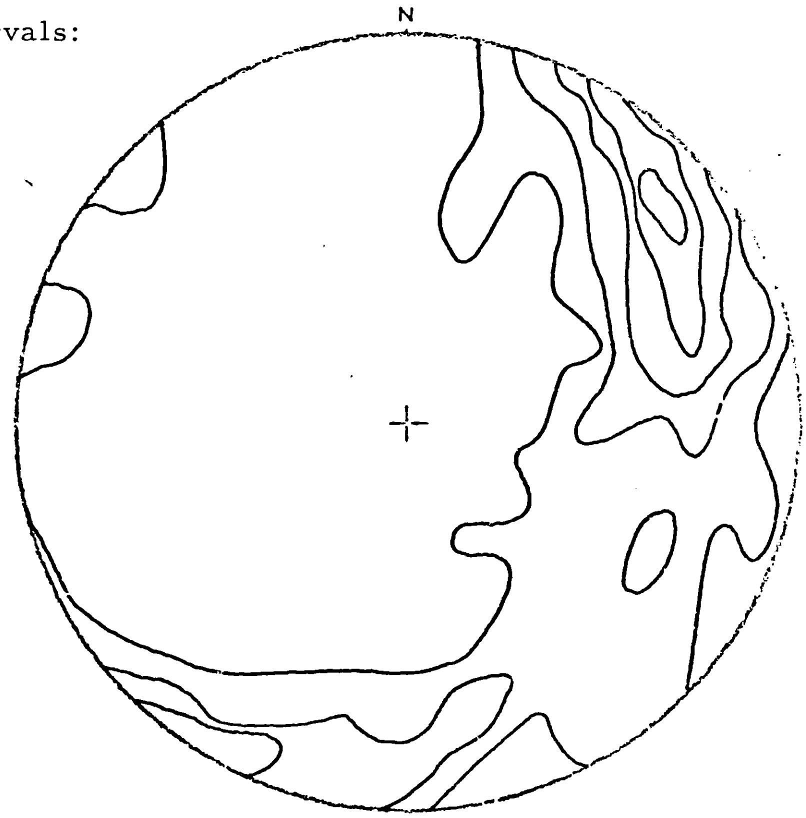


FIG.78 Plunge of lineation L1 in the Lower Bergsdalen Nappe

Area : 1 (fig 51)
N : 180
contour intervals:
$\frac{1}{2}$, 2, 4, 8, 14%



lower hemisphere
equal area
stereographic projection

FIG.79 Poles to F2 axial surfaces (•) and plunge of F2 fold axes (x) Lower Bergsdalen Nappe

Area : 2 (fig. 51)
N : •75
x67

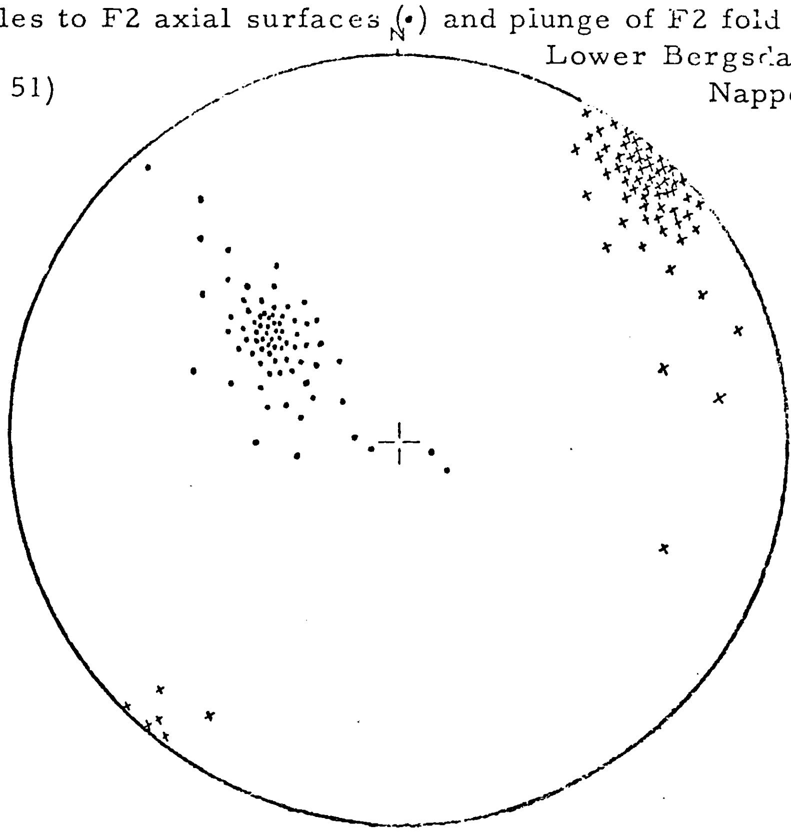
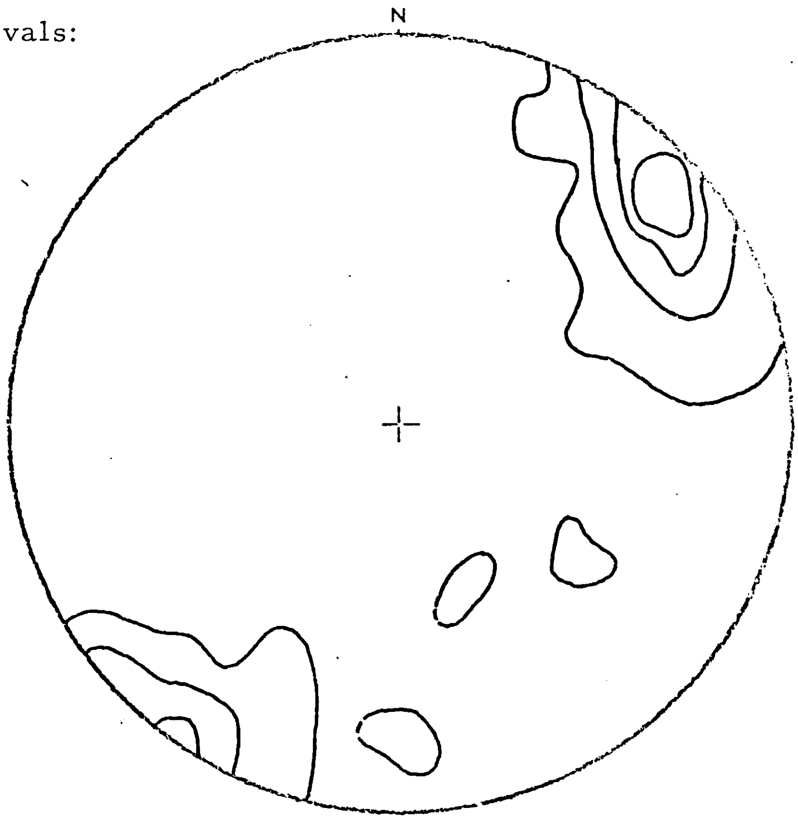


FIG.80 Plunge of lineation L1 in the Lower Bergsdalen Nappe

Area : 2 (fig. 51)
N : 124
contour intervals:
$\frac{1}{2}$, 4, 12, 16%



lower hemisphere
equal area
stereographic projection

FIG.81 Poles to F2 axial surfaces (•) and plunge of fold axes (x) in the Lower Bergsdalen Nappe

Area : 3 (fig. 51)
N : • 31
x 30

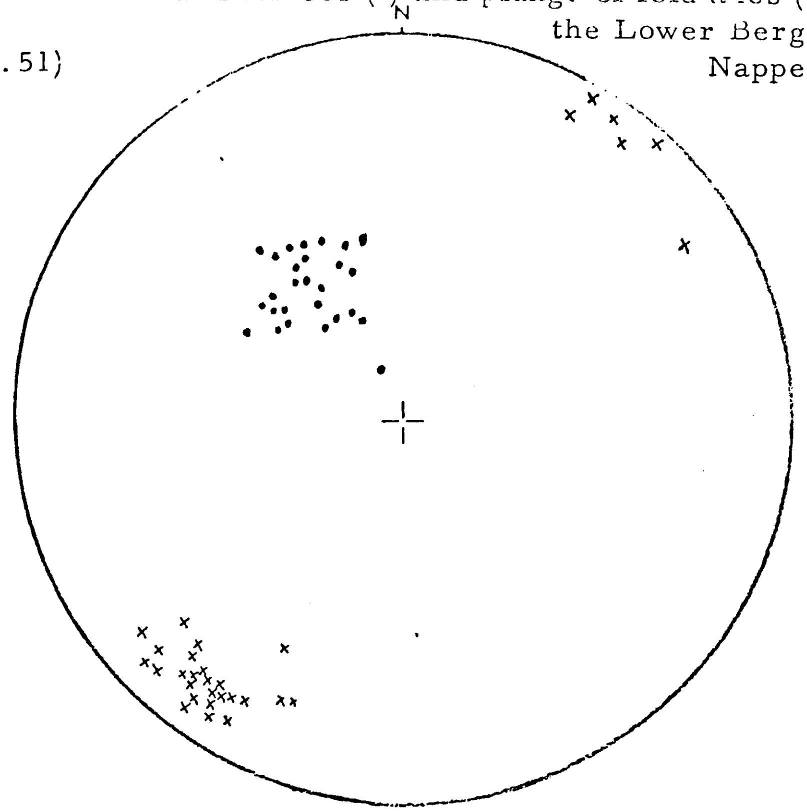
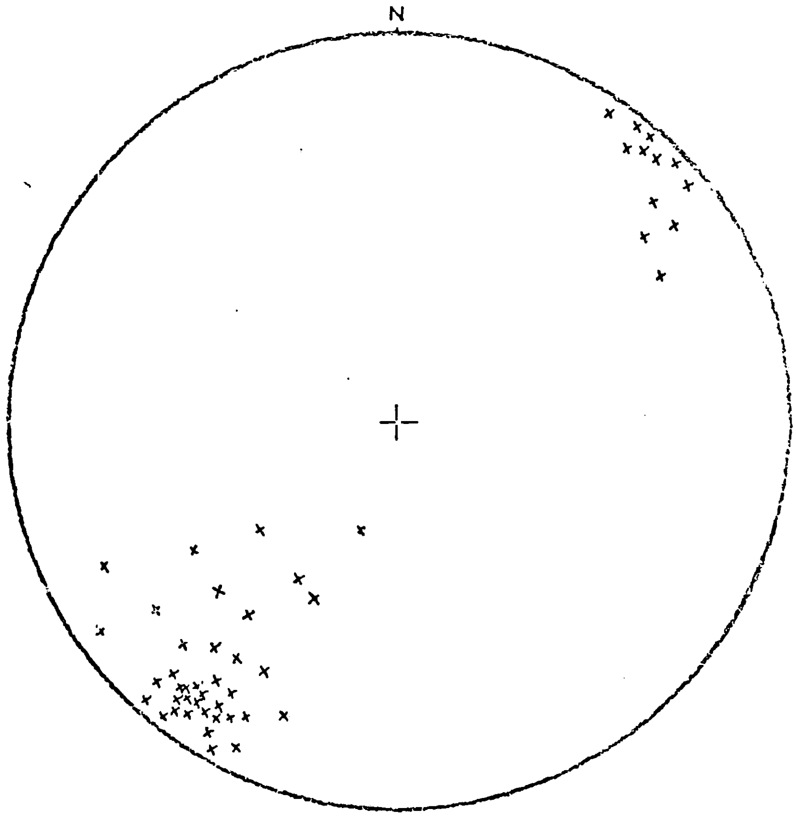


FIG. 82 Plunge of lineation L1 in the Lower Bergsdalen Nappe

Area : 3 (fig. 51)
N : 50



lower hemisphere
equal area
stereographic projection

Three varieties of linear structures are seen:

1. intersection of schistosity (S2) and foliation (S1) in the hinge region of parasitic folds; this is defined by the shape orientation of biotites and hornblendes.

2. very small scale F2 fold hinges locally define fold mullion linear structures

3. a combination of shape fabric and mineral lineation is common, being recognised in both hinge and limb regions. (plate 52). It is probable that this lineation is a composite feature, derived from coaxial deformation of the gneisses.

Fold styles vary only slightly with different lithologies; the major variation is observed in the granite body on Flatafjell (GR 0331667208), where small/medium scale tight folds deform the S1 gneissose fabric in the granite, generating a strong S2 axial planar schistosity, defined by elongate quartzofeldspathic aggregates and biotite. A strong shape fabric (L1) is formed by the intersection of S1 and S2. The fold axes (F2) and lineation (L1) have a trend compatible with that of the country rocks.

D2 in the Granites and quartzites of the Vaksdal region

The granites and quartzites lie structurally above the Banded Gneisses and amphibolites of the central and northern portions of the Bergsdalen area, and are separated from them by a late (D3) thrust. The granites and quartzites (with minor Banded Gneisses and gabbros) form a prominent unit that can be traced south from

Bergsdalen (northwestern slopes of Bukkafjell) into the marginal Bergen Arc area around Vaksdal, where it is mapped in this study.

The unit becomes more complex as it is traced towards the Bergen Arcs, due to the combined effects of increased flattening and the superimposition of D4 folding. Work by D. Winter and J. Evans (pers. comm. 1978) indicates that the ubiquitous S1 fabric of the granites and quartzites in the Bergsdalen area is isoclinally folded by F2. In the Vaksdal region, mapping has not revealed any large scale F2 folding. Locally, within the quartzite, very small scale F1 isoclines are preserved within the S1 foliation, and these are folded by F2. The S1 fabric in the granites is also folded by these structures.

The F2 folds are invariably tight to isoclinal (plate 53) and have a well developed axial planar schistosity; in limb regions, the schistosity and the isoclinally folded S1 fabric together form a composite foliation; S2. This is sufficiently well developed to become the regional foliation in the Vaksdal region (page 261) The axial planar schistosity can locally be related to a strong shape fabric lineation on foliation surfaces.

Quartz veins

All of the rocks of the Lower Bergsdalen Nappe contain thin quartz veins (<2cm thick) that are commonly observed to cross cut the F2 folds. They are best developed in the granite bodies, both on Flatafjell and above Vaksdal, and also within the quartzites.

Thrusting

D2 thrusting controls the present location of the Lower Nappe units, and therefore will be described in detail, in section 4.6 b

Correlation of structures between the Banded Gneisses and the Granites and quartzites of Vaksdal

The correlation of the D2 structures from within the reworked granites and quartzites of the Vaksdal region with those from the Banded Gneisses (etc.) in the Bergsdalen area is based on the structures exhibited by the granite bodies.

The intrusive granite bodies of the Lower Bergsdalen Nappe are assumed to be of the same age; an assumption supported by radiometric dating (Pringle et al. 1975, Gray 1978). They therefore provide time markers. Everywhere the granites post date at least one set of isoclinal folds (Gray 1978, Winter & Evans pers. comm. 1978), yet have a fabric (S1) that is equivalent to the regional foliation (S1) within the Nappe. Thus, the first fabric generated within the granite (S1) forms an important structural marker, being recognised throughout the Lower Bergsdalen Nappe.

In the Bergsdalen area, below the late D3 thrust (map 3) the granite fabric (S1) is tightly folded by F2, often with the development of axial planar quartz veins (plate 53), a schistosity and a lineation. These features are also seen in the granites of the Bukkafjell area, above the D3 thrust (Winter & Evans pers. comm. 1978), although the folding is isoclinal, and a composite fabric (S2) is generated.

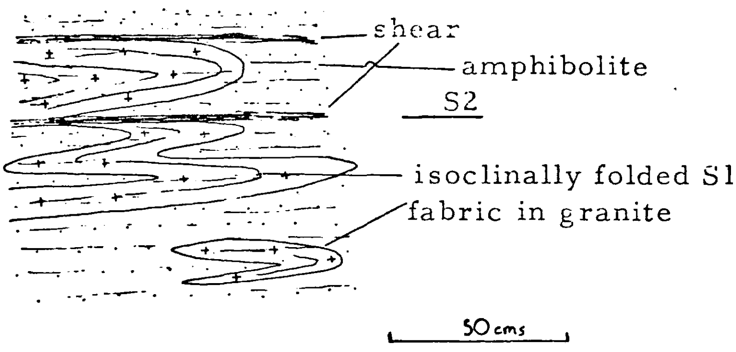
A reconnaissance study from this northern exposure of granites above the D3 thrust, towards the margin of the Bergen Arcs, suggests that there is no variation in the early structural history.

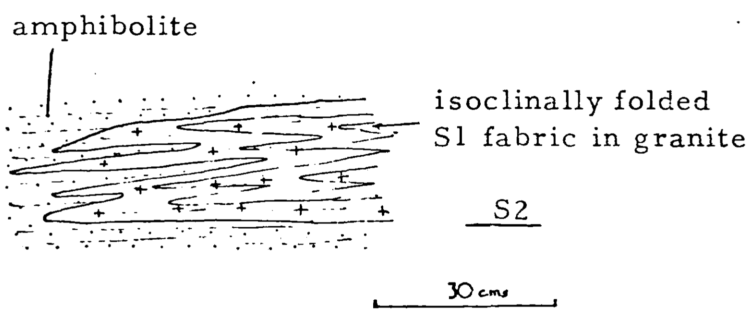
In the Vaksdal region, the granites differ from the other granites of the Lower Bergsdalen Nappe in possessing a much more pronounced fabric (part of the regional foliation), with prominent coplanar quartz veins. On first impression, this fabric could be interpreted as a more intense version of S1, as seen further north. However, locally the gneissic foliation is seen to be S2 in age, as it contains isoclines (F2) that deform the gneissic fabric S1 (fig 83) Thus, the gneissic foliation in the granites of the Vaksdal area is confirmed as equivalent to S2 elsewhere in the Lower Bergsdalen Nappe.

4.6 The Thrust Zones

In this section, field description of the thrust zone is followed by a

FIG 83 Field sketches of isoclinally folded D1 granite bodies, with S2 superimposed upon S1





description of the microscopic features of the associated mylonites and finally a discussion is given involving (a) an interpretation of the Lower Bergsdalen Thrust Zone - metasediments or phyllonites ? (b) the development of the phyllonites, and (c) emplacement of the nappes.

Field Description

Two distinct thrust zones have been recognised:

(a) The Eggjane Thrust Zone

(b) The Lower Bergsdalen Thrust Zone

These thrusts are not the two considered by Kvale (1946); he did not describe the Eggjane Thrust Zone but instead referred to two major schist zones (fig 21), "the zone of Cambro-Ordovician schists between migmatites and the Lower Overthrust mass" (p.78) which in this study, are shown to be part of the Lower Bergsdalen Thrust Zone.

4.6a) Eggjane Thrust Zone (fig 84)

The Eggjane thrust zone consists of 8 steeply dipping shear zones, developed entirely within the Basement Gneisses and Mixed Gneisses, overlain by the low lying Eggjane Thrust; this carries the Eggjane Nappe (Eggjane Gneisses, Banded Gneisses and quartz diorite gneiss - section 2.7) over the Basement Gneisses. The Basement thrusts and the Eggjane Thrust will be described separately.

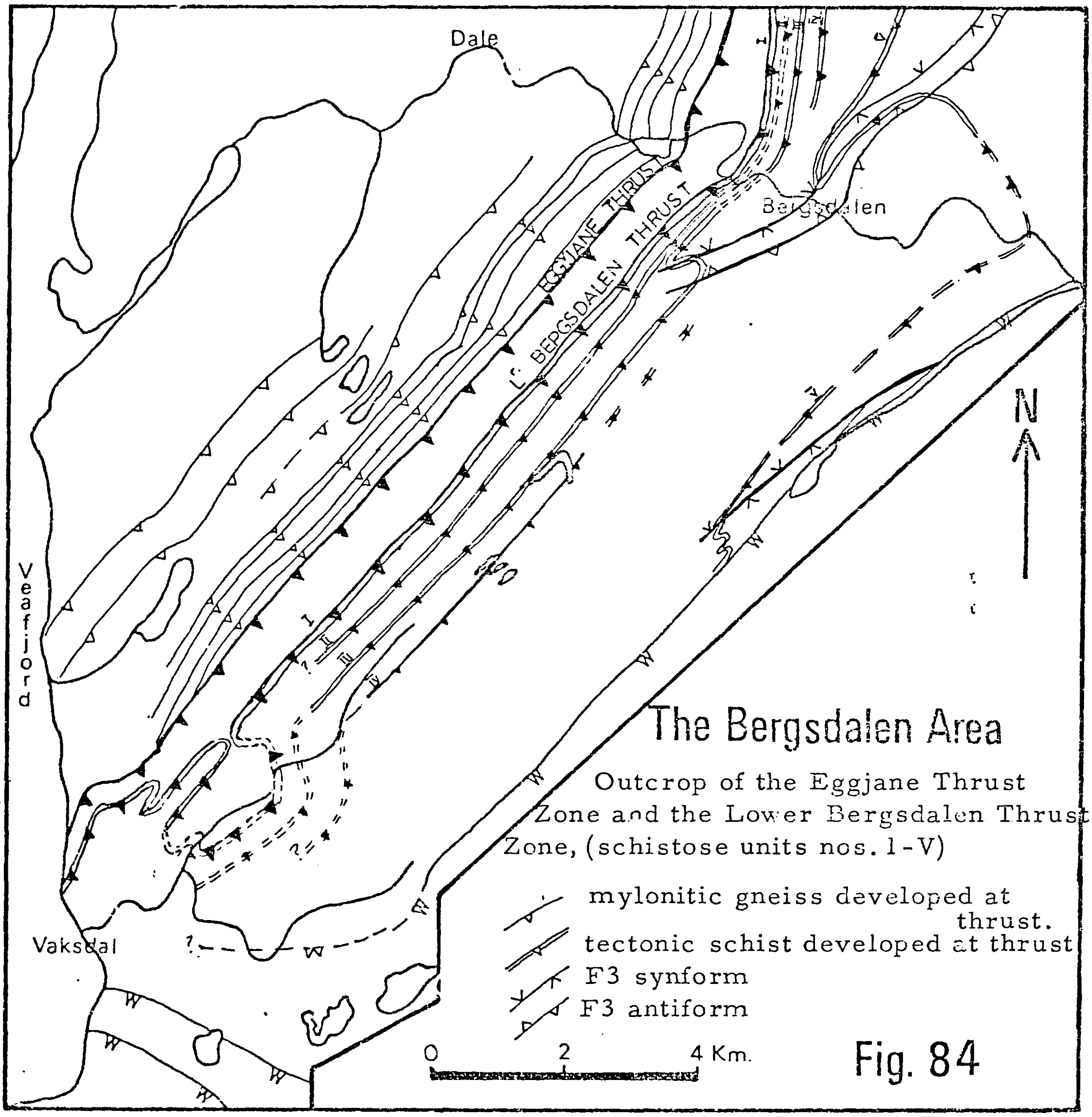

Dale
EGGJANE THRUST
L. BERGSDALEN THRUST
Bergsdalen
Veafjord
Vaksdal
I
II
III
V
N
The Bergsdalen Area
Outcrop of the Eggjane Thrust Zone and the Lower Bergsdalen Thrust Zone, (schistose units nos. 1-V)
mylonitic gneiss developed at thrust.
tectonic schist developed at thrust
F3 synform
F3 antiform
0
2
4 Km.

Fig. 84

1. Basement Thrusts: the Basement thrusts are distributed over a corridor 3km wide, becoming more intensely developed beneath the Eggjane Thrust (fig 84). The thrusts are observed in the field as negative topographic features (plate 54) with the flaggy mylonitic gneisses being readily eroded. These features can be traced for many kilometres and are readily recognised on aerial photographs. The thrusts have a strike parallel to the regional foliation (S2) and dip to the southeast between 40^{o} - 50^{o} (fig 70)

The Basement Thrusts are clearly developed by the shearing out of steep limbs, and hinge regions of large scale D3 folds (plate 55, 56) Traceable lithologic units are cut out by the thrusts. A good example has been mapped on the side of Dystingen (GR 0328667203), where a sizeable foliated granite body is folded into a medium scale D3 antiform; the steep limb of the antiform is missing, having been replaced by a thrust, which carries both the granite body and associated flattened Basement Gneisses over unflattened Basement Gneisses (plate 1 and fig 11). Movement along an individual thrust is confined to a zone rarely greater than 1 metre in thickness. A very flaggy mylonitic gneissic fabric (Sm) is developed parallel to the thrust zone. This fine to medium grained fabric (Sm) is produced by the reworking of the regional gneissic fabric (S2). The mylonitic fabric (Sm) retains a strong mineral lineation defined by orientated amphiboles and biotites, in conjunction with a shape fabric of elongate lenses of quartzo-feldspathic porphyroclasts. The lineation has the same north-easterly orientation as that of the local gneisses (L2). No internal folding has been recognised within the mylonitic gneissic foliation.

If the thrust is developed on the limb of an F3 fold, then the fabric (Sm) is purely an enhancement of the gneissic foliation (S2). However, where the thrust cross cuts the hinge region of an F3 fold, then the ductile nature of the shearing can be observed; the gneissic foliation (S2) is seen to be rotated into the plane of the thrust. The zone of rotation into Sm appears as an intense feature, never having been seen to exceed 5cm in thickness. (plate 55). Often an abrupt high angle junction between the gneissic foliation (S2) and the mylonitic gneiss fabric (Sm) is observed, with no evidence of rotation.

Locally, thin mafic units ($<$50cm) are involved in the thrusting and have developed a strong platey mylonitic fabric (Sm), which tends to weather easily; thus outcrops are rare. The fabric (Sm) is defined by retrogressed amphiboles and biotites, commonly in association with small ($<$10cm), discontinuous quartz lenses. Typically, the quartz lenses are isoclinally folded, and are intrafolial. Invariably, the fabric (Sm) is parallel to the thrust zone.

2. Eggjane Thrust

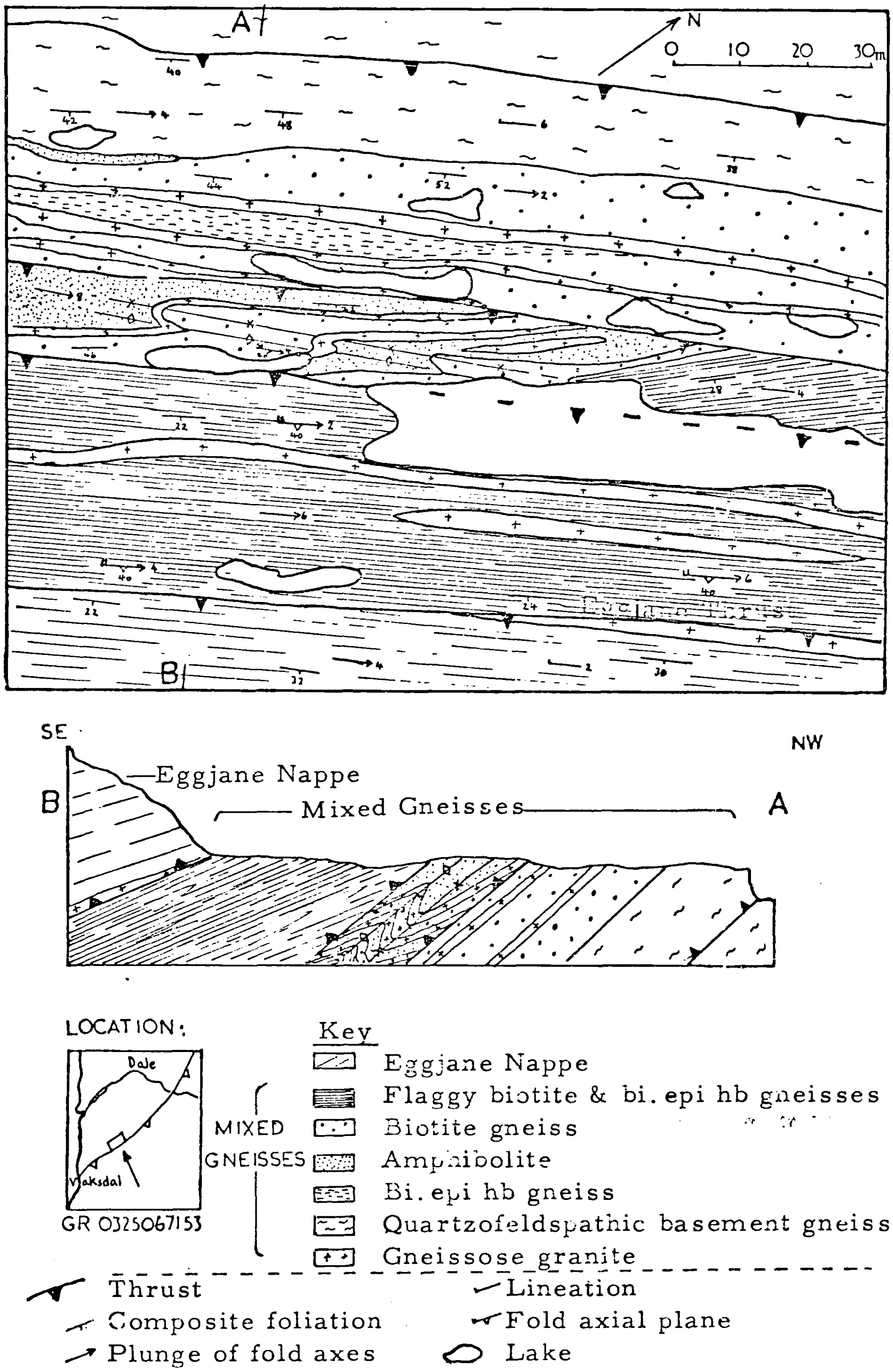
The Eggjane Thrust carries a large scale D3 antiform, with a core of Eggjane gneiss (section 2.8) and envelope of Banded Gneiss and quartz-diorite gneiss, over the Mixed Gneiss and Basement Gneiss lithologies. The thrust oversteps two Basement thrusts in the southwest of the area (fig 84). On the plateau, the outcrop of the Eggjane Thrust is marked by an obvious topographic feature, when viewed from both air and ground (plates 5, 59) However, it becomes very difficult to follow the thrust further north, around Bolstad, due to poor exposure.

In the extreme southwest of the outcrop, the thrust can only be followed with difficulty due to the combined effects of subsequent northwest-southeast folding, and inaccessible topography. This large scale folding (Bergen Arc trend) carries down to road level a higher structural position than observed on the plateau (fig 98) exposing more of the Banded Gneiss and quartz-diorite gneiss.

The Eggjane Thrust is represented by a thickness of flaggy mylonitic gneisses, derived from both Eggjane Gneisses and biotite gneisses (section 4.3). The flaggy partings rarely exceed 2-3cm in thickness. This variably thick (15-30m) unit of mylonitic gneiss lies immediately beneath the Eggjane gneisses of the Eggjane Nappe, and is bounded both above and below by low angle thrusts (fig 85). These mylonite gneisses contain internal small scale folds with an associated axial planar fabric; these are correlated with F2 in the Mixed Gneisses. The long limbs of the folds are often sheared out, and the flaggy fabric observed is thus a composite one - transposed foliation and new schistosity . The regional northeast-southwest lineation (L2) is well developed.

Additional evidence for the age of this flaggy mylonite fabric is derived from the granite lenses within the gneisses. By correlating the granites to those of D2 age within the Basement, (a reasonable supposition due to the close similarity in both lithological and structural appearance) a datum point is achieved for relative structural ages. The gneissic granite fabric is observed to be both isoclinally folded, and locally boudinaged - reminiscent of D3 structures in the Basement and D2 structures in the Mixed Gneisses. It follows from this that the transposed flaggy mylonite foliation is a product of Basement D3. That the unit is invariably developed along the sole of the Eggjane Nappe, and is cross cutting to large scale F3 folds, (although containing the small scale D3 structures) is also indicative of a D3 age for the thrust.

FIG. 85 The Mixed Gneisses and the overlying Eggjane Nappe



The mylonite gneisses dip between 30° - 40° to the southeast forming a low angle discordance with the lowermost Eggjane Gneisses of the Eggjane Nappe. The discordance is observed in the field by the cutting out of Eggjane Nappe F3 axial traces along this margin.

Mineralogy of the F3 Basement Mylonites

The mineralogy of the basement mylonites is entirely dependent upon the nature of the gneiss from which they are derived. Occasionally, this may not necessarily be the adjacent wall rock to the thrust, especially where an amphibolite has been utilised for thrusting. The thrust zone lithologies can be broadly classified into two groups:

1. Acid mylonites - derived primarily from the quartzofeldspathic and gneissose granites. (section 2.2)

2. Mafic mylonites - derived from amphibolites, hornblende and epidote quartzofeldspathic gneisses. (section 2.2)

Acid Mylonites

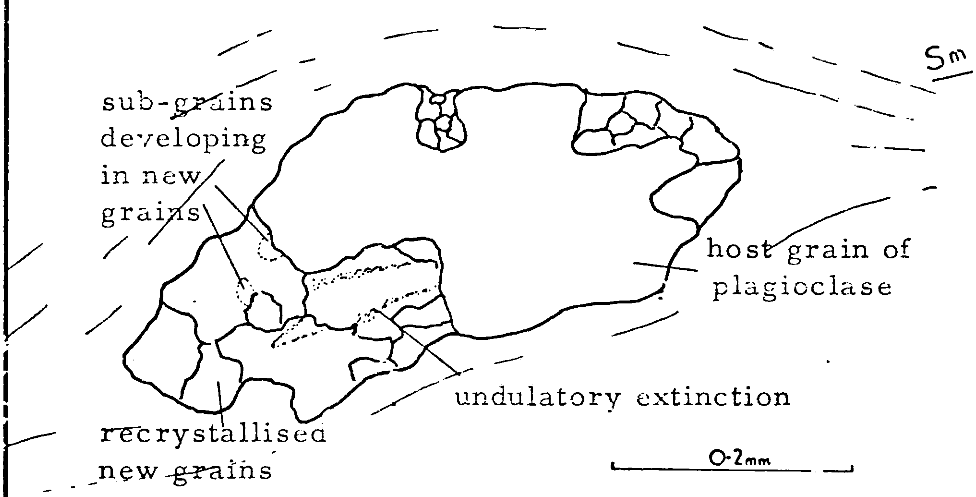
The acid mylonites have a mineralogy dominated by quartz, feldspar and biotite, with the following, visually estimated ranges:

quartz	18-35%
plagioclase	20-40%
k feldspar	15-30%
biotite	12-23%
epidote	1-2½%
chlorite	0-½%
sphene	0-3%
hornblende	0-1½%
calcite	0-½%
apatite	traces
magnetite	traces

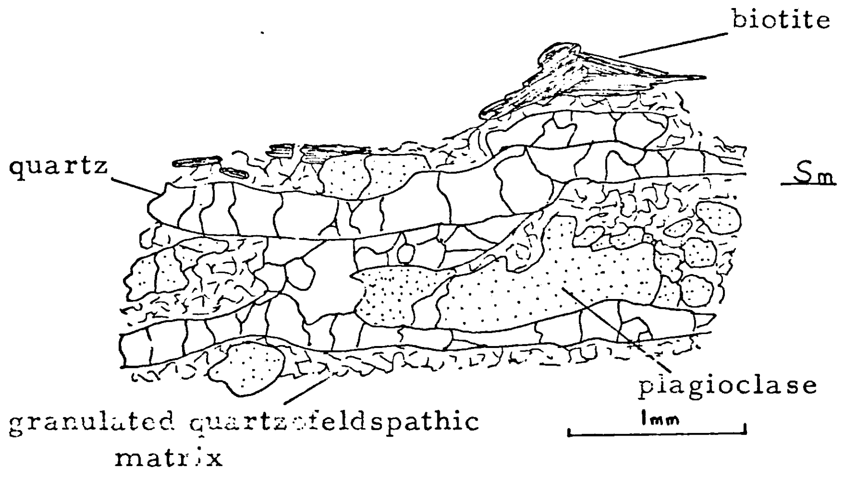
The acid mylonites have a characteristic texture dominated by variable grain size reduction and the generation of a mylonitic (plate 57) fabric defined by shredded biotite and elongate quartzofeldspathic augen. The quartz and feldspar react in a similar manner when deformed, developing abundant strain features, such as undulose extinction and sub grain development. The medium grained granoblastic gneissic texture of the wall rock is only weakly preserved, with both individual grains and clusters (augen) of grains being marginally granulated by the process of dynamic recovery and recrystallisation. The microstructures developed are extensively reported in the literature (for example: Bell and Etheridge 1973, 1976; Tullis et al. 1973; White 1973, Wilson 1975; Marjoribanks 1976, Bouchez 1977). Sub grains and new grains ($<$0.05mm) are developed both marginally and cross cutting to host grains, and themselves are strained with the development of undulatory extinction and sub grains, indicating the continual process of mylonitisation. (fig 86)

FIG 86

Plagioclase porphyroclast within an acid mylonitic gneiss from a D3 basement thrust



weakly strained quartz vein within an acid mylonitic gneiss from a D3 basement thrust



Porphyroclasts of feldspar (with marginal granulation) up to 1mm in size are common, whereas the quartz is highly deformed and usually occurs interstitially. In some samples, the quartz is seen to be introduced at a late stage in the mylonitisation process, forming narrow monomineralic bands and veins cross cutting to an already mylonitised quartz and feldspar texture. The quartz veins are themselves weakly deformed, with undulatory extinction and some marginal granulation. The veins are invariably parallel to the mylonite fabric. (fig 86)

The plagioclase host grains are of oligoclase composition (An_{24} - An_{28}); however, the composition of the recrystallised grains is unknown due to their small size and lack of twinning; some grains are altered to calcite.

Relic wall rock biotite (pleochroic from brown to greenish brown) is often shredded occurring as short stumpy forms typically less than 0.05mm in length. If not shredded, they sometimes show corrosion by quartz, leaving irregular biotite shapes.

Rare chlorite is occasionally seen replacing biotite, and where present, hornblende. The mylonite fabric is overgrown by euhedral sphene, apatites and magnetite.

Mafic Mylonites

Mafic mylonites are commonly developed along thrust zones, and have a mineralogy dominated by feldspar, biotite, hornblende and quartz;

visually estimated ranges:

quartz	6-14%
plagioclase	35-45%
k feldspar	trace - 7%
biotite	8-33%
hornblende	0-20%
epidote	trace - 10%
sphene	$1\frac{1}{2}$-8%
apatite	trace - $2\frac{1}{2}$%
iron oxide	traces
chlorite	traces - $1\frac{1}{2}$%
calcite	traces

As with the acid mylonites, the quartz and feldspar grains suffer marginal granulation, leaving strained relic host grains. Where intergrown with biotite and/or hornblende, the felsic grains show much less straining. (plate 58)

Compared with the mafic wall rock gneisses, the mafic mylonites contain much more biotite than hornblende. The bluish green hornblende is augened by the mylonite fabric, and is often undergoing retrogression, variably to biotite, chlorite, sphene and apatite:

hornblende -- biotite $\pm$ sphene $\pm$ chlorite $\pm$ apatite

hornblende -- chlorite

Hornblendes are sometimes stretched parallel to the mylonite fabric, with quartz recrystallising between the fragments.
The greenish brown biotites are commonly intergrown with sphene, of euhedral or subhedral form, and together define strong augen textures around granulated quartz, feldspar and hornblende.

Locally the sphene is broken down and forms part of the mylonite texture. Epidote, with only rare granulation textures overgrows the biotites.

Metamorphic Facies of the Basement mylonitisation

Determination of the metamorphic facies is difficult within the acid gneisses due to a lack of index minerals, the common assemblage being quartz, feldspar and biotite. The composition of the granulated plagioclase has not been determined. However, the presence of minor chlorite and calcite indicates probable deformation at greenschist facies.

Deformation at greenschist facies is demonstrated in the mafic mylonites by the retrogression of hornblende to biotite and chlorite and biotite to chlorite.

Mineralogy of the Eggjane Thrust Mylonites

Whereas the mylonites from the basements thrusts have readily distinguished textural differences compared with the wall rock gneisses, the Eggjane thrust mylonites are texturally and mineralogically indistinguishable from the hornblende gneisses within the Mixed Gneisses. (section 2.5) The Eggjane thrust is defined by a thickness (15-30m) of very flaggy hornblende gneisses that transgress structures both within the Mixed Gneisses and the Eggjane Nappe.

On structural grounds it is argued (page 268) that the flaggy hornblende gneisses contain flattened equivalents of D2 structures from the Mixed Gneisses, and as such are related to the M2 metamorphic event within the Mixed Gneisses (section 5.2). Petrologic and metamorphic investigation of the flaggy hornblende gneisses bears this proposal out, with the foliation defined by crystallographic orientations of hornblende and biotite, along with granoblastic quartz and feldspar. The felsic minerals exhibit minor amounts of strain generated microstructures, such as undulatory extinction, and sub/new grain formation. This, however, is also typical of the M2 (Mixed Gneisses) texture (section 5.2c) which locally has associated discrete planes of mylonitisation.

The most pronounced textural difference between the thrust gneisses and the M2 Mixed Gneisses is the complete recrystallisation within the thrust gneisses, along with some augening of the biotite fabric, compared with the inhomogeneous recrystallisation of the Mixed Gneisses during M2, which leaves partially granulated minerals - especially quartz and feldspar.

The metamorphic grade assigned to M2 is lower amphibolite (section 5.2c). The paragenesis of the flaggy hornblende gneiss is:

> quartz - oligoclase plagioclase - epidote - hornblende - biotite ± chlorite

This locates the metamorphic facies close to the Lower amphibolite/upper greenschist boundary, with the rare occurrence of chlorite replacing hornblende important in defining the boundary. (Winkler 1976 p.170).

b) <u>The Lower Bergsdalen Thrust Zone</u>

The Lower Bergsdalen Thrust Zone lies structurally above the Eggjane Nappe, separating it from the Lower Bergsdalen Nappe (fig 84). The thrust zone consists of at least 5(numbered here I-V) units of a quartz feldspar muscovite schist, of variable thickness (<5m) which weather typically a rusty brown.

Kvale (1945) mapped two of these units, tracing them north-eastwards from Vaksdal for many kilometres, up to and beyond Eksingdalen, eventually following them into a thick zone of schist, termed the Voss phyllite. (figs 2, 21) By correlating the two schistose units with the Voss phyllites, Kvale concluded that the thin schist horizons defined the margin of the Lower Bergsdalen Nappe. He proposed that the schists, of Cambro-Ordovician age, (by correlation with fossiliferous schists on Hardangervidda - section 1.11) separated Precambrian rocks, and were utilised by the thrusting as planes of easy sliding. Kvale provided evidence for the tectonic siting of the schists, including: a. their occurrence along the contact between two petrographic complexes; b. the east-south-east plunge of their linear structures, that is parallel to linear structures of the thrust zone; c. their cross cutting relations to the gneissic foliation of the country rock.

Although Kvale only mapped two units of schist along the length of the Lower Bergsdalen Nappe, (calling them thrusts of the first order, i.e. separating main tectonic units), he also recognised other schist horizons, which he termed thrusts of the second order, and related to movement within the tectonic units.

The present work confirms the presence of these schistose units, although a different origin (cf. Cambro-Ordovician metasedimentary schists) is suggested. Also, no division has been made into thrusts of the first and second order. All of the schistose units are thought to belong to one thrust zone. This is because there is no obvious major difference in litho-tectonic units between each schistose horizon, each schistose horizon is structurally of the same age, and the zone of schistose units is no greater than 500m thick, occurring at the base of the Lower Bergsdalen Nappe.

As Kvale suggests, two main schistose horizons can be traced to the northeast from the Vaksdal region. (fig 84) The lowermost structural unit (no. I) sits almost immediately above the Eggjane Gneisses of the Eggjane Nappe. It is noticeable that everywhere, strongly foliated and folded members of the Banded Gneiss litho-tectonic unit lie immediately beneath and above this lowermost schistose horizon, overstepping at a low angle (on a small scale conformable) the strike of the Eggjane gneisses. In the plateau region the underlying horizon of Banded Gneisses is typically less than 5m; it does, however, thicken northwards, and similarly to the southwest. Other than this schistose horizon (no. I) immediately above the Eggjane Nappe, the remaining horizons (no. II-V) are sited well within the Banded Gneiss lithotectonic unit, although locally, gneissic granites are closely involved.

Tracing the lowermost schistose unit (no. I) is an easy task apart from the southwest margin of the area (close to the Bergen Arcs) where it is thickened by tight folding. It forms a thin (~3m) cap to the mountain tops, (plate 60) running in a northeasterly direction. The unit thickens to the north, until it forms a prominent 5-10m thick horizon, south of Bolstad. The complex outcrop form of this lowermost unit immediately north of Vaksdal (fig 84) is attributed to erosion, which has left a klippe of Bergsdalen Nappe in an envelope of tectonic schist, sitting on the Eggjane Nappe; subsequent folding adds to the complexity.

Kvale's (1946) "second" schistose unit (no.III) (fig 84) which is less than 3m thick, if traced northeast from Vaksdal, forms an easily followed scarp feature, once on the plateau. However, immediately to the northeast of Vaksdal, only sporadic outcrops can be observed (plate 9). These two units (nos. I & III) are individually continuous and remain separated by a thickness of about 100m of Banded gneiss for the length of the area mapped. However, a discontinuous unit (~2m) of schist (No. II) can be traced, lying between the two more obvious units for much of their length (fig 84)

A fourth tectonic feature (no. IV) can be recognised in the easterly part of the thrust zone, although not represented by a schistose horizon. This feature is a ductile thrust of the same apparent age as the tectonic schists(page 285) and like them, is sited within the Banded Gneisses. This thrust carries more amphibolitic members of the Banded Gneisses including the amphibolite over the more biotitic members. It is traced northwards into poorly exposed ground, where it is seen no further. In its place there are thin (75cm) sporadic horizons of schist, locally with discordant relations, (plate 61) confined to a narrow (20m) zone that is traced with difficulty to the north east. It is not known whether the sporadic nature of the schist is due to a limited development or to a limited outcrop.

The distribution of schistose units becomes much more complex towards the north easterly margin of the mapped area. This is due to the effect of subsequent east north east trending folds (F3 of the Bergsdalen Nappe), which increase in intensity towards the north east, resulting in repetition of horizons. It is within this folded area that a discrepancy between Kvale's (1946) map, and that of this study, is observed. Kvale traces his second schistose unit (no.III) across Bergsdalen, and on towards Bolstad (fig 21). However, the present mapping has shown that it is tightly folded by a large scale F3, and can be seen to cross Bergsdalen further to the northwest (fig 84). The unit that Kvale considered to be the continuation of schist no.III on the northern side of Bergsdalen, is in fact a structurally higher unit, no. V, which does not crop out south of the road in that area, due to the effects of folding. In the northern part of the mapped area, a large granite body immediately overlies the structurally highest schist unit (no. V). Schist no. V can be observed to cross Bergsdalen further to the southeast; through sporadic outcrop, it can be traced south, until being cut out by a younger (D3) thrust - the Bukkafjell thrust. (fig 84).

Two further schistose units, within Banded Gneisses above the Bukkafjell thrust can be traced in the hills immediately to the southeast of Vaksdal. These horizons are tightly folded by F3 and are subsequently cut out by thrusts (fig 24)

Several units of schistose granite also exist in the ground above the Bukkafjell thrust, east of Vaksdal. They form complex outcrop patterns, due to the superimposition of F3 and F4 folds (fig 24). Locally, along the margin of the Bergen Arcs, the schistose granite has been mixed with garnet-mica, and quartz-mica schists of metasedimentary origin. These units can be traced to the northwest onto the island of Osterøy, (Hopper 1980) forming part of the Major Arc of the Bergen Arcs.

Field Description of the Schists of the Lower Bergsdalen Thrust Zone

The schistose units are readily recognised in the field, with their distinctive rusty brown weathering, intense schistosity and the small erosional features marking their outcrop. Differences between individual horizons are small; variability is restricted to the following:

1. Marginal Relationships with the Gneisses

The different schistose horizons have either sharp or irregular margins. Where the margin is sharp (plate 62), a very thin (0.5cm) layer of almost pure muscovite, readily eroded, lies at the contact between gneiss and schist. However, margins of this nature are not common, most being irregular. Such margins are developed over a variable thickness of gneiss, ranging from about 1m down to 5-10cm. Despite the size range, the appearance is very similar with thin anastomosing bands of schist reaching into the gneiss. These bands have a planar attitude, parallel and subparallel to the schistosity within the core of the horizon. The density of the anastomosing bands is variable, being typically low in the thicker margins, and high in the thin margins (plates 63, 64). The bands often act as channels for subsequent iron staining, giving the gneiss a patchy appearance. If the anastomosing bands are closely developed, then the margins appear to be gradational, with an inhomogeneously developed schistosity, that rapidly passes into the schistose core. However, the gradational development of the schistosity in the tectonic schists is markedly different in appearance to that of a compositional change in lithology (plate 10). The muscovite fabric developed at the margin of schistose units is invariably parallel to that margin, with no rotational features indicating possible directions of movement.

2. Central Zone of Schist Units

The central zone is often observed to be featureless, with only a well developed schistosity invariably parallel to the margins. It is defined by muscovite books up to 6cm in length (although books about 1-2cm in length are more common) that locally can be inhornogeneously developed. This gives areas of the schist a patchy appearance, with lenses and "ghosts" of background gneiss. (plate 65). These areas containing only a weakly developed, inhomogeneous muscovite schistosity that may range in thickness from 2-20cm. The background gneiss recognisable within the schists is invariably fine or medium grained and quartzofeldspathic, with minor proportions of biotite.

More definite lenses of gneiss, up to 2-3m in length are also observed. Some retain their original character and fabric (biotite gneiss with the fabric almost invariably parallel to that of the schistosity), while some are cross cut by thin ($<$5mm) muscovite bands - very similar in appearance to the anastomosing margins. (plate 66). It is noticeable that the lens margins are often rather indistinct, merging with the schists. The schistosity is locally seen to be intrafolially folded on a very small scale, with axial planar orientation of muscovite books. Thin quartz veins, often followed by veins of iron ore ($<$1mm thick), also develop along the axial planes.

Typically, the quartz veins, along with relic pods of pegmatite are augened by the schistosity; pods of amphibolite are occasionally included as well.

The schistose horizons retain the same character, despite the nature of the adjacent lithology, be it biotite-hornblende gneiss, gneissic quartz-diorite, amphibolite or granitic gneiss. However, in these situations, the contacts are rarely irregular.

Structural Position of the Schists of the Lower Bergsdalen Thrust Zone

Following the proposals of Kvale (1946) these schistose units are thought to represent tectonic features; this is suggested from the present study because: a. on a large scale, the lowermost schistose unit, (no. I) oversteps the strike and F2 axial traces within the Eggjane Nappe; b. similarly, schistose units are undeformed by the large scale (F2) structures of the Lower Bergsdalen nappe, and overstep lithological boundaries; and c. on a small scale, fold hinges and gneissic foliation, in both Eggjane and Lower Bergsdalen Nappes, are seen to be truncated by the schistose horizons.

That movement has occurred along the planes represented by the schistose horizons cannot be doubted. The position of the lowermost schistose horizon (no. I) between two very different lithotectonic complexes is conclusive.

The disruptive nature of the schists in the hinge region of folds of identifiable age allows an accurate relative structural age to be determined:

Age Relative to Structures within the Eggjane Nappe

Within the Eggjane Nappe, the Eggjane gneisses and the thin overlying unit of Banded Gneisses are folded together by folds (F2) ascribed to D3. The lowermost schistose horizon (no. I) is seen to cut across the hinge zones of these folds on a small scale, (plate 67) and to cut out at a low angle, their axial traces. (map 2). There is little associated tightening of the folds in the Eggjane gneisses, and no variation in axial orientation in the vicinity of the schists, retaining the same northeasterly plunge and lineation of the main body of the gneisses. However, the F2 (Eggjane Nappe) structures in the Banded Gneisses immediately below the lowermost schist (no. I) locally become tight to isoclinal, with their limbs forming a transposed fabric, that is sub parallel to the fabric of the schist. Again, the linear features retain the northeasterly attitude.

Age Relative to Structures of the Lower Bergsdalen Nappe

Small scale examples of the schistose units replacing long limbs of F2 folds within the Lower Bergsdalen Nappe are commonplace, be it in Banded Gneisses (plate 68) or gneissose Granites; the resulting schistosity is invariably parallel or sub parallel to the F2 axial plane (fig 87), dipping to the south east between 30^{o} - 40^{o}. This is however, modified in the north and south by subsequent deformation. The schists also replace long limbs of F2 folds on a large scale (map 3) although the outcrop of the schists is parallel to the axial traces of those folds.

Linear features are not common in the schists of the central portion of the area. The ubiquitous northeasterly trending lineation of the local gneisses is only poorly represented by an intersection lineation; locally, a crenulation lineation plunging to the east north east or south east has been imparted upon the schists. These are correlated with subsequent folding (F3 in the north, and F4 in the south, respectively).

Internal structures are rare within the schists; where seen, they almost invariably appear as isoclinally folded quartz or pegmatite veins, with the schistosity axial planar (plate 69)

As mentioned previously, (page 280), the schistose horizon no.IV is in part not represented by a schist, but by a mylonitic gneiss.

FIG. 87 Poles to schistosity of the tectonic schists (phyllonites) of the Lower Bergsdalen thrust zone

Area Lr. Bergsdalen T. Z.
N : 52

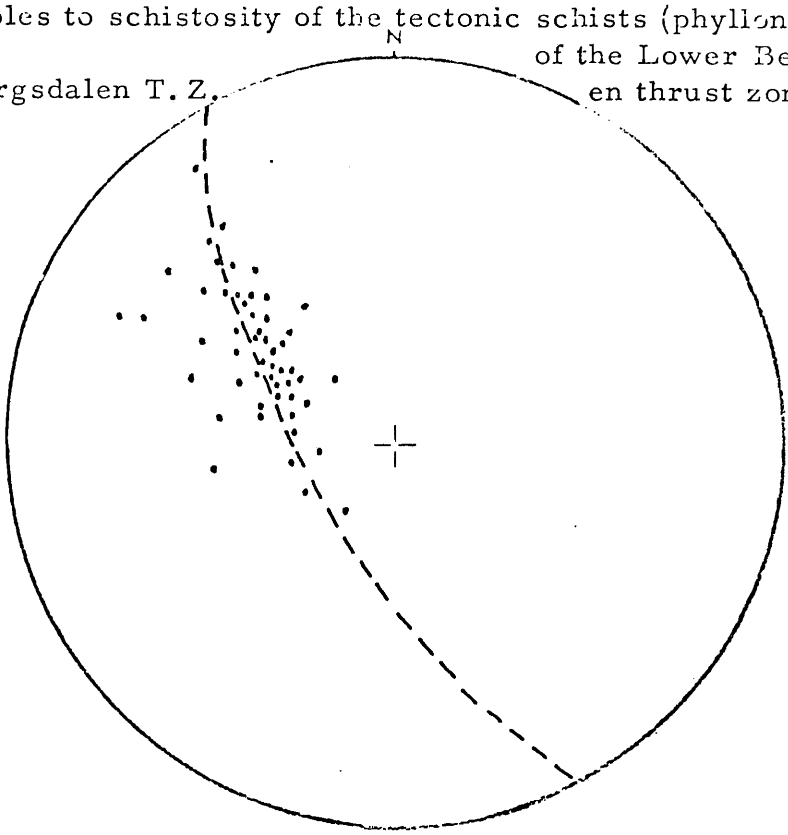
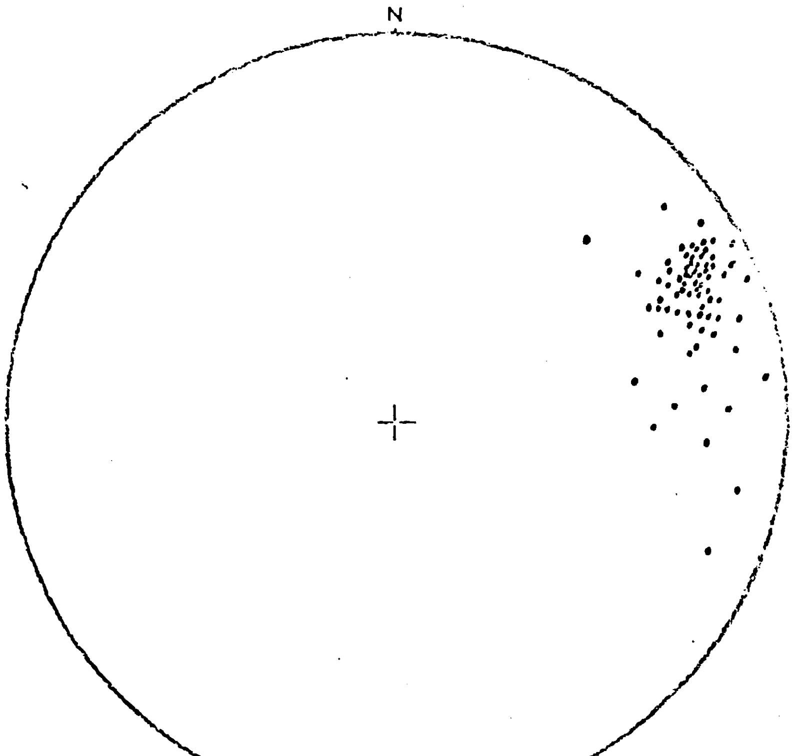


FIG. 88 Plunge of lineation L2 in the Lower Bergsdalen Nappe

Area : 1&2 (fig. 51)
N : 72



lower hemisphere
equal area
stereographic projection

The mylonite is 3m thick forming a very flaggy (1-2cm parting) zone, with a sporadic development of muscovite flakes on foliation surfaces; there is no obvious internal folding. This flaggy zone forms an obvious feature (plate 70) that can be traced cutting through the nose region of a large scale F2 (Lower Bergsdalen Nappe) antiformal structure (map 3). On the small scale, the mylonite has an axial planar attitude to F2 parasitic folds, often replacing the long limbs.

Other Tectonic Schists

Other than the Lower Bergsdalen Thrust Zone, schistose horizons of apparent tectonic character are also developed in the Lower Bergsdalen Nappe above the Bukkafjell thrust, and are to be observed in the hills to the southeast of Vaksdal (Blåfjell and Bogafjell). Three varieties of schistose units are developed, depending on the associated lithologies:

1. Rusty brown weathering quartz muscovite schist, within Banded Gneisses.

The rusty brown weathering schist is superficially very similar to that of the Lower Bergsdalen thrust zone. The outcrop of this schist is limited to two horizons within the Banded Gneisses that are folded and cut out by D3 (Lower Bergsdalen Nappe) thrusts (fig 24) No conclusive evidence has been obtained for its structural age;

intrafolial isoclines within the Banded Gneisses predate its development, with limbs being replaced in an axial planar fashion. Deformation subsequent to the generation of the tectonic schist is limited to recognisable F3 and F4 structures.
A suggested correlation of the isoclines with F2 in the Bergsdalen nappe is made.

2. Light grey weathering quartz feldspar muscovite schist, within Granites.

The light grey weathering quartz-feldspar schists are the most extensively developed schistose units in this southwestern area. Their outcrop pattern is complex, due to the superimposed effect of F3 and F4 folding (fig 24). They form prominent features, that outcrop at the roadside in southern Vaksdal. Unfolded schistose horizons are rarely greater than 10m thick, often less than 3m; the apparent thickness, after superimposed folding can be up to 50 metres. These schists are invariably seen within granitic gneisses, of which there is an extensive development.

Whereas the schistose units of the Lower Bergsdalen thrust zone are relatively homogeneous, the schists associated with the granites display exceptional inhomogeneity. Lenses of granitic material, often with diffuse margins, are common within the schists; the muscovite fabric in part tends to sweep around the lenses, but also can be seen to invade them partially, dying out internally (plate 71). Contacts between the schistose horizon and the granitic gneiss may be either sharp or gradational. The gradational contacts show lenses of granite being partially enveloped in a muscovite fabric. The relative position of the development of the schistose units within the structural history can be placed from two sources: a. a margin between granite and schist has been observed in which lenses of granite, containing the regional fabric, are being incorporated into the schistose matrix (plate 72). It has been argued (section 4.5c) that the regional fabric observed within the granites of this area is a product of F2 flattening. Thus, the tectonic schist must develop post F2. It can be clearly seen that these horizons are deformed by F3 structures; an age of development between F2 and F3 is thus proposed.

b. An F2 medium scale fold in quartzite, adjacent to a granitic body, is seen to be cut out by a schistose horizon, that replaces part of a long limb. Both are subsequently deformed by F3 folds.

The tectonic schists where thus developed post F2, pre F3.

3. Light grey or creamy weathering quartz muscovite schist, at the boundary of quartzites.

The light grey, quartz muscovite schist is developed at the lower contact of the quartzite, being adjacent to either amphibolite or Banded Gneisses. The schist is no greater than 2m thick, and can be traced for several hundred metres along the quartzite contact. When in contact with the amphibolite, it is most common to observe a progressive strengthening, over a metre, of the amphibolite fabric towards the contact. This is relatively sharp with lenses of quartzite and amphibolite incorporated into a muscovite matrix that sweeps around them. The lenses of quartzite may be up to 30cm in length, while the amphibolite lenses are typically under 10cm. The muscovite fabric is parallel to the margins.

The age of the development of this schistose unit is easily placed; F2 isoclinal folds (containing small scale F1 intrafolial folds) in both quartzite and amphibolite are cut out along axial planes by the schists. F2 isoclines within the quartzite are locally incorporated as lenses within the schists. F3 folding deforms the schists.

Tectonic schists generated within the Lower Bergsdalen Nappe, and now sited above the Bukkafjell thrust, were thus developed during a phase of deformation that disrupted F2 folds, with the shearing out of long limbs. This age is directly correlated with the generation of the schists of the Lower Bergsdalen thrust zone.

Petrology of the Lower Bergsdalen Thrust Zone Schists

The quartz-feldspar-mica schists of the Lower Bergsdalen thrust zone have a relatively consistant mineralogy along their length of outcrop. Muscovites are very common, forming in books up to 6cms in length and 3mm. in thickness. However, the concentration of books varies along an outcrop, leaving small patches within the schist looking like a fine grained gneiss. (plate 65) Despite the main body of the schist being mineralogically homogeneous, the margins can show a variable development of mica. Thus, the schists will be describes in two parts:

1. Marginal schists
2. Central schists

1. Marginal Schists (plates 73, 77)

Effectively, marginal schists are rocks that are classified as the enveloping biotite (± garnet) gneisses of the Banded Gneiss lithologic unit, yet, being located immediately adjacent to the schist zone, have the additional inhomogeneous development of muscovite books and strings typical of the Central schists.
A similar inhomogeneous texture has also been seen in a shear zone that lies along the axial plane of an F2 fold in biotite gneiss (on Högdifjell GR 0329267173). Platey biotite and muscovite books and "strings" define the new fabric, yet a true tectonic schist is not generated. The petrology of this zone will be included in the

description of the marginal schists. The modal analyses of the marginal schists are visually estimated:

quartz	20-27%
feldspar	35-50%
muscovite	3-15 %
biotite	15-30%
garnet	1-3%
sphene	traces
iron oxides	1-10%
apatite	traces
chlorite	traces

for a comparison with the biotite gneisses, see section 2.10

Texturally, the marginal schists are similar to that of the biotite gneisses (section 2.10) being fine to medium grained with quartz rarely exceeding 0.3mm and feldspar 0.5mm in length. Typically, the quartz and feldspar are aligned in tabular or subtabular fashion with biotites confined to the grain boundaries; biotites may also overgrow the febic boundaries, the combined effect is to define a strong fabric. (S2) Feldspars are considered to be universally of plagioclase composition, although rare traces of microcline are seen. The plagioclases are often untwinned, and contain dusty inclusions. Where twinned, the An content has been determined to be albitic, from An_4 - An_8 using the Michel Lèvy test. This contrasts with the oligoclase/andesine compositions of plagioclases from the biotite gneisses of the Lower Bergsdalen Nappe. Garnets occur as porphyroclasts, with the biotite fabric sweeping around them.

This S2 fabric is modified only slightly at the margins of the schist zones; discrete zones of mylonitisation occur, resulting in a range of deformation structures in the quartz and feldspar: undulose extinction, along with sub grain and new grain development with a trend towards grain size reduction which may be masked by subsequent recrystallisation. Biotites locally become shredded. In many samples, it is difficult to distinguish the strain features that are an integral part of the S2 biotite gneiss fabric, from those associated with the generation of the schistose horizons.

The most obvious textural differences between marginal schist and biotite gneiss are:

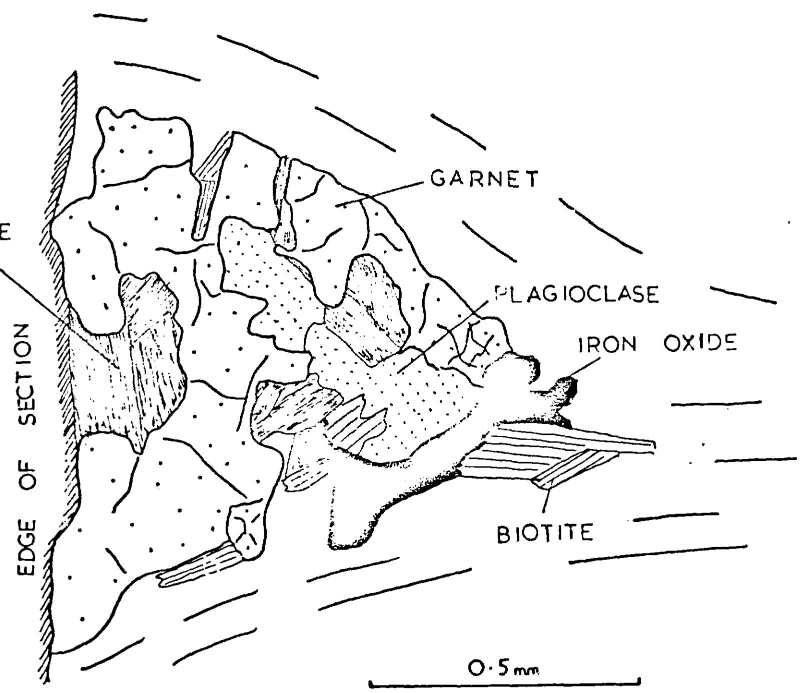
1. retrogression of garnets
2. growth of muscovite
3. iron rich veining

1. Retrogression of garnet

Almandine garnets show signs of retrogression within the marginal schist; this is in contrast to the stable garnets of the S2 fabric in biotite gneisses of the Lower Bergsdalen Nappe. The garnets have an anhedral form, and are set in a matrix of mica. Local knots of mica, set within the fabric suggest a complete pseudomorphing of the garnets.

Observed reactions involved in the retrogression: (plate 73 fig 89)

FIG 89 Garnet porphyroblast within a marginal tectonic schist, undergoing replacement by muscovite



almandine + biotite = biotite

almandine + biotite = biotite + muscovite + iron oxides

almandine + biotite = muscovite + iron oxides

All the reactions are ± quartz, plagioclase

2. Muscovite Crystallisation

The development of muscovite is the most important textural change from that of the biotite gneisses of the country rock. It is rarely present in the biotite gneisses (section 2.10) yet occurs on a large scale within the schists.

The muscovite develops as either individual crystals or in thin aggregates that often define isolated "strings" that run through the gneiss. The "strings" are parallel, or occasionally subparallel to the strong S2 fabric of the gneisses, especially where taken from shear zones within the hinges of F2 folds (plate 74)

The muscovites are considered to be developing as a new phase, additional to the normal mineralogy of the gneisses, for the following reasons:

1. On a macroscopic scale, the muscovite schistosity occurs as discrete (all be it up to 5m. thick) planes, that are cross cutting to the regional structures, within biotite gneisses and schists that have only rare bands containing

any modal muscovite.

2. On a microscopic scale, muscovite aggregates can occasionally be seen to be cross cutting, at a low angle, the S2 fabric that is defined by biotite and elongate quartz and plagioclase (plates 74,75)Associated with the new muscovite fabric is straining of the quartz and plagioclase, with the generation of sub, and new grains, and local elongation of the recrystallised grains parallel to the muscovite fabric.

3. Obvious planes of mylonitisation, parallel to the S2 fabric are sometimes observed, with distinct grain size reduction and shredding of the biotites. Muscovites overgrow these mylonitic textures, usually parallel to the mylonite plane; however, their growth is not restricted to the planes, although the association is not uncommon. Where garnets occur, the mylonite planes sweep around the, often leaving partially retrogressed (to muscovite) augen.

4. Muscovite crystals commonly are seen partially wrapped around plagioclase grains, appearing to be a breakdown product from the feldspar. (see page 303) and (plate 76).

5. Muscovite books are typically interspersed with biotite grains; thin cleavage flakes of biotite are incorporated within the books, whilst tiny grains of iron oxide are situated along the cleavage planes of the muscovites. Again, muscovite appears as a breakdown product from biotite (plate 80) and (page 304).

Central Schists (plates 78, 79)

The medium grained schists are, mineralogically, quite homogeneous along their length, having the following ranges:

quartz	30-40%
muscovite	20-30%
plagioclase	15-26%
biotite	5-15%
iron oxides	1-8%
apatite	trace
sphene	trace
tourmaline	trace

values determined from 1000 points counted per sample.

The matrix of the schists is composed of fine grained quartz and plagioclase, that range in size from 0.1-0.5mm, although exceptional grains both coarser and finer are seen occasionally. There is no segregation into quartz or plagioclase rich bands- both minerals being equally distributed within the matrix. However, thin quartz veins are locally observed; they are distinguished from the matrix by their coarser grain size and monomineralic nature.

The grains within the matrix have stable forms that are polygonal with triple junctions, or tabular; however, these forms do show modification due to strain induced features, such as undulose extinction and recrystallisation. The polygonal and tabular host grains can be seen to be broken down along their margins to sub and new grains, which often are elongate parallel to the strong muscovite fabric. This deformation is distributed throughout the felsic matrix, although some discrete planes of extreme grain size reduction can be seen, always parallel to the muscovite fabric. There is no apparent large scale crystallographic orientation of the quartz and/or the plagioclase grains of the matrix, as determined by the sensitive tint accessory plate.

Plagioclase shows only rare albite twinning, from which an albite (An_4 - An_6) composition has been determined optically. More commonly, the plagioclase is untwinned, with dusty inclusions. Muscovites are often seen to be partially enclosing and replacing the plagioclases along their margins. (plate 76).

The fabric is invariably dominated by muscovite, that is mainly in book form. (size ranges from 0.4mm - 2cms, with extreme books up to 6cms in length) although smaller aggregates and individual grains do occur. The books and aggregates tend to grow in an anastomosing form, enclosing lenticular areas (for variable size) of the felsic matrix. In contrast, patches of the felsic matrix may sometimes be seen to be extensive (up to 3cms in length), containing only one or two small muscovite books growing as individual lenses.

The muscovite books commonly have inclusions along their cleavage planes and margins, of tiny iron oxide grains and fragmented biotites, Occasional small patches of strained quartz and feldspar are also included by the muscovite books. The tails of the muscovite books often appear ragged, with the individual muscovite grains being fine grained, along with shredded biotite and mylonitised quartz and plagioclase. Despite this, the main body of the muscovite books are unstrained. Fine grained biotites commonly grow along the grain boundaries of the polygonal quartz and plagioclase resulting in gneissic texture very similar to that of the biotite gneisses. The fabric defined by the biotite, quartz and feldspar is readily recognised within the augen that are enveloped by the muscovite books. Most commonly, the internal (gneissic) fabric is parallel to that of the schistosity. However, within some augen, the internal fabric is discordant, and being overprinted by the muscovite schistiosity (plate 75). Rare isoclinal fold hinges, defined by the biotites are preseved within the augen.

The muscovite books are overgrown by occasional apatites and tourmaline. The apatites tend to have a subhedral, oval shape, and never exceed 0.3mm in length. Tourmaline is euhedral-subhedral, and is faintly pleochroic from pale yellow to yellow; the size is up to 0.5mm. The colour suggests that the Mgrich variety of tourmaline dravite, is present. Many of the tourmalines are rimmed by tiny grains of iron oxide, which were eventually included along the tourmaline margins. (plate 78).

Origin of the muscovite in the schistose units

Observations indicate that the schists and biotite gneisses are closely linked, with the schists representing either a more pelitic facies or, they are derived from the biotite gneisses through tectonometamorphic processes. If the schist is considered to represent a pelitic facies, utilised by the thrusting, then there is no explanation required for the variation in modes, especially of the muscovite, from gneiss to schist. However, if it is assumed that the schist is derived tectonically from the biotite gneiss, then this modal change must be explained.

The most obvious modal increase, from marginal to central schist is that of muscovite, which ranges from 3-15% in the margins (compared to the muscovite poor biotite gneiss), and increases to 20-30% in the central part of the schist. It has been shown that the muscovite is a secondary mineral phase, thus its dramatic increase must be explained. The most commonly observed reaction is that involving the breakdown of sodic plagioclase, to muscovite and quartz:

$K_2+(F+OH)_4 + 6(Na, Ca)\ Al\ Si_3\ O_8$ -------$K_2Al_4(Si_6Al_2O_{20}) +$
$(OH, F)_4 + 12SiO_2 + Na, Ca$

It can be seen that in order for the equation to balance, K, F, OH must be added to the system, while primarily Na and some Ca must be removed. It is possible for some Na and Ca to replace K in the muscovite, but not, presumably, in the quantities required.

Therefore, from microscopic observations, the breakdown of plagioclase supplies muscovite and quartz. In association with this, it is noticed that the quartz content of the central schists is increased, whilst that of the plagioclase decreases:

	margin	centre
quartz	20-30%	30-40%
plagioclase	35-50%	15-26%

The increase in quartz content could also be explained by silica enrichment from hydrothermal sources. However, vein quartz is seen to predate the muscovite schistosity.

A second reaction, involving the breakdown of biotite to liberate muscovite has also been seen (plate 80). Similarly, biotite depletion from margin to centre is noted in the schists:

	margin	centre
biotite	15-30%	5-15%

It is common to observe thin biotite flakes along muscovite cleavage planes and grain boundaries, with tiny iron oxide grains in attendance. A reaction, making biotite over to muscovite was suggested by Beach (1973):

Biotite ---------- Muscovite + Fe + Ti + K + Si

There is obvious loss of elements from the system. However, the Fe, Mg and Ti can be accounted for in the development of iron oxides and sphene; and K could be utilised in further muscovite development, involving plagioclase and the Si could be involved in further quartz growth.

The mobility of elements within shear zones has been studied in detail by Beach (1972, 1973, 1976), who shows that there is good evidence for infiltration metasomatism to occur. This is characterised by a high water/rock ratio, with the introduction of a fluid along the shear zone. The effect is for the rock to change in composition during the metasomatism as it tends towards equilibrium with the fluid. Beach (op. cit.) provides evidence for the enrichment of K, and the depletion of Ca, Na along with general desilicification.

From the optical determinations, it would appear feasible to assume that K enrichment, and Na, Ca depletion has occured from the margins to the centre of the schists. However, no geochemistry has been undertaken to confirm this assumption.

Discussion

Pelites or Gneissic Derivatives?

The process by which gneisses may be enriched in phyllosilicates has been discussed. The problem remains, are the schists derived from pelites or gneisses?

The traditional interpretation was proposed by Kvale (1946), who described the contact between the Lower Bergsdalen Nappe and the Basement gneisses as being marked by two narrow strips of mica-schist. He concluded that the schists were Cambro-Ordovician pelites, because they could be traced further to the northeast, where they joined the main zone of the Cambro-Ordovician fossiliferous phyllites (The Voss Phyllites). Kvale thus suggested that Nappe movement took place by slip along planes that had incorporated, and tectonically thinned the Cambro-Ordovician pelitic sediments. This interpretation is supported by Gray (1978), who remapped the contact between the Voss phyllites and the two strips of mica schist. In the study area the schists assumed to be correlatives of the Voss Phyllites by Kvale may however be derivatives of gneisses and thus their origin is of considerable importance.

Mineralogically, the Lower Bergsdalen schists have a typical pelitic character, containing a high proportion of coarse muscovite, along with quartz, plagioclase and biotite. Texturally, the schists exhibit obvious mylonitic features, with pronounced grain size reduction of quartz and plagioclase. Muscovite tends to develop as books, inhomogeneously distributed through the rock. From these features, it could be said that the schists are derived from pelites, that have been deformed during thrusting; the inhomogeneous muscovite distribution being controlled by local metamorphic differentiation driven by strain effects.

However, additional features are suggestive of the rock being derived in the main from gneisses:

1. The development of muscovite in a small scale shear zone within biotite gneisses (plate 74); in this situation, sporadically distributed muscovite books and strings occur parallel to the developing shear fabric that replaces the long limb of an F2 fold within muscovite free biotite gneiss. In addition, there is mylonitisation of the quartz and feldspar.

   There is no evidence for the introduction of any pelitic sediment along the shear, instead the phyllosilicates are being generated in part from plagioclase and biotite, and thus a schist is derived from a gneissic lithology. Although occuring on only a small scale, this shear could be indicative of the type of process involved in the main schist units.

2. The marginal relationships of schist to gneiss, with characteristic anastomosing veins, or strings of muscovite which may indicate a progressive reworking of the gneiss. Intensification of veining would lead to the development of schist.

3. On the microscopic scale, the biotite gneisses contain obvious secondary muscovite books growing adjacent to schist horizons. In contrast, the central cores of the schist units often have augen, that retain the character of the biotite gneiss fabric enveloped by the muscovite books; these relics are also sometimes discordant to the muscovite fabric. Similarly, on the macroscopic scale, relic lenses and ghosts of biotite gneiss are left within the schistose units. Thus, the texture seen in the central part of the schists may be interpreted as being the completed process of phyllosilicate enrichment, whereas the marginal features reflect an intermediate stage in the process.

To summarise, the evidence from this study suggests a derivation of the schist units, at least in part, from Precambrian biotite gneisses.

The end product of the process is a schist that has been generated under tectonic conditions, and as such should be defined accordingly: the term phyllonite was introduced by Sanders (1911), and was redefined by Knopf (1931) "a rock of phyllitic appearance that, as a rule, is indistinguishable from a normal phyllite .... being formed by the mylonitic degredation of an originally coarser grained rock." This definition implies that only a fine grained phyllitic looking rock can be called a phyllonite. However, in practice, the term is used in a more general way, to include mylonitic rocks of varying grain size, with a well developed phyllosilicate fabric. As such, phyllonites have been recognised from many tectonic zones (Soper and Wilkinson 1975, Banham 1968, Beach 1973). Phyllonites are not necessarily generated from rocks already rich in phyllosilicates; rocks of gneissic character have also been transformed to phyllonites due to tectonic processes (Banham 1968).

Model for the development of the schistose units

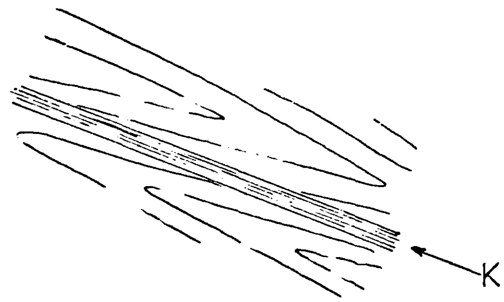
The schistose units (phyllonites) are of typical mylonitic appearance, both macro and microscopically, with the schistosity often defining a fluxion texture around augen containing granulated felsic minerals. The units are locally cross cutting to the regional biotite gneiss foliation yet having the internal schistosity everywhere parallel to the margin of the shear zone, with no sigmoidal curvature as recorded by Sibson (1977). It is therefore obvious that the muscovite schistosity is a strain controlled feature, generated under condition of shearing.

Thus, the proposed model for the derivation of the schistose unit is as follows: (fig 90)

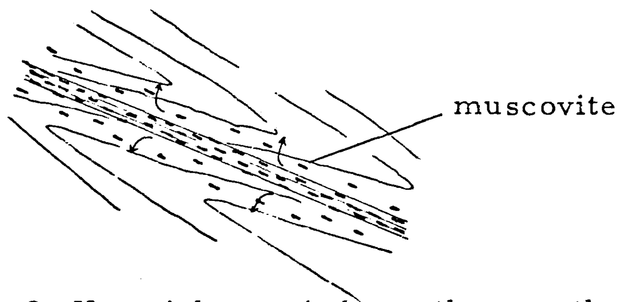
Banded gneisses undergo mylonitisation along discrete planes, controlled by the geometry of the F2 folds; thus a fluxion texture is initiated with narrow bands of granulated quartz and feldspar augening coarser porphyroclasts. Locally, small scale fold hinges are preserved within the augen. A fluid phase is postulated to be introduced synchronously with deformation, along the planes of shear; the effect of the fluid phase - assumed to be water, is as follows: (a) the water enhances migration of elements along the shear zones (Beach 1973), enriching the mylonite in potassium, and possibly removing some Ca and Na. The presence of potassium encourages the breakdown reactions involving plagioclase and biotite, to give muscovites in their place. (b) water lowers the temperature at which grain boundry diffusion can cause significant deformation, by the inducement of pressure solution (Sibson 1977)

(c) water acts as a plasticising agent, resulting in a reduction of yield strength, thereby increasing ductility (Griggs 1967)

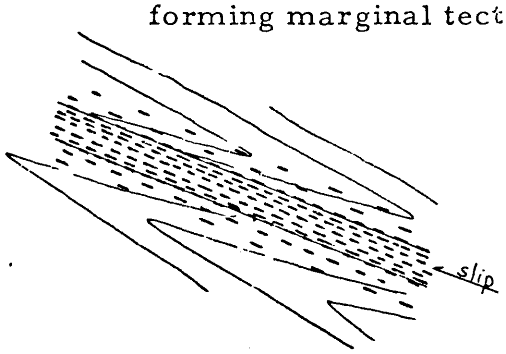
FIG 90 Model for the development of the tectonic schists (phyllonites)



1. discrete mylonite planes develop axial planar to F2 folds in zones of high strain. The mylonite planes act as channels for a fluid phase , which introduces elements such as K, and removes Ca and Na.



2. K enrichment induces the growth of muscovite; minor diffusion into the wall rock results in sporadic development of secondary muscovite-forming marginal tectonic schists.



3. continued deformation and recrystallisation of muscovite along plane of weakness defined by the muscovite schistosity. The margins of the schist zone are tectonically enhanced, although blocks of the wall rock gneiss may be preserved within the schistosity.

(d) water can play a direct mechanical role, whereby the increase in fluid pressure can cause a correspondingly greater decrease in differential stress required for further shear failure.

Thus, the muscovites crystallise synchronously with deformation, overgrowing and including strained quartz and feldspar. The muscovite tends to enhance the augen created by the initial mylonitisation, and a new foliation is generated, defined by the basal section of muscovite. Shearing continues during muscovite development, with further slip being taken up along the muscovite books wherever possible. Local, very small scale isoclinal folding of the muscovite books, and recrystallisation of the muscovite parallel to the axial planes is indicative of combined movement and recrystallisation during shearing. Adjacent muscovite books are often joined by discrete planes of mylonitisation, which develops when strain is taken up in the felsic matrix.

Fluid movement was confined primarily to these shear zones, although lateral diffusion might be expected, thereby creating "marginal schistose units" (biotite gneisses with secondary muscovite). However, continued movement during shearing emphasised the shear zone, typically creating a moderately sharp contact between phyllonite and wallrock.

4.7 The emplacement of the Eggjane and Lower Bergsdalen Nappes.

The following elements must be considered, in constructing a model to account for the emplacement of the nappes:

1. The Eggjane Nappe overlies a series of basement thrusts that are characterised by the development of steeply dipping ductile mylonitic gneisses, with mortar texture developed under greenschist facies. In contrast, the base of the Eggjane Nappe, is defined by low lying recrystallised ductile mylonites, derived primarily from the gneisses within the nappe, and formed at Lower amphibolite facies. This is termed the Eggjane thrust.

2. The geometry of the Eggjane thrust and the basement thrusts is very similar to that seen in the Moine Thrust Zone of Scotland, where the low lying Ben More thrust overlies steeply dipping thrusts within the Lewisian basement.

3. The intense development of basement thrusts immediately beneath the Eggjane thrust gives them an imbricated attitude, and as such they are overstepped from the southeast by the Eggjane Nappe (under Grånipa GR 0322067130).

4. The lowermost schist unit (no.1) lies structurally above the Eggjane Nappe, but is everywhere separated from it by a thin (2-5 metres) concordant horizon of very flattened Banded Gneisses (almost invariably of the biotite gneiss facies) which contain tight to isoclinal folds, often with attenuated limbs. These folds, because of their identical appearance and geometry, are considered to be equivalent to the F2 structures that immediately overlie the schistose unit.

5. The thin horizon of flattened Banded Gneiss immediately beneath the lowermost schistose unit (no.1) is in tectonic contact with the Eggjane Nappe, transgressing F2 structures within it. However, in both the northeast and southwest the Banded Gneisses are folded with the Eggjane Gneiss by F2 structures, thereby becoming part of the Eggjane Nappe (map 3).

6. Strongly folded (F2) Banded Gneisses separate the successively higher schistose units, which, apart from the highest (no. V) are invariably parallel.

The following model is suggested to account for Nappe emplacement:

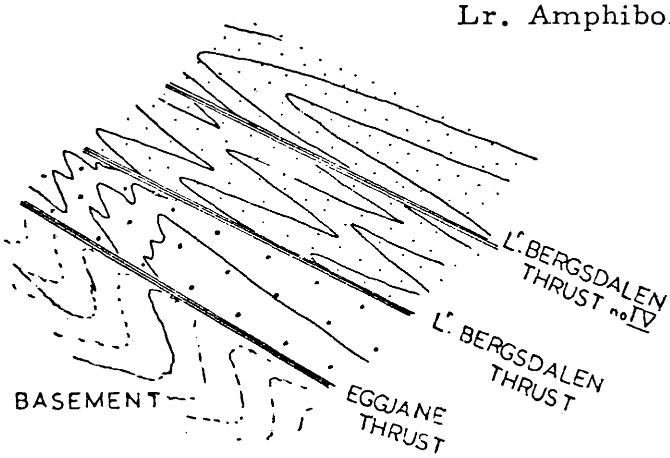
Folding on a northeasterly axis, with a northwesterly vergence, deforms all of the lithologic units that are incorporated in the basement/cover complex. The correlation of these fold structures (F2 in nappes, F3 in basement) across the complex is suggested from the identical geometry and the intimate association of folding and thrusting in each tectonic unit. (see also section 4.8)

Translation is initiated at moderate crustal levels, under Lower Amphibiolite facies (fig 91) conditions (approximately 550-600°C, 3-5kb equivalent to about 15kms. depth) by the attenuation of large scale fold limbs. The resulting juxtaposition of units occurs synchronously with metamorphism, so that recrystallised flaggy mylonitic gneisses are generated i.e. as seen at the base of the Eggjane Nappe. This phase of attenuation also juxtaposes Banded Gneisses against Eggjane Gneisses in the limb region of a major antiform, and generates zones of high strain within the Banded Gneisses i.e. juxtaposing amphibolites and Banded Gneisses (thrust zone No. IV)

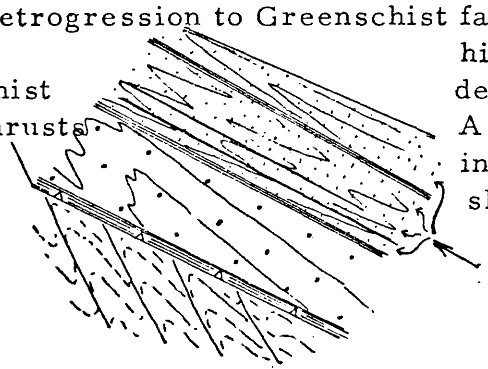
Continued stress is taken up by further uplift and translation along the flaggy mylonitic zones, primarily it would seem, at the base of the Eggjane Nappe (fig 91). At higher structural levels, translation is taken up along discrete planes of mylonitisation, which have associated retrogression to

FIG. 91 Model for the emplacement of the Lower Bergsdalen and Eggjane Nappes

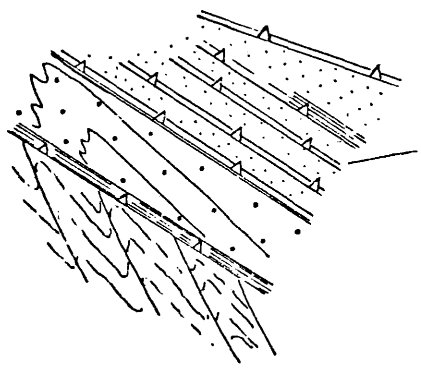
(a) movement is initiated along zones of high strain that develop, at Lr. Amphibolite facies, axial planar to F2 folds; flaggy mylonites are generated along these zones.



(b) uplift occurs with continued movement along more discrete, brittle, higher level thrusts that develop within the Lr. Amphibolite mylonites, causing local retrogression to Greenschist facies. Steeply dipping high level thrusts develop in the basement. A fluid phase, enriched in K is introduced along shear zones in the Lower Bergsdalen Nappe.



(c) continued movement is taken up along the developing Greenschist facies tectonic schists, resulting in a minor restacking of the Lower Bergsdalen Nappe.



Greenschist facies, and development of mortar texture. The Greenschist facies basement thrusts are also generated in these final stages.

Evidence for discrete planes of translation beneath the Eggjane Nappe is limited; detailed mapping at one location (fig 85) has shown that the base of the ductile mylonite gneisses is in thrust contact with the underlying Mixed Gneisses, with the thrust sporadically defined by a greenschist facies mylonite (with mortar texture)

Whereas the basement thrusts and the base of the Eggjane Nappe are characterised by high level brittle thrusts, the Lower Bergsdalen Nappe has its own characteristic tectonic features - namely the schistose units.

The schistose units are at Greenschist facies, so must have been generated late in the phase of nappe emplacement. It is envisaged (page 309) that the tightly folded Banded Gneisses near the base of the Lower Bergsdalen Nappe were invaded by a fluid phase during F2 deformation. Due to the subsequent metasomatic recrystallisation along narrow shear zones controlled by the D2 deformation, the schistose units that developed took up further translation within the Lower Bergsdalen Nappe.

However, it can not be shown whether the schistose units are generated during the main phase of nappe emplacement, or whether it represents a much later reworking, utilising the pre-defined structural grain.

Amount and direction of movement

Movement along the basement thrusts is considered to be minimal (probably no greater than 100-200 metres), as shown by the small displacements across outcrops of D1 and D2 (map 1) granites. However, no confident estimates for the amount of translation of the Eggjane Nappe can be made; the presence of flattened basement gneisses within the structurally lower part of the nappe, and the occurence of Eggjane Gneisses within the basement suggests that the nappe is not exotic.

Estimates for the amount of translation during D2 for the Lower Bergsdalen Nappe are not easily made. The possibility of only limited transport compared to the minimum distances proposed for the structurally higher Jotun Nappe complex (290-1000kms. Hossack 1978) is suggested from the presence of Banded Gneisses within the Mixed Gneiss tectonic unit.

The direction of nappe transport can only be deduced from the vergence of fold structures, and the limited knowledge of the thrust geometry. Folds associated with the thrusting in the basement and Eggjane Nappe are invariably overturned towards the northwest; small scale thrusts reflect movement in the same direction (plates 55, 56).

However, F2 folds in the Lower Bergsdalen Nappe, although verging to the northwest, are not seen in a complete enough form on the large scale for the sense of translation to be decided.

Evidence from the thrust geometry between the Eggjane thrust and the basement thrusts reflect a classical overstepping of the higher thrust from the southeast, indicative of translation from that direction (plate 91).

4.8 Correlation of structures across the basement/nappe complex (fig 92).

Correlation of structures across the basement/nappe complex is dependent upon the presence of recognisable structural markers. Granite and pegmatite bodies provide this marker, being intrusive into north easterly trending folds in every tectonic unit investigated.

The Rb/Sr isochron ages derived for the intrusion of the granites from both the basement (section 2.2a) and Nappe

(Gray 1978, Pringle et al. 1975) places them in the Sveconorwegian orogenic phase.

Thus, a general correlation can be made: (fig 92)

D1 structures from the nappe are intruded synkinematically by the Sveconorwegian granites, and are thus correlated with D2 folds in the basement that are also intruded by granites of the same age. Although not dated, granites of identical appearance intrude D1 structures in both the Eggjane Nappe and Mixed Gneisses.

This data however does not provide a specific correlation between fold phases; it is a more general statement that the gneisses of both the nappe and the basement were deformed and intruded during the Sveconorwegian orogenic phase.

Correlation of events across the basement/nappe interface that predate the granitic intrusive phase must necessarily remain uncertain with all of the gneisses exhibiting structures common to gneissic terrains throughout the world. i.e. intrafolial folds, amphibolite bodies, pegmatite and aplite veins.

Post granite intrusion structures do however exhibit very similar features; late D2 basement thrusting is correlated

FIG. 92 Summary and correlation of the structural sequences of the Bergsdalen Area

Basement Complex	Mixed Gneisses	Eggjane Nappe	Lower Bergsdalen Nappe
D"early": S"early"	D"early": S"early"	D"early": S"early" lineation (easterly trend)	D"early": generation of Banded Gneisses, intrusion of quartz diorite. early isoclines calc-silicate bands quartzite deposition
D1: F1 isoclines L1 lineation (easterly trend) granite intrusion amphibolite intrusion S1 developed	youngest position for tectonic mixing of the gneisses	amphibolite intrusion	
D2: F2 isoclines & shears, L2 lineation, S2 schistosity } NE-SW trend	D1: F1 tight/isoclinal, L1 lineation, S1 schistosity } NE trend	D1: F1 isoclinal, L1 lineation, S1 schistosity } NE trend	D1: F1 isoclines+shearing S1 schistosity
granite intrusion (1050±20ma)	granite intrusion	granite intrusion	granites intruded (950-1200ma)
flattening-enhance S2	flattening-enhance S1	flattening-enhance S1	flattening-enhance S1
thrusting . . . . ?	sliding		
D3: F3 closed/tight, enhance lineation L2 } NE-SW trend	D2: F2 closed/tight, enhance lineation L1 } NE trend	D2: F2 tight, enhance lineation L1 } NE trend	D2: F2 tight, Lineation L1, Schistosity S2 } NE trend
Thrusting	Thrusting	Thrusting	Thrusting
			D3: F3 closed/tight Lineation L2
			Thrusting
D4: F4 open/closed, quartz veins } NW-SE trend	D3: F3, quartz veins } NW-SE trend	D3: F3, quartz veins } NW-SE trend	D4: F4, quartz veins, Lineation L3 } NW-SE trend

with the introduction of the Mixed Gneiss tectonic unit during the late D1 phase of that unit (fig 92).

Similarly, the folding associated with Nappe emplacement is believed to be expressed in both basement and nappes (D3 and D2 respectively). The geometry of the folding, and its intimate association with thrusting on either side of the basement/nappe contacts is identical; in the case of the basement-Mixed Gneiss tectonic unit correlation, direct proof is furnished by the two units being folded together prior to thrusting during D3 (basement).

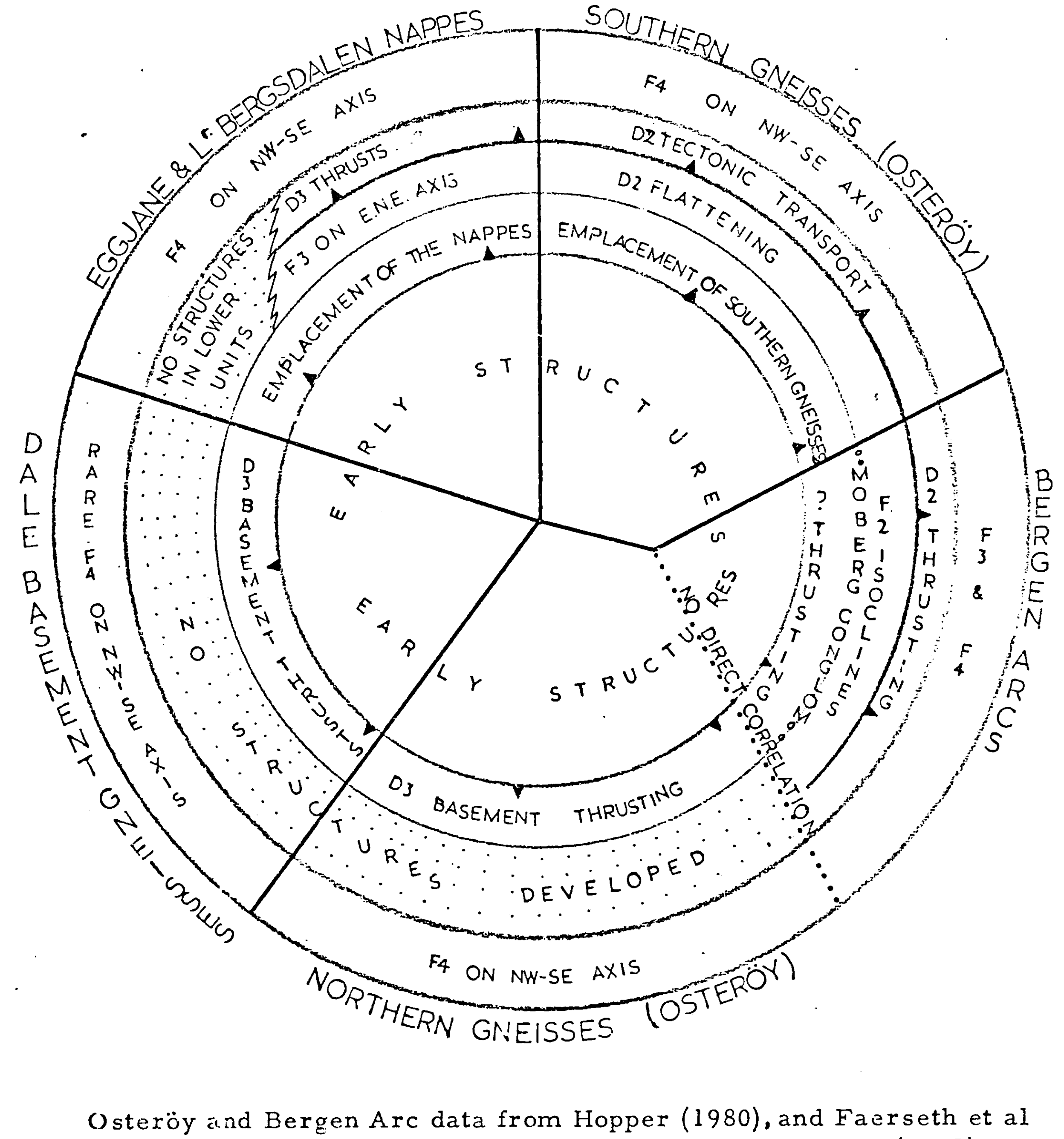
Nappe emplacement provides a second important structural marker, upon which subsequent events may be correlated. Although D3 (nappe) is entirely restricted to the higher units of the Lower Bergsdalen Nappe in the area mapped, D4 is recognised in every tectonic unit, being distinctive due to its cross fold nature.

4.9 Correlation of basement structures from North Osterøy and Eksingdalen to those seen at Dale (fig 93)

Correlations of basement structures are readily made between the areas. The same history is recognised in all three areas (Gray 1978, Hopper 1980), with the additional element of a phase of eastsoutheast folding within Eksingdalen (Gray op. cit)

FIG. 93

Correlation of structures developed in association with Nappe transport in the basement and nappes of the Bergen area.



Osteröy and Bergen Arc data from Hopper (1980), and Faerseth et al (1977)

Younger basement structures are developed more intensely towards the Bergsdalen Nappe front; F3 folds are only rarely developed in north west Osterøy, moderately developed in north east Osterøy and strongly developed immediately beneath the nappe pile. In Eksingdalen (Gray op. cit) recognition of this phase is complicated by the development of post nappe emplacement folding (F3 in the Bergsdalen Nappe) this is similar in appearance to the F3, pre-nappe folds of the basement. Because of this, Gray (1978) has combined the two phases F2 and F3 that are recognised in the Osterøy and Dale basement, into one phase, and has termed the post-nappe emplacement structures F3 in both basement and nappe.

4.10 Post Nappe Emplacement Structures

These structures are identified because they deform nappe emplacement thrusts.

(a) Deformation D3 (Lower Bergsdalen Nappe)

Structures associated with this deformation phase are almost entirely restricted to the Lower Bergsdalen Nappe, although rare low amplitude open folding has also been seen in the Eggjane Nappe, (on the northwestern flank of Storafjell, GR 032806 7180). Large scale D3 folds within the lowermost unit of the Lower Bergsdalen Nappe occur only in the central and northeastern quadrant of the mapped area, dying out to the southwest (towards Vaksdal). However, in contrast, the D3 folds occur throughout the higher structural levels, above the Bukkafjell thrust, intensifying towards the southwest, and the Bergen Arcs. (fig 23 . map 2)

The structural sequence recognised for the D3 phase is as follows:

1. Folding (F3), lineation (L2)

D2 structures are seen to be deformed on both a small and large scale by D3 folds (plate 85 Fig 94). Both the outcrop pattern of the amphibolite/Banded Gneisses on the north facing slope of Bergsdalen, and the granite outcrop patterns on Flatafjell are due to the superimposition of large scale F2 and F3 folds (fig 23).

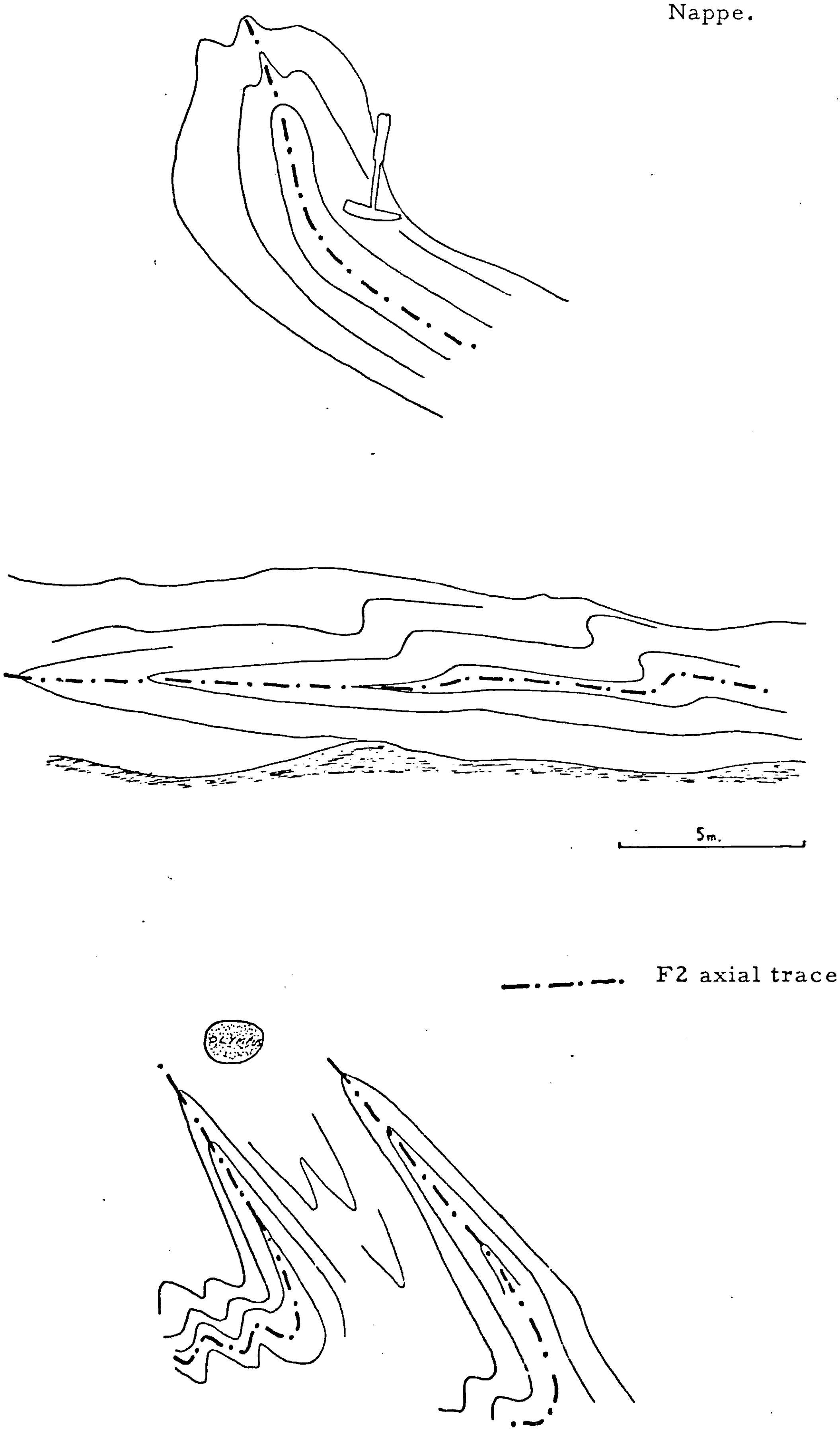
Locally, F2 and F3 may appear very similar in profile, with a similar axial trend, so that the presence of D2 phyllonites can form an important marker. Another obvious D2 feature - the strong shape fabric lineation, folded around some F3 hinges. F3 folds are recognised on all scales, from having a regional importance, down to being represented by a crenulation in phyllonites

Large scale structures

Two major folds, each with paired antiform and synform, are

FIG. 94

Sketches, from photographs, of the superimposition of F2 and F3 structures in the Lower Bergsdalen Nappe.



recognised in north of the mapped are, having a wavelength of 2km. and minimum amplitude of 600 metres; their axial traces can be followed for up to 12 kms. (fig 76). These folds control the present outcrop distribution of several of the schistose units (fig 23).

In the southwest of the area, above Vaksdal and structurally overlying the Bukkafjell thrust, two major F3 folds have also been traces from the north easterly Bergsdalen trend into the northwesterly trending margin of the Bergen Arcs (fig 100). The large scale F3 folds are closed asymmetrical structures, overturned towards the northwest, with axes plunging at 20^o towards the east north east. The short, steep limbs dip between 60^o - 80^o towards the southeast, whilst the long limbs have a low dip of 20^o - 30^o in the same direction.

Small scale structures

Small scale structures occur dominantly within the hinge regions, and on the steep limbs of the major folds. The small scale folds are often markedly non-cylindrical (in contrast to the cylindrical nature of the large scale folds), and vary in tightness of interlimb angles (plate. 84); the axes take both variable orientations and plunges, although the axial planes retain the planar attitudes (plate 85). The non-cylindricity of the small scale folds accounts for the scatter of orientation data (fig 95). The mean trend of the small scale fold axes is towards the east north east with an approximate plunge of 20°. Axial surfaces dip towards the southeast at 50°. (fig 96).

Small scale crenulations are common within the more schistose units(including quartz schist), and locally a new schistosity (plate83) and (plate 72) is generated, especially in the southwest of the area, above Vaksdal.

As mentioned above, the D2 lineation(L1)is folded around F3 hinges. This feature is fairly rare, as L1 and F3 often tend towards being coaxial; thus, a strong shape fabric lineation (probably L1) often appears to be associated with F3. However F3 folds are not always coaxial to L1, due to the non-cylindrical nature of the folds. It is these, more irregularly trending F3 axes that show folded shape fabric lineations (L1) (plate 85).

Lineations ascribed only to F3 (and not composite F2, F3) are typically of the crenulation type, with a little recrystallisation of biotite parallel to the axes (L2). Locally, within the hinge region of the tighter F3 folds, a shape fabric lineation is generated parallel to the axis. (fig 97)

The strong shape fabric lineation in the granites (L1) is

FIG. 95 Plunge of F3 fold axes in the Lower Bergsdalen Nappe

Area : 1 (fig. 51)
N : 130
contour intervals:
1, 4, 10, 15, 20%

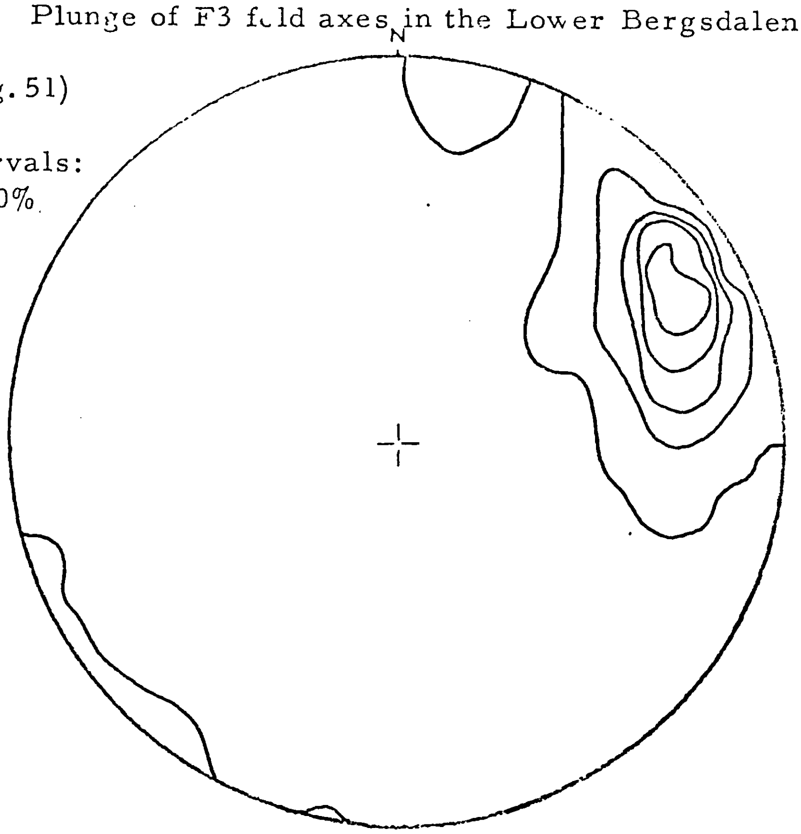
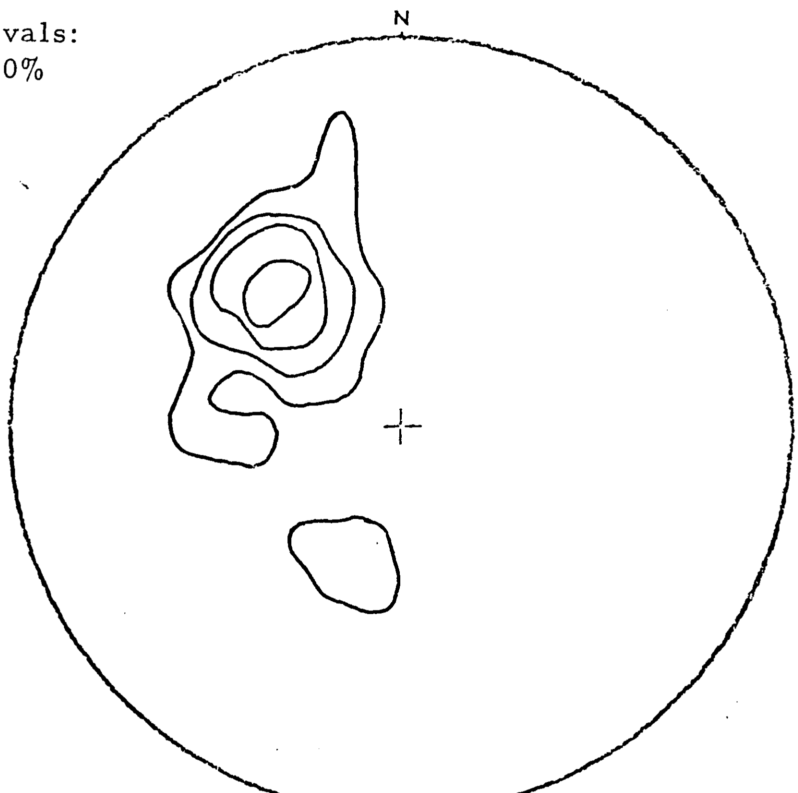


FIG. 96 Poles to F3 axial surfaces in the Lower Bergsdalen Nappe

Area : 1 & 2 (fig. 51)
N : 103
contour intervals:
1, 5, 15, 30%



lower hemisphere
equal area
stereographic projection

FIG. 97 Plunge of lineation L2 in the Lower Bergsdalen Nappe

Area : 1 & 2 (fig. 51)
N : 72

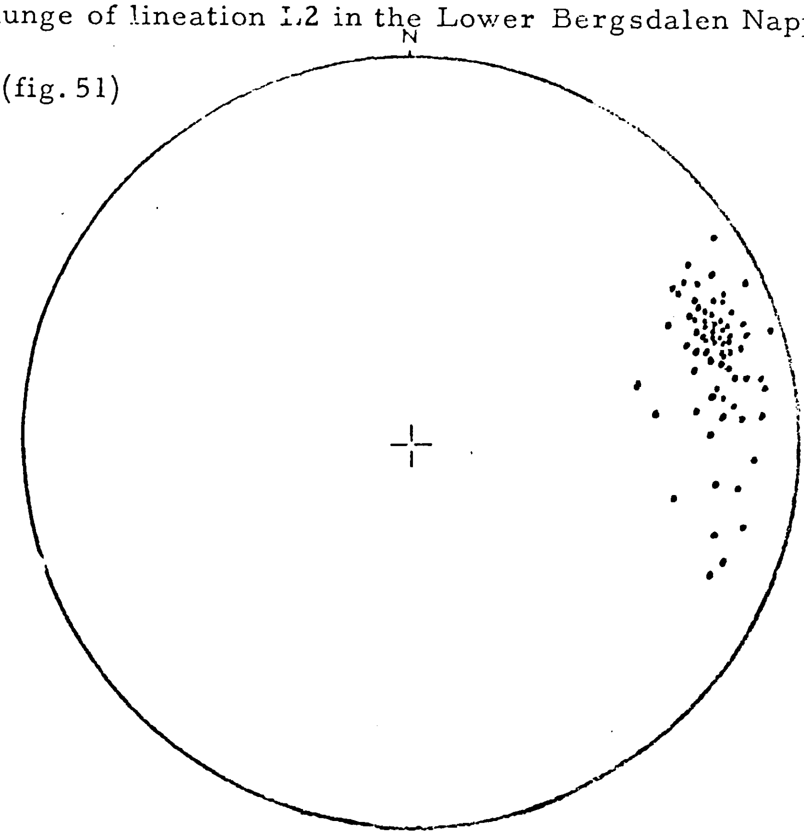
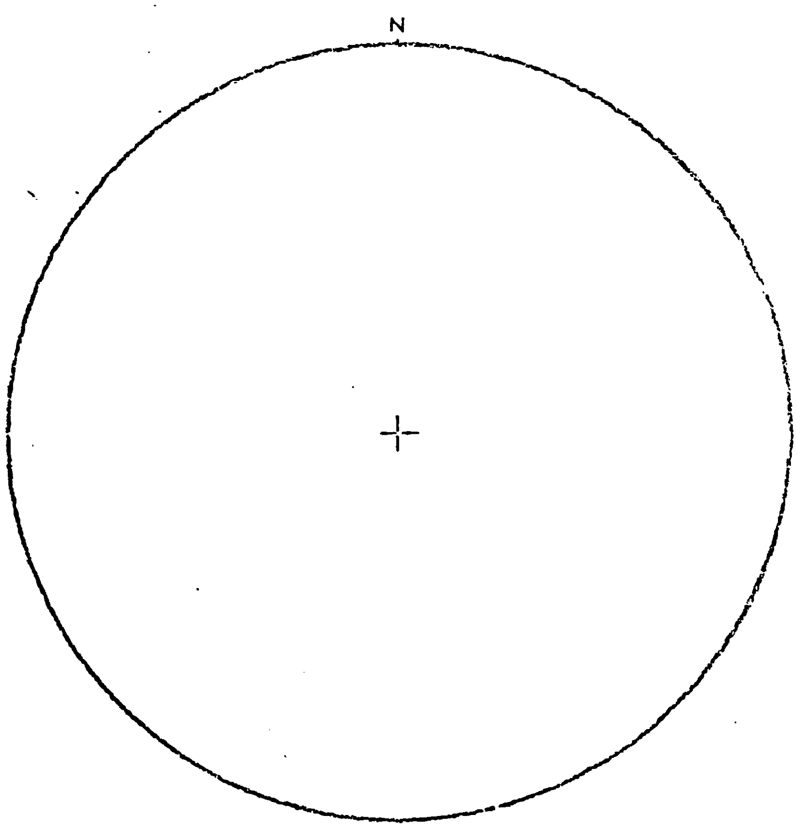


FIG.

Area :
N :



lower hemisphere
equal area
stereographic projection

seen to be folded by the gentle F3 folds on the shallow limbs of the major folds, yet is apparently coaxial to the closed-tight F3 folds in the hinge zone of the major folds. In the southwest, above Vaksdal, no separation into L1 or L2 can be made. In both the granites and quartzites, there is shape fabric lineation that is parallel to the F3 fold axes. A crenulation lineation occurs in the granite phyllonite.

2. Thrusting

Two thrusts of D3 age have been mapped; (fig 76)both trend to the northeast, at an angle of approximately 20° to the strike of the structures they cut. The structurally lowest thrust, termed the Bukkafjell thrust, carries extensive granitic and quartzitic lithologies over the Banded Gneisses, and is marked by an obvious topographic feature (plate 82) Kvale (1960) considered this thrust to separate the middle and upper sheets of the lower Bergsdalen Nappe. Large scale D3 structures are cut out along its length, including a folded schistose unit (no. V), immediately to the southwest of Gråvatnet (GR 0329967148) (fig 76). The Bukkafjell thrust dips steeply towards the southeast, although the thrust plane is only poorly exposed. When traced towards the southwest, the thrust becomes less distinct, due to topographic and vegetation cover, and can only be postulated to pass through Herfendal, and on towards Vaksdal.

The second, and structurally higher thrust is sited within the granites and quartzite lithologies . The thrust replaces the steep limb of a large scale D3 antiform (fig 98) with the resulting truncation of a horizon of Banded Gneiss and a schistose unit.

Again, the thrust forms a well defined topographic feature, and has been followed for several kilometres away from the Bergen Arcs (fig 100). The thrust dips to the southeast at approximately 50^{o}; until modified by subsequent (D4) deformation in the vicinity of the Bergen Arcs. Exposure is good along the thrust, with the thrust plane defined by a 1 metre thick flaggy mylonite gneiss, possessing a strong shape fabric lineation that is parallel to that of the enveloping lithologies.

These two thrusts juxtapose rocks that are strongly deformed by D3 structures against the Banded Gneisses that are only deformed by D3 in the more northerly portion of the mapped area. By making a traverse from northeast to southwest in the Banded Gneisses, one is passing into structurally deeper levels. Consequently, within the Banded Gneisses, the D3 folds die out towards Vaksdal, whilst they increase in intensity

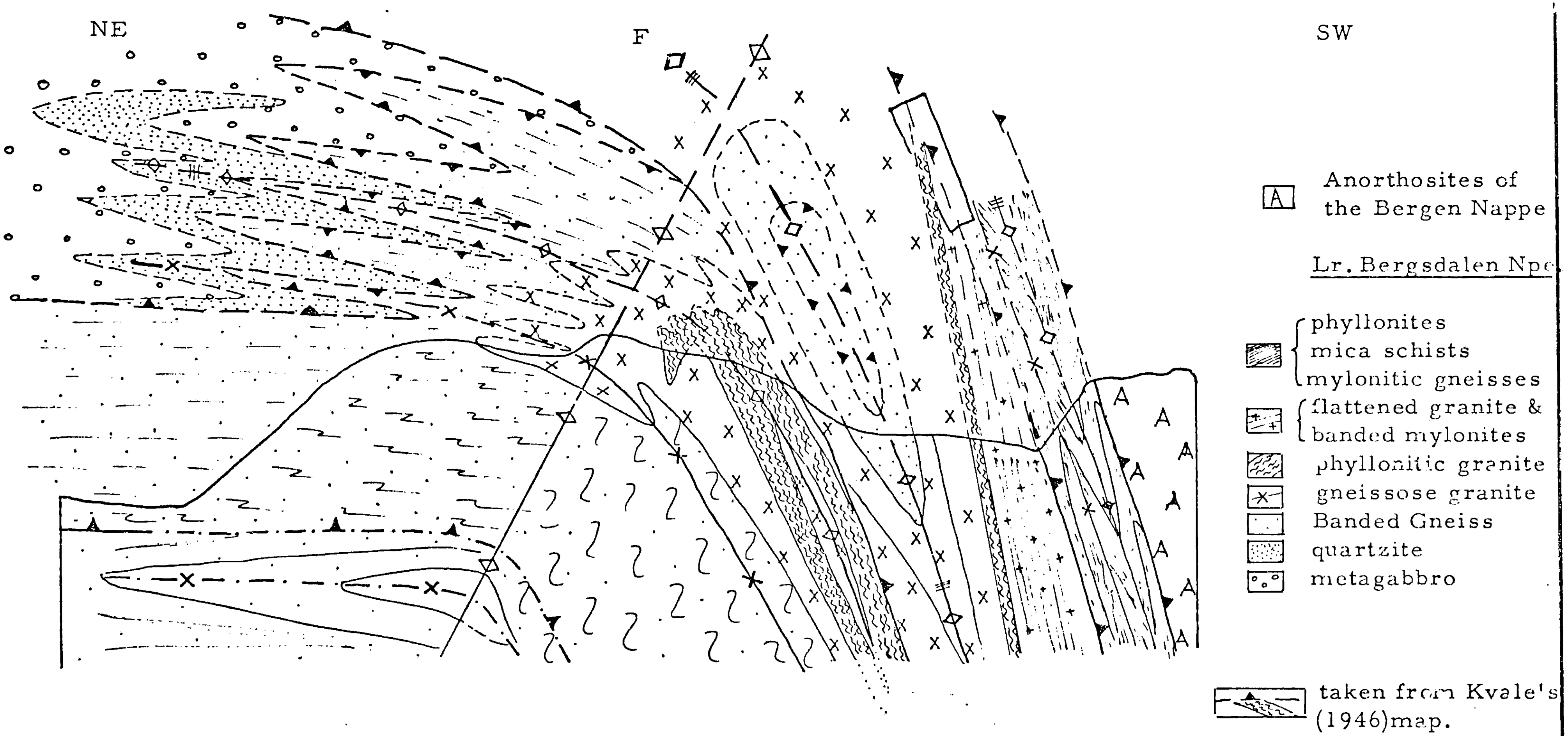


FIG 98 Profile across the Lower Bergsdalen and Bergen Nappe interface.

towards the northeast, as described by Gray (1978), who shows that F3 folds the northwest margin of the Lower Bergsdalen Nappe, along with the underlying autochthonous basement.

4.10 b

Deformation, D4 (Nappes and Basement)

The fourth deformational phase is dominated by a single, large scale (amplitude ~ 2kms) antiform (fig 98), the axial trace of which outcrops on a north west - southeast trend in the extreme southwest of the area (fig 99). Most of the mapped area lies on the shallow, upper limb of the structure, consequently it is affected by only minor folds of sporadic occurence. However, the area to the south west of the axial trace forms the steep limb, with foliation dipping between 50° - 90° towards the southwest, and is dominated by small scale folding. The D4 antiform controls the outcrop patterns, swinging the Bergsdalen Nappe and all of its inherent structures (including thrusts) onto a northwest - southeast trend, thus defining the margin of the regional Bergen Arc structure (fig 100)

D4 minor structures deform earlier structures within the gneisses; the most obvious expression of this being the strong shape fabric lineation (in both basement and nappes) folded over the F4 hinges (plate 87), imparting a steep plunge towards the southwest. (figs 101, 102) The refolding of F3 (nappe) folds by F4 results in small scale interference patterns, of type 2 and type 3 (Ramsay 1967, p. 528) (plate 86)

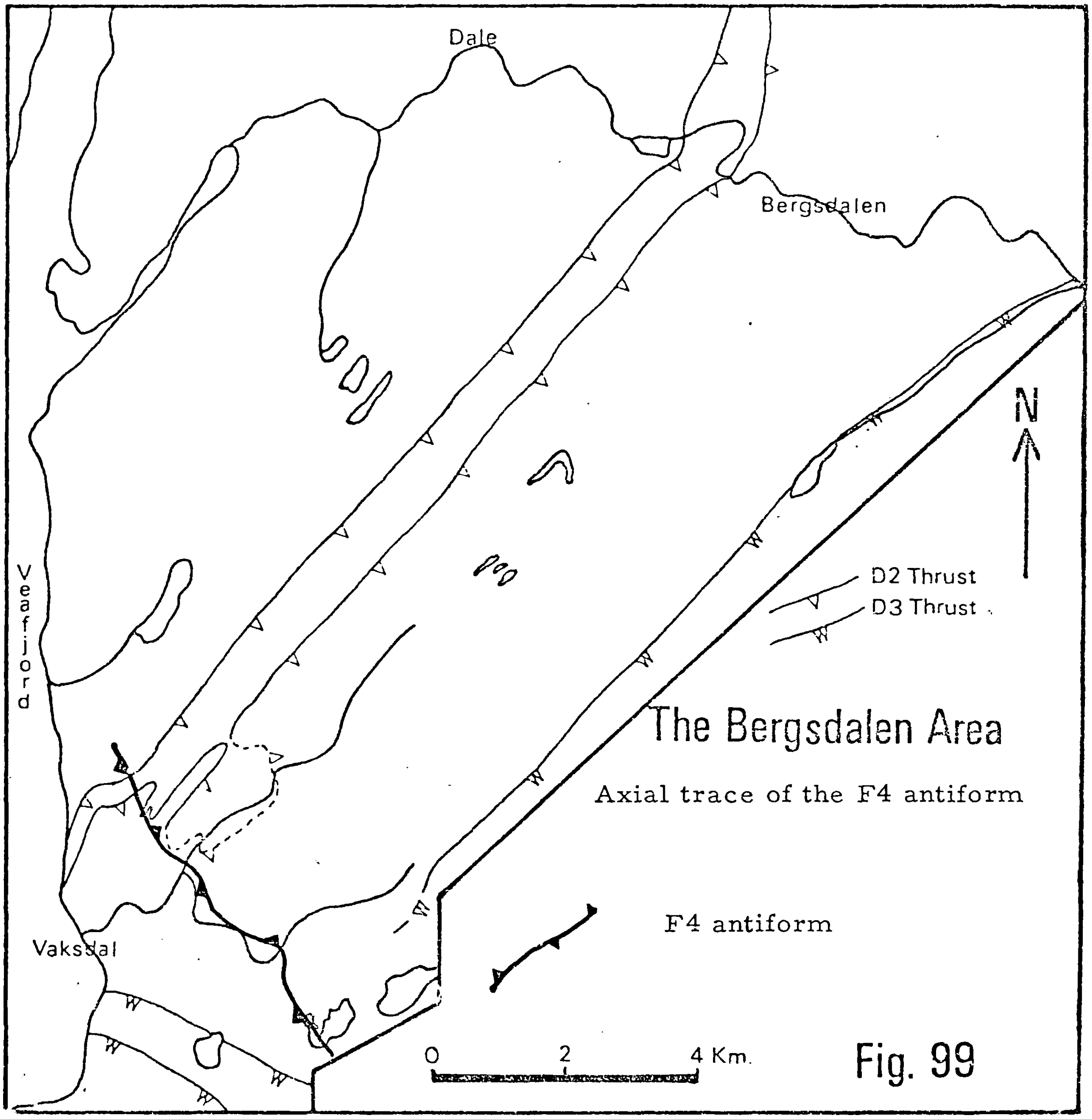
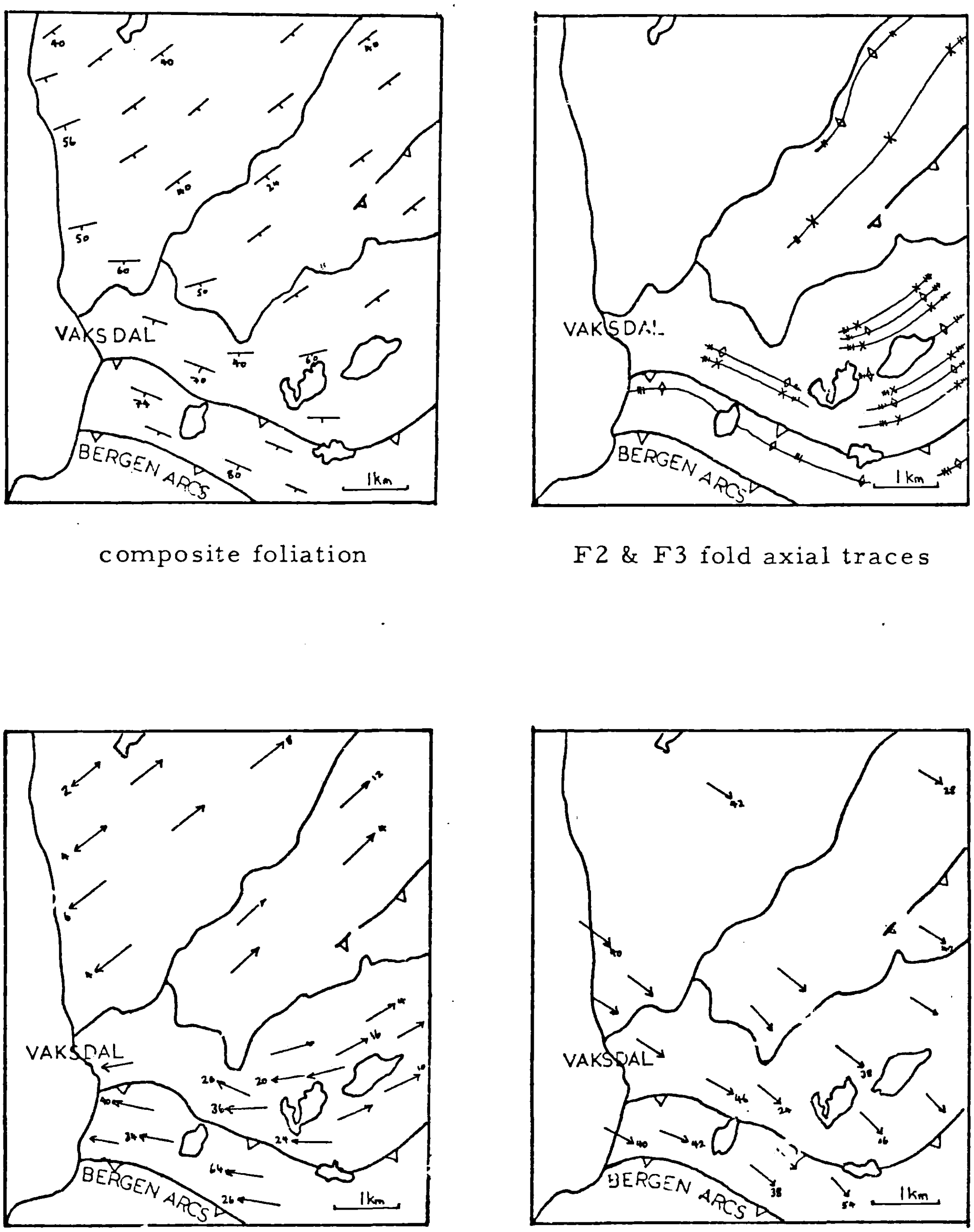

Dale
Bergsdalen
Veafjord
Vaksdal
N
D2 Thrust
D3 Thrust
The Bergsdalen Area
Axial trace of the F4 antiform
F4 antiform
0
2
4 Km.

Fig. 99

FIG.100 Effect of F4 on structural elements within both autochthonous and allochthonous units of Bergsdalen.



composite foliation — F2 & F3 fold axial traces

plunge of F2 & F3 fold axes — plunge of F4 fold axes

FIG. 101 Plunge of F3 fold axes in the Lower Bergsdalen Nappe

Area : 4 (fig. 51)
N : 31

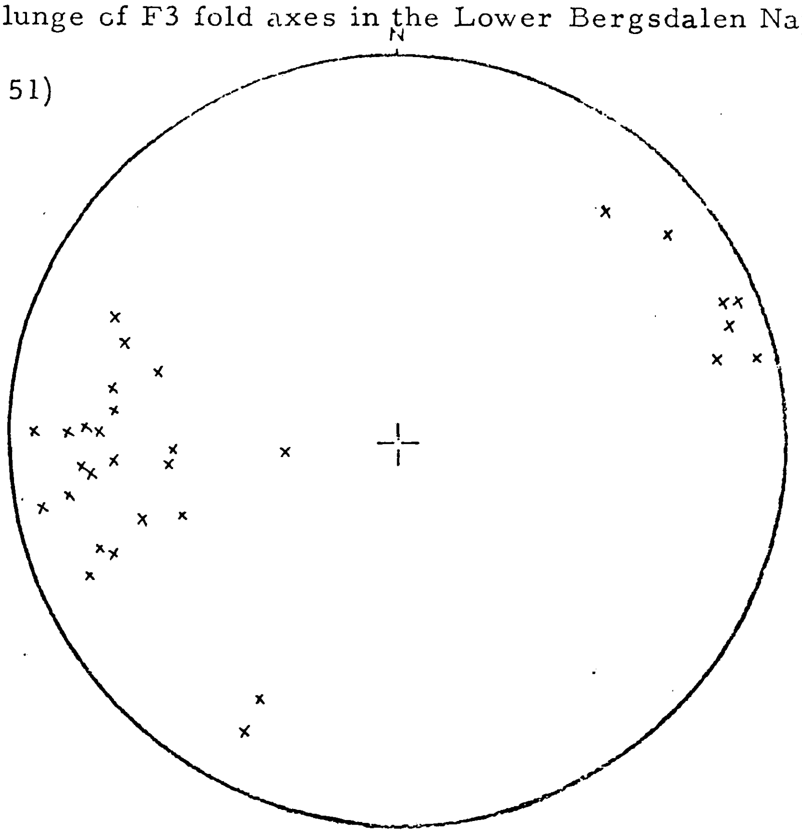
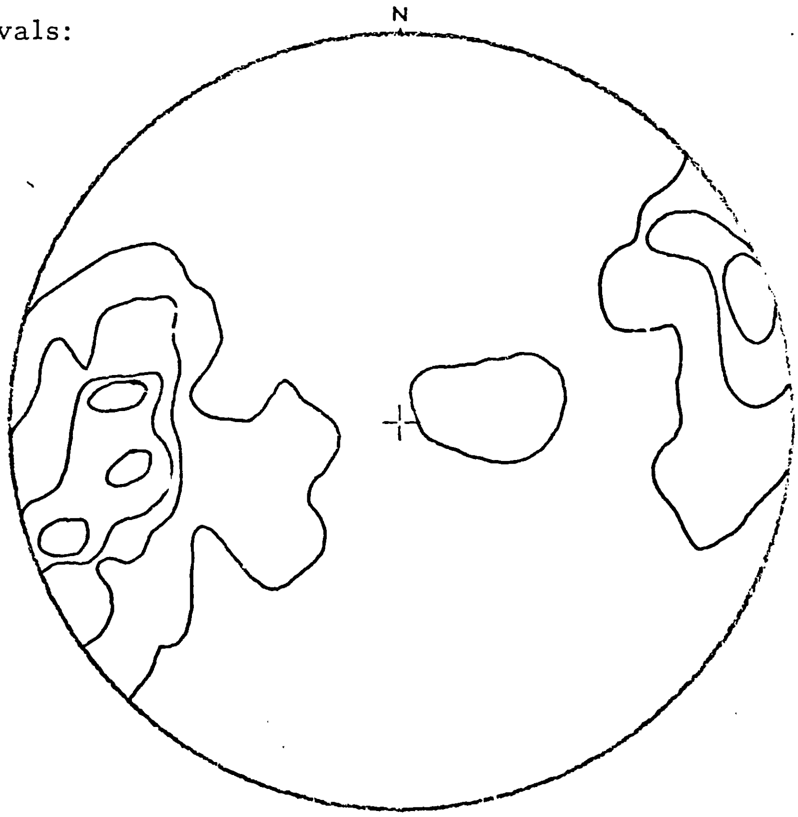


FIG.102 Plunge of lineation L2 in the Lower Bergsdalen Nappe

Area : 3&4 (fig. 51)
N : 100
contour intervals:
1, 4, 7, 10%



lower hemisphere
equal area
stereographic projection

FIG. 103 Poles to F3 axial surfaces in the Lower Bergsdalen Nappe

Area : 4 (fig. 51)
N : 54

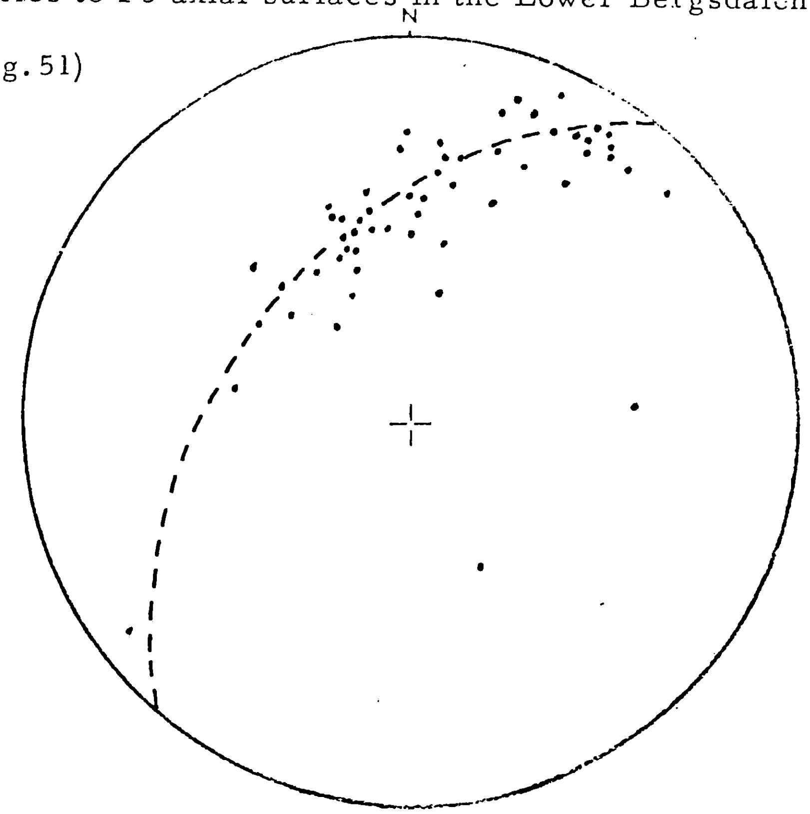
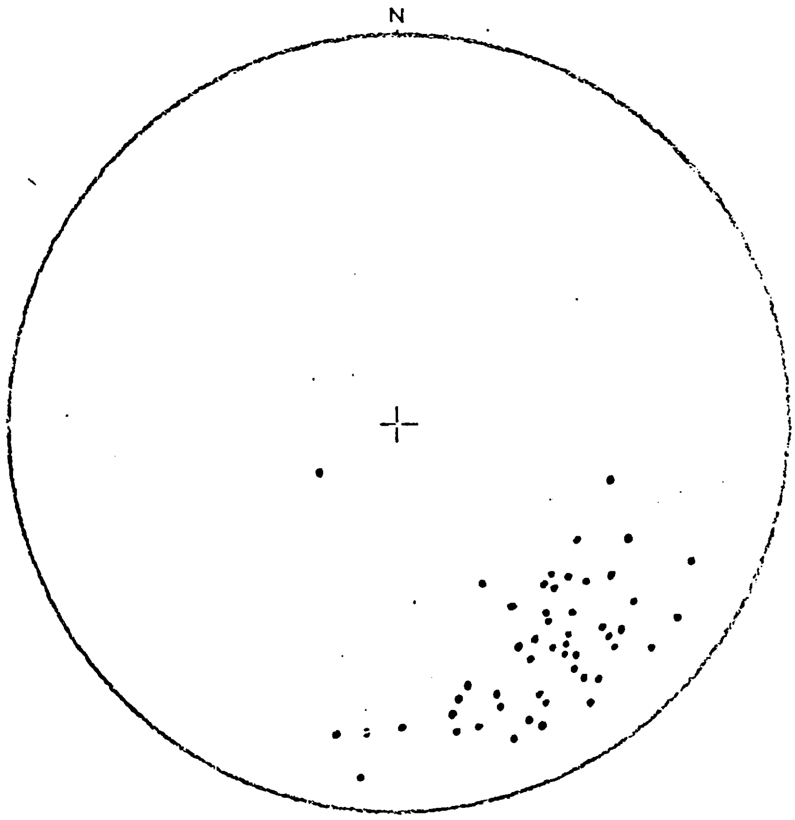


FIG. 104 Plunge of lineation L3 in the Lower Bergsdalen Nappe

Area : 3 & 4 (fig 51)
N : 52



lower hemisphere
equal area
stereographic projection

FIG.105 Plunge of F4 fold axes (x) and pole to F4 axial surfaces (•) in the Basement complex

Area : B (fig 51)
N : x 74
• 50

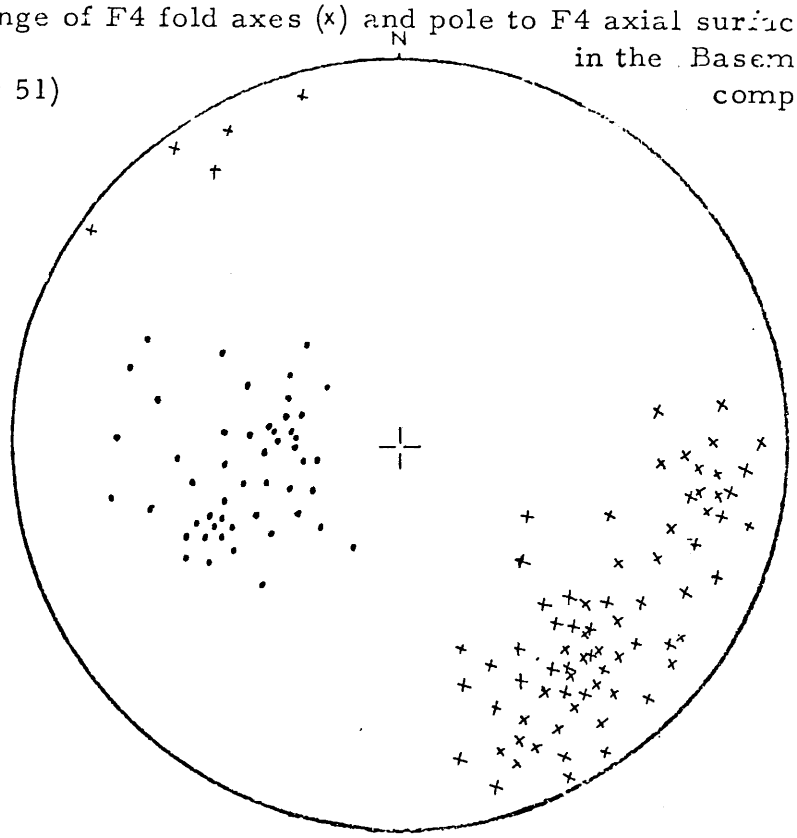
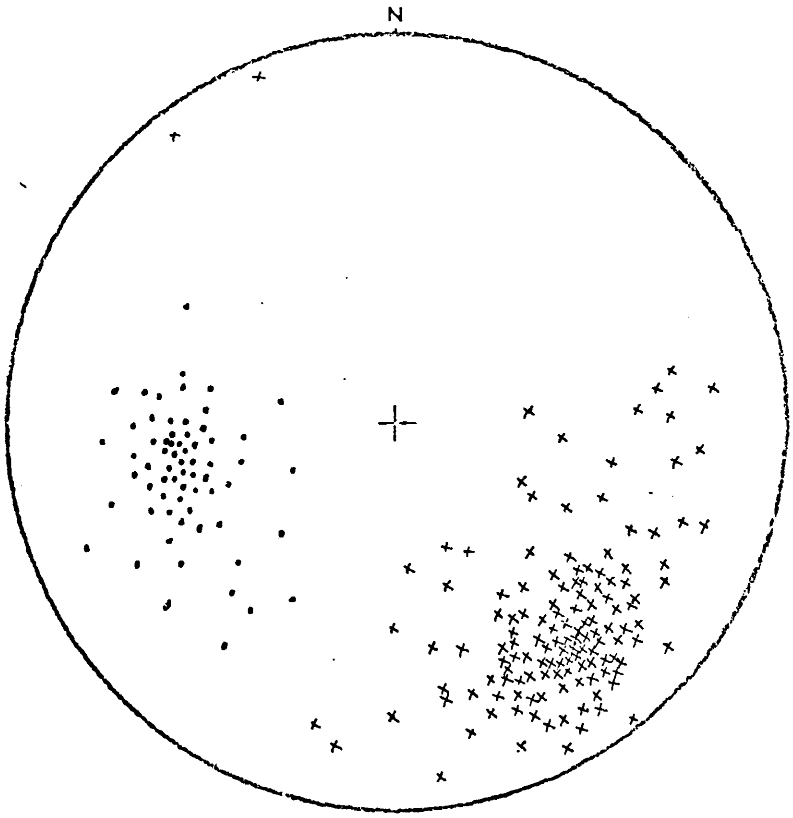


FIG. 106 Plunge of F4 fold axes (x) and poles to F4 axial surfaces (•) in the Lower Bergsdalen Nappe

Area :3 & 4 (fig 51)
N : x 135
• 66



lower hemisphere
equal area
stereographic projection

F4 small scale folding is typically non-cylindrical, with hinge lines being curved, trending towards the southeasterly quadrant; the axial planes dip consistently at a moderate angle towards the eastern sector (figs 105,106) Fold profiles are asymmetric, varying from open to tight, are invariably overturned towards the southwest.

A distinctive feature of D4 in both basement and nappe is the association of axial planar quartz lenses whilst in the basement, the gneisses have sheared (with a movement sense from the northeast to southwest) rather than folded.

A plunge parallel lineation (L3) is developed (fig 104), primarily on the steep limb of the regional antiform. Typically, the lineation is a crenulation, and as such is of variable strength, depending upon the anisotropy of the deformed lithology. Minor recrystallisation of micas, parallel to the axial surfaces, results in a weak schistosity and intersection lineation, that complements the crenulation lineation.

4.11 The structural relationship between the Lower Bergsdalen Nappe and the Bergen Arcs.

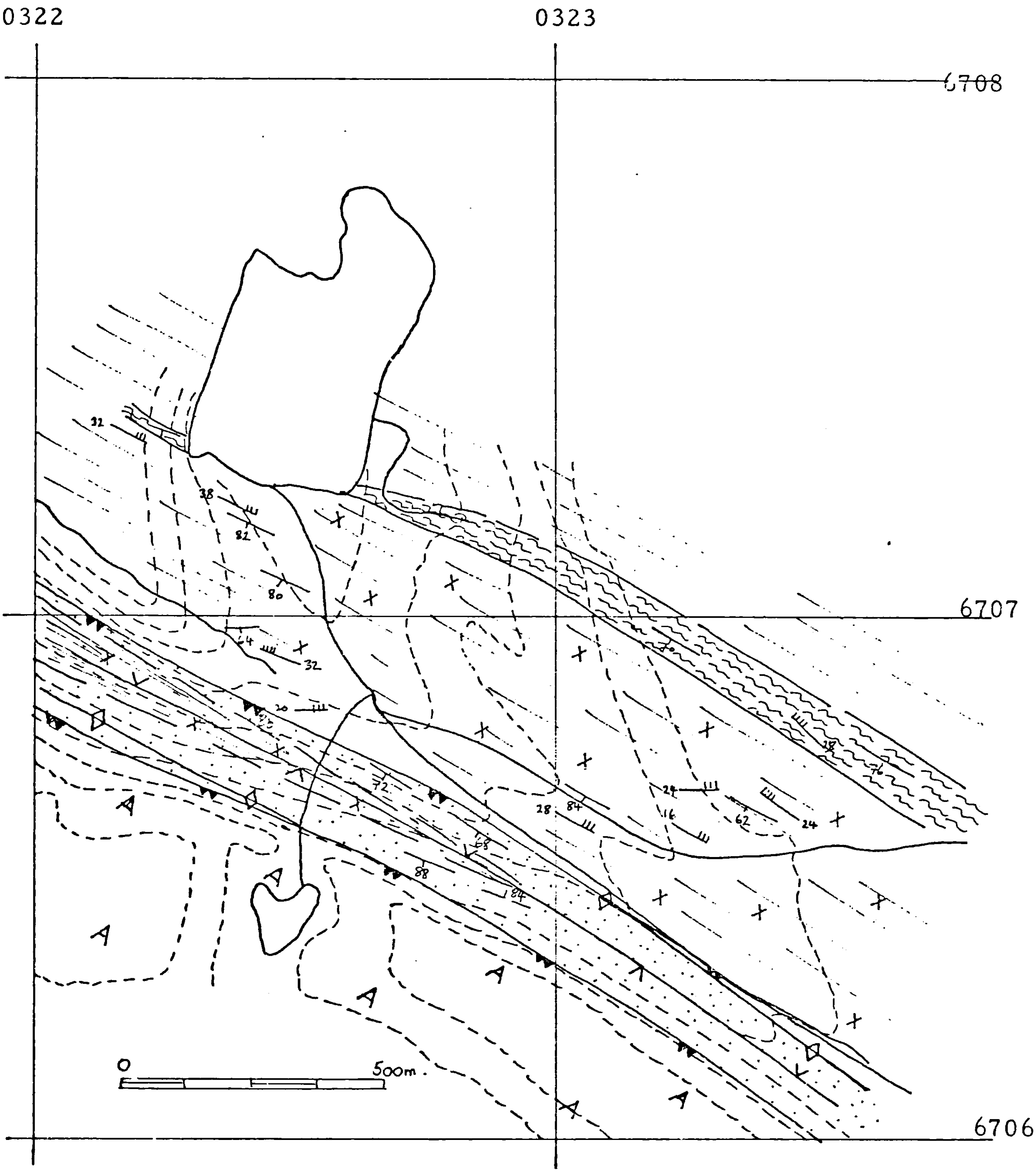
Field observations show that the structurally higher units of the Lower Bergsdalen Nappe (involving predominantly quartzite and granite) are deformed by large scale eastnortheast- west southwest trending D3 folds that are subsequently refolded by the large scale D4 northwest-southeast trending antiform (fig 100). The effect of the refolding is to produce a marked swing in strike of the Lower Bergsdalen Nappe, to that now seen as the steeply dipping margin of the Bergen Arc structure.

In order to compare structures of known chronological position developed within the Lower Bersgsdalen Nappe, with those seen at the margin of the Arcs, a descriptive traverse upwards in the structural sequence from northeast to southwest, perpendicular to the Arc margin (fig 108) can be made

1. A large scale F3 antiform, involving gneissose granite, quartzite and Banded Gneisses, with its lower limb replaced by a D3 thrust (page 330) can be traced into the marginal zone (fold, F on fig 98). The F4 deformation results in the axial trace and the thrust being rotated into a northwest - southeast trend, with associated steepening of the dip. The F3 fold axis changes in attitude, from a 20^{o} plunge towards the eastnortheast, to a 50^{o} - 60^{o} plunge (locally greater) towards the westsouthwest (figs 101, 102)

2. The upper limb of the antiform involves a concordant granite phyllonite of D2 age (section 4.6b); structurally above this are highly deformed gneissic granites (figs 107, 108) with a pervasive D2 fabric (S2) (section 4.5c) that dip to the southwest between 60^{o} - 80^{o}. Also involved with the gneissose

FIG 107 The margin of the Bergen Arc



A	Anorthosite kindred (augen gneiss) - Bergen Nappe	
	Mica schist, phyllonite and mylonites	Lower Bergsdalen Nappe
	Phyllonitic granite	
	Flaggy granitic gneiss; in places mylonite	

strike of foliation — D3 thrust

Lineation L2 & L3 — F3 antiform

topographic contours — F3 synform

lake and river

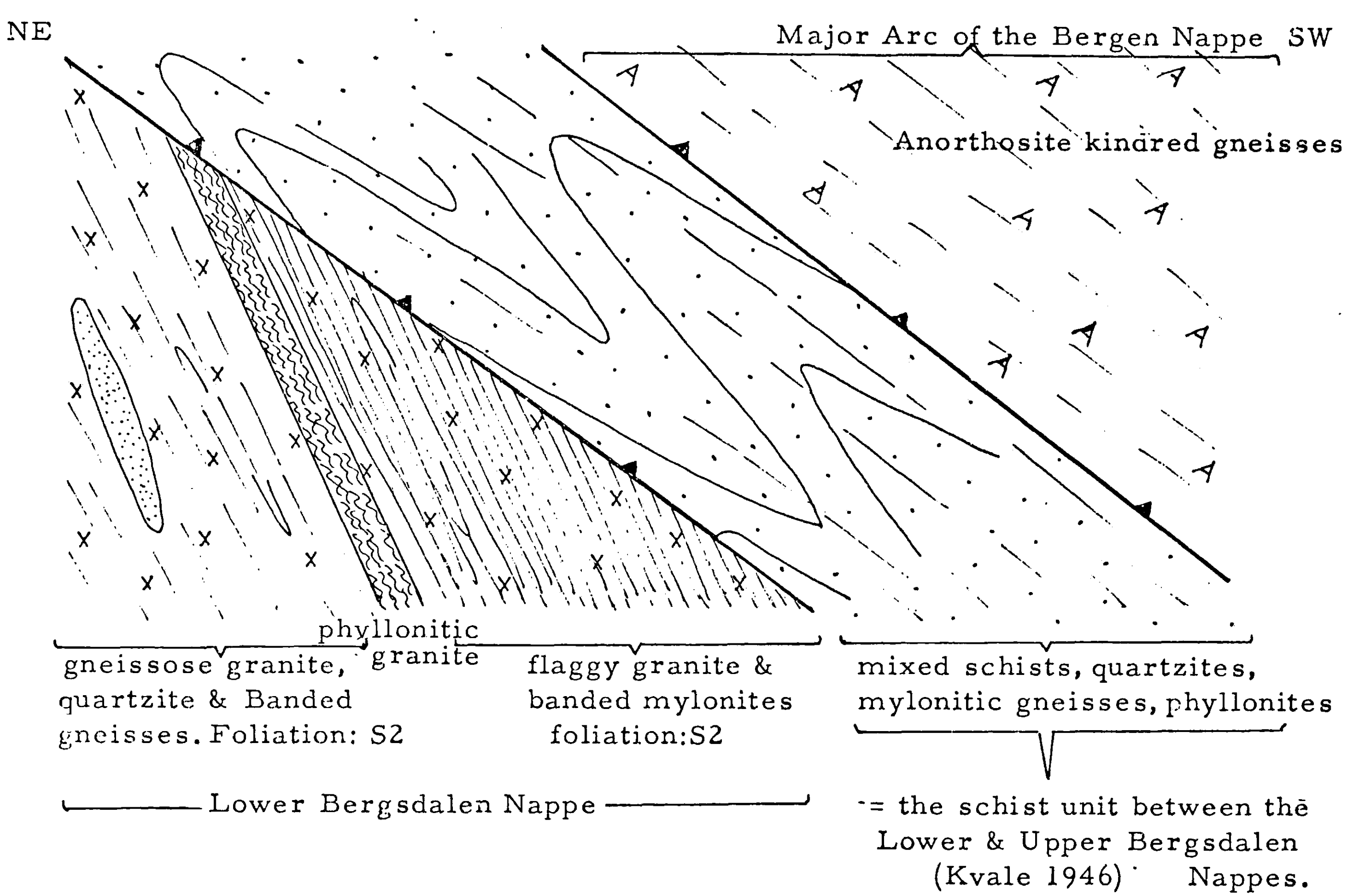


FIG. 108 Schematic tectonic section across the Lower Bergsdalen Nappe and the Bergen Nappe

granites are banded mylonites (with the mylonite fabric equivalent to S2) that include granitic, amphibolitic and psammitic lenses with locally, internal isoclinal structures; the mylonitic banding is folded on a small scale by tight or isoclinal D3 folds (plate 88).

3. Overlying this highly flattened unit of flaggy granite and mylonitic gneiss is a folded unit of mixed metasedimentary garnet mica schist, phyllonites, quartzite lenses and mylonitic granite. The contact between these schistose units and the underlying mylonitic gneisses is interpreted as tectonic because:

a) the mixed schist unit is tightly folded on a large scale. The lower limb of the fold, and the axial traces are cut out along the contact (fig 107 , plate 89).

b) Kvale's map (1946) shows that the granite phyllonite and the mylonitic gneiss are cut out further to the southeast, along the lowermost contact of the schist unit. (fig 98)

Both features are indicative of a thrust contact; similarly the upper contact of the mixed schists is considered to be thrust, with fold limbs and axial traces truncated along the base of the overlying Anorthosite kindred gneisses of the

Bergen Arcs (Faerseth et al 1977)

Discussion

Structural correlation across this traverse is difficult; the large scale antiform that is folded into the Bergen Arc trend is F3 in age, and is cut by D3 thrusts. However, the schistose unit, being a thrust bounded block contains no readily identifiable 'markers' that might aid correlations.

Thus, a structural correlation is made on the following basis:

a) the tight, large scale folds within the schistose thrust block have an identical orientation to the tight F3 folds that structurally underlie the thrusts in this marginal belt.

b) the mylonitic granites amongst the schistose units are superficially identical to those produced by the D2 deformation within the granites of the Lower Bergsdalen Nappe, immediately beneath the marginal thrust belt. Similarly, the mica shists, phyllonites and the mylonitic granites share the same fabric which is deformed by the tight folds.

By making the assumption that the granite phyllonites and mylonites are of the same age as those seen in the marginal granites of the Bergsdalen Nappe, the tight folding of the schistose units may be considered to be F3 in age, a correlation supported by fold orientation.

A consequent conclusion would be to extend the correlation to include the thrusts making them equivalent to the D3 thrusts. This implies that the thrust margin to the Bergen Arcs is a D3 structure, reorientated by the large scale D4 antiform.

<u>Correlation of structures from the Lower Bergsdalen Nappe into the Bergen Arcs</u> (fig 93).

A correlation of Lower Bergsdalen Nappe and Bergen Arc structures has to be through the intervening Southern Gneisses of Osterøy, that form an along strike extension of the Lower Bergsdalen Nappe (Hopper 1980). Direct correlations between the SouthernGneisses of Osterøy and the Bergen Arcs have been made by Hopper (op. cit)

The Lower Bergsdalen Nappe was emplaced at the end of D2; other structural features generated during this phase include an S2 schistosity, that develops sufficiently in the Vaksdal area to become the regional foliation, and an ubiquitous pervasive shape fabric lineation, L1 that trends to the northeast.

The Southern Gneisses of Osterøy were emplaced at the same time as the Lower Bergsdalen Nappe and Bergen Arcs, at the end of a period of high strain that generated a thick sequence of mylonites (Hopper 1980). The mylonite foliation and the penetrative lineation of the Southern Gneisses of Osterøy can be compared to the S2 foliation and L1 lineation of the Lower Bergsdalen Nappe at Vaksdal. Therefore, the D2 phase of the Lower Bergsdalen Nappe is correlated with D1 of the Southern Gneisses.

Hopper (1980) correlated D1 of the Southern Gneisses with the pre-Holdus deformation within the Bergen Arcs (Faerseth et al 1977), thus implying that the Bergen Arcs and the Lower Bergsdalen Nappe were emplaced prior to the deposition of the Moberg Conglomerate, and marbles of Ashgillian age.

In the Vaksdal area, S2 in both the Lower Bergsdalen lithologies and the mixed metasediments is deformed by large scale tight/ isoclinal folding (F3) that have limbs replaced by thrusts; these define the structural blocks that lie along the margin of the Bergen Arcs in this southwestern corner. (page 343). However, Hopper (1980) does not recognise large scale folding, instead referring to a period of further flattening and superimposition of a new schistosity (D2 giving rise to S2 in the SouthernGneisses of Osterøy) along with an element of tectonic transport that carries Bergen Arc lithologies over, to cut out the Southern Gneiss. By removing the effects of the D4 northwest - southeast folding, it can be seen that Hopper's (op. cit) D2 phase has the same orientation as that of D3 in the Lower Bergsdalen Nappe.

Hopper (op. cit) has made a direct correlation between the D2 structures in the Bergen Arcs, and D2 of the Southern Gneisses.

The large scale F4 antiformal structure is readily traced from the Vaksdal area to the Osterøy area, and from there is correlated by Hopper (op. cit) with F3 in the Bergen Arcs.

Thus, the following important points arise:

1. The Lower Bergsdalen Nappe, Bergen Nappe and Southern Gneisses were emplaced during the same structural phase.

2. Emplacement of these nappes occured prior to Upper Ordovician sedimentation.

3. Continued deformation produced restacking within both the Bergsdalen and Bergen Nappes.

4. The cross cutting Bergen Arc feature is a product of post nappe emplacement deformation. A late Devonian age for this is suggested due to the incorporation of Devonian sediments in the deformation, further north in the Nordfjord area (fig 2)

Proposed Model for the development of the Bergen Arc structure

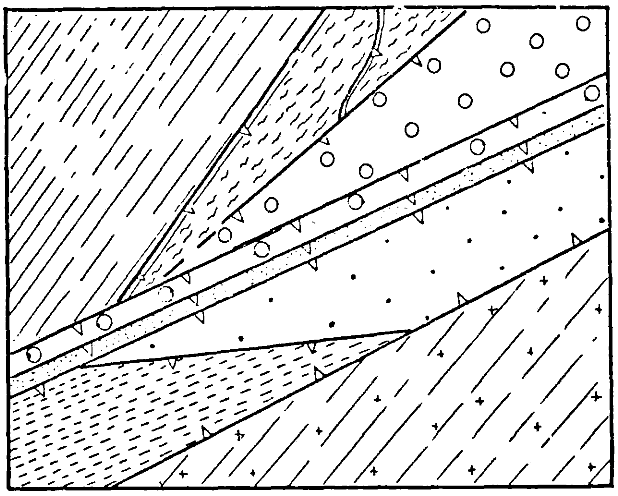
The Bergen Arc structure is essentially a large scale antiform and synform (wavelength ~30km) with a northwest-southeast trend, that has been refolded by an antiform that plunges to the east. The resulting arcuate pattern is superimposed upon the complex structures within the Basement and the Bergen and Bergsdalen Nappes. Consequently, the outcrops pattern of the Bergsdalen Nappes along the southeastern margin of the Bergen Arcs is difficult to resolve (fig 2)

The following model is suggested to account for the present configuration of the Bergsdalen and Bergen Nappes:

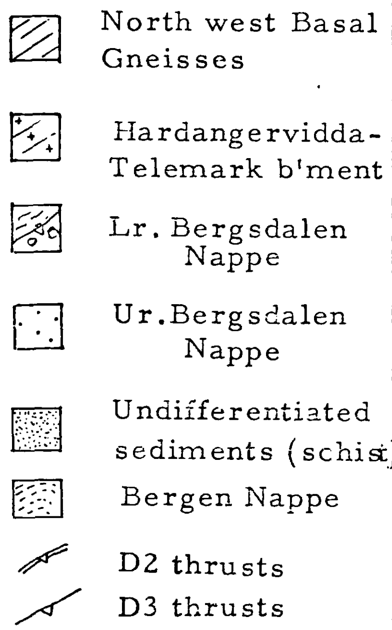
1. The present outcrop pattern of the Lower Bergsdalen Nappe is dependent upon the large scale eastnortheast and northeast trending folds ascribed to D3 (Gray 1978, Winter and Evans pers.com.) Restacking of the original Nappe sequence occurs along thrusts associated with the steep limbs of these structures. Excursions within the Upper Bergsdalen lead the author to believe that there is little structural variation between the Upper and Lower Nappes, and that the large scale D3 phase is regionally developed.

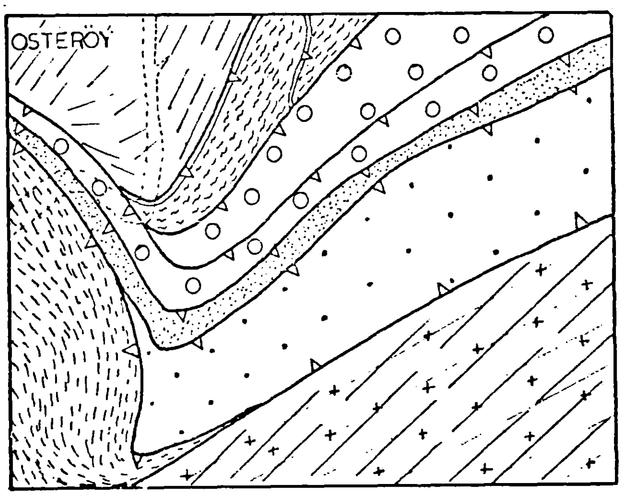
   It has been shown that the Bergen Nappe (Hopper 1980) has undergone a structural history very similar to that of the Lower Bergsdalen Nappe (page 345) and, may be considered to be part of the Bergsdalen-Jotun complex.

FIG. 109 Proposed sequence of events to account for the distribution of tectonic units at the eastern margin of the Bergen Arcs

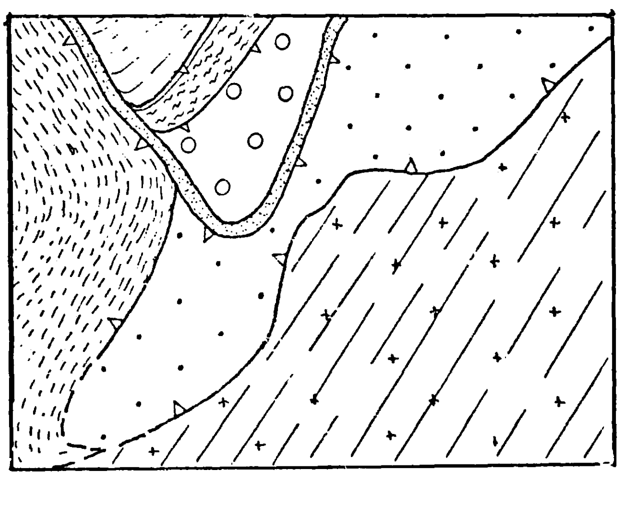


(a) pre D4 (post Llandovery)





(b) D4 (and later) arcing late Devonian



Tectonic units at the eastern margin of the Arc, as mapped by Kvale (1960 plate 1)

Therefore, a pre D4 (post Ashgillian) outcrop pattern can be postulated for the Nappe complex, whereby the Bergsdalen and Bergen Nappes form inter-related thrust blocks that lie on an eastnortheast trend (fig 109)

2. This complex structural block is folded into a northwest - southeast trending antiform and synform. (fig 109)

3. Superimposed upon this large scale antiform and synform is folding on an east - west axis; which effects tightening and steepening (vertical in places) of structures in its hinge region. This east-west folding deforms Devonian sediments further to the north.

Section 5 METAMORPHIC PETROLOGY

The metamorphic petrology for each of the four tectonic units: Basement gneisses, Mixed gneisses, Eggjane Nappe and Lower Bergsdalen Nappe will be described in turn.

5.1 Metamorphism of the Basement Gneisses

The various lithologies that together form the Basement gneisses (section 2.11) (quartzofeldspathic gneisses, hornblende quartzofeldspathic gneisses and amphibolites) are considered together, metamorphically, as there is every indication (structural and textural) that they have acted as one throughout all of the deformational phases recorded.

Because of the common history, the details of the metamorphic history can be presented together:

5.1a Metamorphism, M "early"

The earliest recognisable metamorphic effect in the Basement gneisses is the small scale (less than 1cm) segregation into felsic and mafic layers, that is the basis of their present banding.

Bands and augen rich in quartzofeldspathic (K feldspar being a common component) minerals, with marginal biotite and biotite-hornblende layers or envelopes are indicative of this segregation.

Rarely a biotite fabric that predates the M1 fabric (section 5.1b) indicates that there was a stage of fabric generation either synchronous with the segregation, or at an intermediate stage between segregation and M1.

Evidence that might indicate the coarseness of this postulated early fabric is rare; however, because feldspar grains within augen show subparallel optic orientation, it is probable that prior to granulation, K feldspar grains may have been up to at least 3-4mm in size, with an elongate form. (fig110)

5.1b. Metamorphism, M1

The regional foliation (S1) upon which subsequent structures are superimposed, is a product of the first metamorphic event (M1). It is pervasive and is recognised mainly by its effect on reducing the coarse grain size generated by the early metamorphism (or metamorphisms). The first metamorphism accompanied by deformation reduced grain size by breaking down the feldspars, by the process of dynamic recovery and recrystallisation (Bell & Etheridge 1973, Hobbs, Means and Williams 1976, chapter 2). This is shown by the original grains which are replaced wholly, or in part, by aggregates of new grains, that may become elongate, parallel to S1; sub grains also form, marginal to the host grain. Where planes of grain size reduction

FIG 110 Deformation of an M early feldspar grain during M1, resulting in grain size reduction of the quartzofeldspthic gneiss.

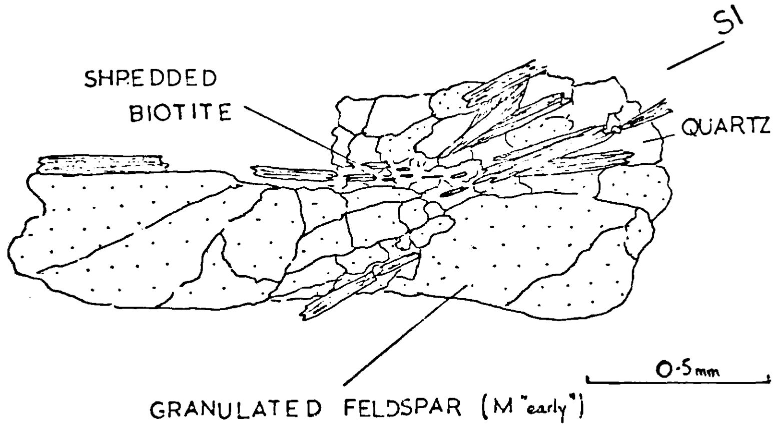
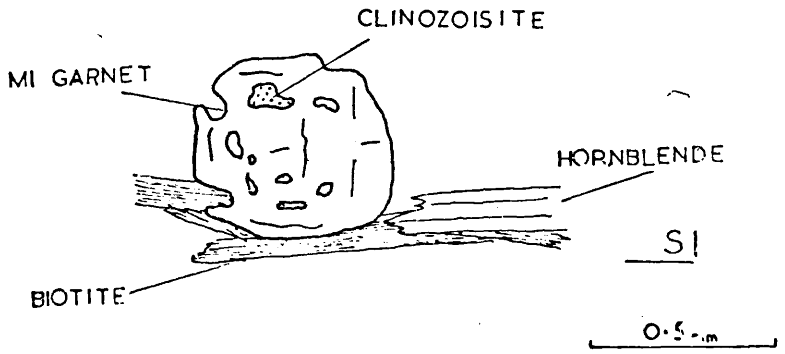


FIG 111 Post kinematic M1 garnet overgrowing the S1 fabric in a biotite-garnet gneiss of the Mixed Gneisses.



cut through feldspar grains, it is not uncommon to find small quartz grains included within the recrystallising zone (fig 110)

The result of this mylonitisation process is to generate an inhomogeneous feldspar texture, with very variable grain shape and size. Host grains rarely remain greater than 1mm in size, whilst the new grains are usually less than 0.5mm. M1 plagioclase compositions, determined optically using the Michel Lèvy test on 14 samples from throughout the Basement gneisses, is oligoclase (An_{24} - An_{28}).

M "early" biotite, sited along the grain boundaries of the early coarse feldspars, is also deformed by the mylonitisation process. Typically, it is either shredded into much finer grains, or it is broken down into 2 or 3 fragments "stretched" parallel to the M1 fabric, with quartz recrystallising between the grains. (fig 110). Hornblendes however, have undergone sufficient subsequent recrystallisation to mask any possible breakdown textures.

Quartz appears to have reacted differently to the process of mylonitisation. Apart from sporadically distributed small grains that are intergranular to, and deformed along with the feldspars, quartz is also seen as coarse ribbons that are parallel to, and assist in defining the M1 fabric. These ribbons may be up to 3-4cm in length, and less than 1.0mm in width; they can have a network appearance, isolating patches of deformed feldspar (plate 92), although individual ribbons are more common.

The quartz ribbons cut across the mylonitised feldspar grains, yet they themselves have only weak deformation features: local small patches of marginal grain size reduction, along with some undulatory extinction.

The occurrence of quartz, as microscopic intrusive veins, suggests that it passed into solution during the stage of mylonitisation, crystallising only in the waning stages of deformation, thus taking up only minor strain features. The ribbons are overgrown, and locally included by, hornblendes and biotites that are parallel to the M1 fabric. (S1).

From the composition of the brokendown M1 plagioclases (An_{24} - An_{28}), the mylonitisation appears to have proceeded under amphibolite facies conditions (Winkler 1976 p.169). The presence of overgrowing hornblende late in the cycle, suggests that the amphibolite facies conditions persisted during the recrystallisation stages.

5.1c Metamorphism, M2

Metamorphism, M2, is considered to be most important for its effect in generating a new schistosity (S2) which is most intensely developed in F2 fold hinges (section 4.2c) However, M2 is not restricted to hinge zones, and its effects are recognised in most rocks. Problems do arise in distinguishing weak M2 effects from M1 features, where the two are co-planar. In these cases, a composite fabric is generated.

A weak granoblastic texture is generated by M2, with the recrystallisation of the granulated M1 texture. The result is a felsic matrix of quartz and feldspar with variable grain sizes up to 1mm. The M1 quartz ribbons can locally be recognised, although they tend to be broken down into smaller lengths, and are partially overgrown by plagioclase feldspars that have a rather irregular form.

The fresh plagioclases show both twinned (albite and pericline) and untwinned varieties, the former having an oligoclase composition (An_{22} - An_{28}).

K feldspar occurs distributed throughout the felsic matrix with a form indistinguishable from that of the plagioclases, having a polygonal habit and grain size up to 1mm.

Quartz has a variable elongation, parallel to the S2 schistosity; local M2 quartz ribbons may be generated in the hinge regions of F2 isoclines, again defining S2.

M2 biotites define the S2 schistosity and have the same pleochroic scheme (brown to dark brown) as the M1 biotites, locally overgrowing them. However, M2 biotites are partially overgrown and corroded by the M2 quartz, feldspar and epidote.

M2 hornblendes sometimes have a bluish green body colour, and are recrystallised parallel to the S2 schistosity, including epidote and quartz.

The paragenesis for M2 is:

quartz - oligoclase plagioclase - Kfeldspar - biotite $\pm$ hornblende,
epidote, sphene, apatite

The presence of hornblende and oligoclase plagioclase is indicative of metamorphism within the lower - middle part of the amphibolite facies (Winkler 1976).

The flaggy quartzofeldspathic gneisses, (section 2.2b)beneath the nappe complex have undergone more extreme D2 deformation, with a resulting modification to the usual M2 texture. The major difference is the slightly finer grain size of the flaggy gneisses, and a more pronounced augening of the felsic matrix by the biotite fabric despite recrystallisation. Whereas the normal M2 texture is comprised of grains up to 1 mm in diameter, the grains in the flaggy gneiss are less than 0.6mm in diameter, but have a granoblastic texture.

The plagioclases remain as porphyroclasts, with the biotite fabric augened around them, in contrast to the normal planar M2 texture.

5.1d Metamorphism, M3

The third metamorphic event in the basement gneisses is only well developed in the flaggy gneisses that underlie, and are involved in the nappe complex. Elsewhere within the basement, textures purely attributable to this event are rarely recognised. Weakly porphyroblastic plagioclase growth of albitic composition, with occasional epidote inclusions, compare to the oligoclases of the M2 matrix, probably reflecting the M3 response in the deeper basement.

In the flaggy gneisses, where F3 folding is stronger, recrystallisation of M2 quartz and feldspar occurs in fold hinges, with occasional discrete mylonite planes. Biotite and epidote recrystallise in the hinge areas parallel to the axial plane, and define a weak schistosity, that is usually only recognisable microscopically. Hornblende is locally retrogressed to biotite, or rarely chlorite.

A classification of the metamorphic grade is made on the following paragenesis: quartz - albite/oligoclase - biotite - epidote $\pm$ K feldspar, chlorite

The albite - epidote $\pm$ chlorite indicates that M3 occurred at Upper Greenschist facies.

5.2 Metamorphic History of the Mixed Gneisses

Although comprising several different lithologic units, the Mixed Gneisses can be shown to have undergone the same pervasive deformational events (section 4.3) effectively masking earlier data that might have given some indication as to the origin of the mixing. Similarly, the later metamorphic events have been pervasive, and thus the history for these Mixed Gneisses can be treated as one, with different paragenesis reflecting only composition, not metamorphic control.

Much of the information on the metamorphic state of the Mixed Gneisses is derived from the biotite-epidote-hornblende gneisses, due to their volumetric importance. In addition, detail was also obtained from the Banded Gneisses, and minor amphibolite horizons.

The following sequence of metamorphic events is realised:

5.2a Metamorphism, M "early"

Information concerning M "early" is sparse, due to the subsequent pervasive M1 metamorphism, that almost invariably resulted in a total recrystallisation of the early paragenesis. The limited information available has been derived from Banded Gneisses (both biotite gneiss and biotite-hornblende gneiss varieties) exclusively.

The two stable parageneses are: biotite + quartz + plagioclase
biotite + hornblende + plagioclase + quartz

In both, the quartz and plagioclase has either a polygonal or tabular form, often with biotite growing along grain boundaries, defining the fabric. Hornblende, where present, is also aligned parallel to this S "early" fabric. The texture in general is moderately fine grained ($<$ 1mm).

Plagioclase composition (determined from grains with their albite twins parallel to the S "early" fabric) is invariably andesine, ranging from low to middle in the Ca poor biotite gneisses (An_{32} - An_{36}) and from middle to upper andesine in the more calcic biotite-hornblende gneisses. (An_{38} - An_{46}).

The two parageneses indicate metamorphism at a medium grade, based mainly on plagioclase composition (Winkler 1976 p.169).

The presence of middle to upper andesine in the more mafic rock suggests mid amphibolite facies conditions.

5.2b. Metamorphism, M1

The first pervasive metamorphism is allied to the main fabric forming event in the Mixed gneisses (S1). As such, it is readily recognised within all of the different lithologies. The gneissose granites have a strong fabric defined by elongate aggregates of quartz, oligoclase plagioclase (An_{24} - An_{28}) and biotite.

In the more mafic rocks, the paragenesis involved is:

biotite + hornblende + epidote + plagioclase + biotite
$\pm$ garnet, quartz

The foliation (S1) associated with M1 is composed of recrystallised biotite and hornblende (sub to euhedral) that locally have abundant quartz inclusions, along with minor euhedral sphene. Sub to euhedral epidote, sometimes with allanite cores, are also stable, partially or wholly enclosed by hornblende, and occasionally seen to be overgrowing the S1 biotite fabric in the presence of plagioclase.

The quartz and plagioclase have either a granoblastic polygonal form or sometimes a poorly developed tabular form, elongate parallel to the fabric. The plagioclase composition remains at middle to upper andesine (An_{40} - An_{46}) as in M "early" in hornblende bearing lithologies.

The biotite gneisses have a paragenesis of: biotite + plagioclase + quartz ± epidote ± garnet, with minor amounts of K feldspar. The epidote occurs as either tiny grains within plagioclase or (more commonly) as subhedral forms overgrowing the biotite fabric (S1). Similarly, plagioclase, although often defining the S1 fabric, do also marginally overgrow the S1 biotites, indicating some late stage recrystallisation. Plagioclase composition ranges from lower to middle andesine (An_{32} - An_{38}).

Where garnet occurs, it overgrows and includes both the M1 biotites and hornblendes. It is sub to euhedral, often with a circular ring of inclusions of epidote and quartz indicating post kinematic growth. (fig 111)

The metamorphic grade associated with these parageneses is no different from that of M "early", retaining the mid amphibolite facies characteristics. However, the increased presence of epidote may indicate some retrogression within the confines of the amphibolite facies.

5.2c <u>Metamorphism, M2</u>

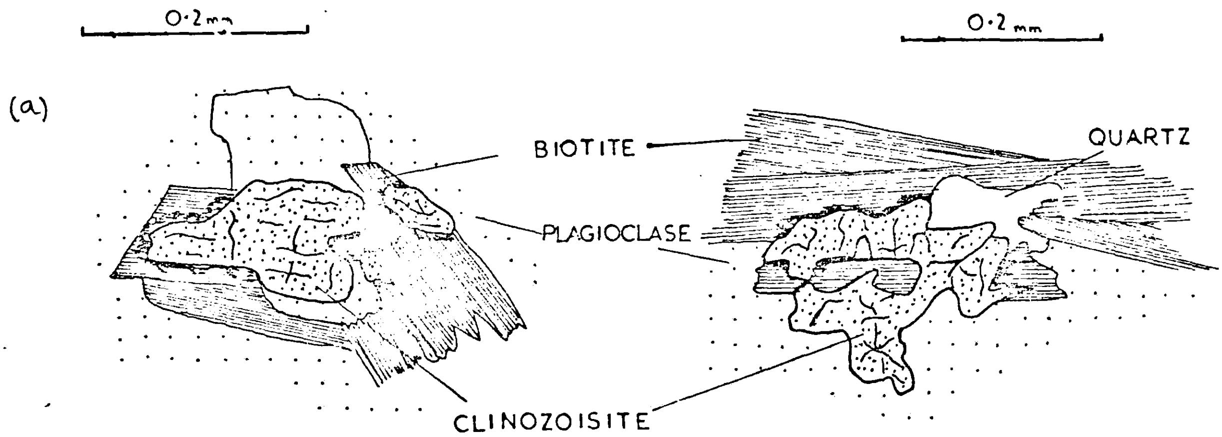
The pervasive fabric, S1, that was generated during M1 is only partially recrystallised during M2, although recrystallisation is complete in the hinge regions of folding (F2), with the resulting development of a schistosity; however, limb regions have only minor recrystallisation textures that can be attributed to M2.

The second metamorphic event is retrogressive from the combined peaks recorded by M "early" and M1. The most notable feature is the increase in epidote growth, which replaces wholly or partially the M1 biotites. In complete replacement situations, small granular epidotes cluster together, forming a poor pseudomorph after the biotite, sometimes leaving small patches unaltered (fig112c). Typically, dusty margins rim the individual epidote grains indicating that not all of the Fe from the biotite is taken into the epidote lattice. Plagioclase is usually, but not invariably, involved in the reaction. Where plagioclase is not involved, it is assumed that there is sufficient small scale mobility of Ca during metamorphism for its incorporation into the biotite -- epidote reaction.

In addition, twinned plagioclase is sometimes seen to be breaking down to an untwinned plagioclase with lower refractive index, indicative of a lower An. content. The composition of the plagioclase has not been determined. Saussuritised plagioclase with margins overgrowing the M2 schistosity is also seen.

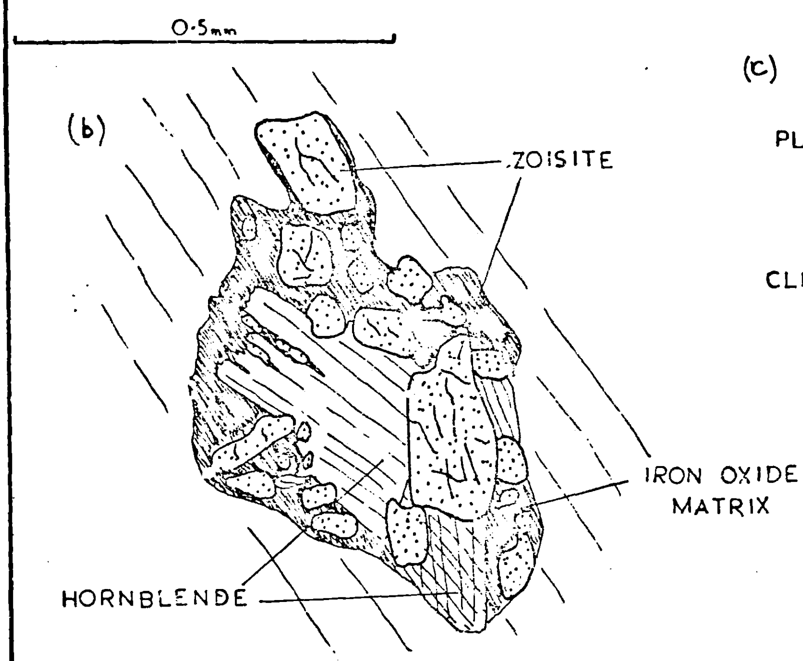
FIG. 112

(a)



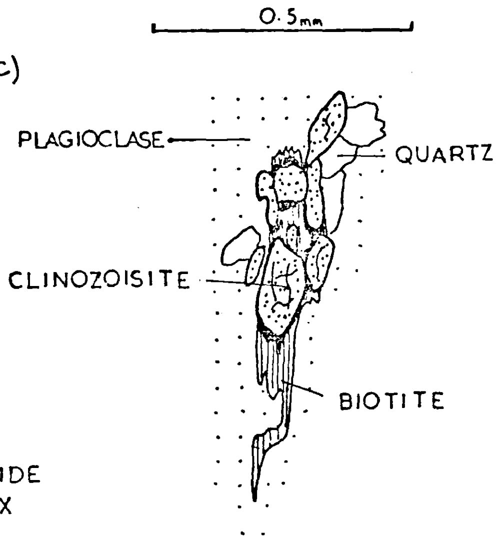
Biotite being replaced by clinozoisite, in the presence of plagioclase; note the iron enriched haloes around the clinozoisite, within the biotite. From biotite gneiss (Banded Gneiss), Lower Bergsdalen Nappe.

(b)



M1/M2 hornblende being replaced by zoisite, within an iron oxide matrix; from an amphibolite of the Lower Bergsdalen Nappe.

(c)



As above; from a biotite gneiss within the Mixed Gneisses.

The quartz and plagioclase are typically recrystallised by M2 in the hinge regions (F2) being left as polygonal grains with some elongate habit. The M2 schistosity (S2) is defined by orientated biotite and hornblende; however, the hornblende is locally seen to be retrogressed to biotite (plate 93), and tiny euhedral sphenes. In addition, occasional discrete mylonite planes are developed in the hinge regions, resulting in the development of tiny new and sub grains from the quartz and plagioclase. Where a mylonite plane passes around a hornblende, its margin is slightly granulated, and tiny fragments are "plucked out" and included in the mylonite.

M1 garnet is weakly augened by the M2 biotite and hornblende fabric (S2), yet retains a stable appearance, but does not recrystallise.

The M2 metamorphic event has a paragenesis that is difficult to determine absolutely; the presence of abundant epidote, retrogressive plagioclase, and hornblende locally replaced by biotite suggests a position on the border between Upper Greenschist and Lower Amphibolite.

5.3 Metamorphic History of the Eggjane Nappe

There are two varieties of the Eggjane Gneiss (section 2.8) that containing only biotite and epidote as the mafic minerals, and that containing in addition, hornblende. The reason for the variation is unknown; it may represent either (a) an original compositional difference or (b) a metamorphic isograd (biotite/ hornblende) that reflects an early unrecognised metamorphic event.

The following metamorphic history for these gneisses is recognised:

5.3a Metamorphism, M1

In both gneiss varieties, M1 generated a fabric (S1) that is locally preserved in areas of low subsequent M2 recrystallisation. Texturally, the two gneisses are identical and are described as one, differences being described as necessary.

The M1 fabric (S1) is identified in the Eggjane Gneisses by the presence of a biotite$\pm$hornblende fabric that is modified by the later (M2) textures. The following features are characteristic of the M1 event:

a) quartz and plagioclase are fine to medium grained (0.5-1.0mm) with an elongate granoblastic texture, parallel to the S1 fabric. The plagioclases are of low to mid andesine in composition (An_{32} - An_{38}).

b) biotites are fine to medium grained (0.5 - 1.0mm) and define the S1 fabric, along with hornblendes, where present.

The biotites are locally overgrown and marginally included by the M1 plagioclase. Hornblendes locally have an anhedral skeletal form that overgrows the felsic matrix; however, euhedral or subhedral fine - medium grained (1-2mm) hornblendes are more common, with rare epidote inclusions.

The M1 fabric is defined by the assemblage:
quartz + low/mid andesine plagioclase + biotite ± hornblende.

This is typical of the medium grade of metamorphism (Winkler 1976 p. 169), equivalent to the lower to middle amphibolite facies.

5.3b <u>Metamorphism, M2</u>

The M1 fabric (S1) is tightly folded by F1, with the development of an axial planar schistosity (S2), and almost complete recrystallisation of the M1 fabric. Thus, S2 is the most readily recognised fabric within the Eggjane Gneisses.

The following features are characteristic of M2:

a) . M1 quartz and plagioclase grains are strained, and undergo recrystallisation, with the general effect of grain size reduction. The coarser M1 grains are broken down into aggregates of several smaller grains, that have only a poorly defined elongate fabric parallel to S2.

b) The plagioclase composition becomes more albitic, as represented by individual andesine plagioclases breaking down internally to plagioclases with a lower refractive index.

c) M1 biotites and hornblendes are overgrown by epidote,(plate 94) that sometimes have allanite cores. They occur as subhedral forms, with their long axes parallel to the S2 fabric, reflecting syntectonic recrystallisation.

The observed reactions are:

biotite + plagioclase -- epidote $\pm$ biotite $\pm$ quartz $\pm$ sphene
hornblende ($\pm$biotite) + plagioclase -- epidote $\pm$ biotite $\pm$ sphene
(plate 94)

However, chlorite is not a member of the retrogressive assemblage.

d) M2 biotite recrystallises, and defines the S2 schistosity, along with the retrogressed hornblende.

Métamorphism, M2 (associated with deformation D1) is characterised by retrogressive textures superimposed upon the mid-amphibolitic facies of M1. The assemblage is as follows:

quartz + plagioclase (oligoclase) + biotite + epidote $\pm$ hornblende $\pm$ sphene

The development of epidote, without chlorite, is typical of the lower part of medium grade metamorphism (Winkler 1976 p. 169) which is equivalent to the lower amphibolite facies.

5.3c Metamorphism, M3

The third metamorphic event recognised is related to the F2 fold structures within the Eggjane Nappe. The structures (section 4·4c) deform the S2 foliation, and have a weak axial planar schistosity (S3) developed under M3 conditions.

The following features are characteristic:

a) texturally, the M2 quartz and plagioclase undergo only minor changes. There is further marginal granulation and recrystallisation, following the general trend towards grain size reduction, whilst plagioclase does not undergo any noticeable further drop in An. content.

b) some hornblendes undergo minor recrystallisation, parallel to the weak S3 schisosity, although it is more common for the M1/M2 relic grains to be augened by the S3 biotite fabric. The fine grained M3 biotites therefore define the S3 schistosity along with minor epidote.

The metamorphic grade remains unchanged from the M2 event, with the only significant difference being the recrystallisation of biotite to define the S3 schistosity.

Thus, the assemblage:

quartz + plagioclase (oligoclase) + biotite + epidote ± hornblende ± sphene is retained, and is indicative of the lower amphibolite facies of metamorphism.

5.4 Metamorphic History of the Lower Bergsdalen Nappe

Of the eight lithologies recognised in the Lower Bergsdalen Nappe, only the extensively developed Banded Gneisses, amphibolites and gneissose quartz diorites are good indicators of the metamorphic events undergone in conjunction with the phases of deformation. Consequently, the description of the metamorphic history will be based primarily on the evidence from these lithologies, although where appropriate, the evidence from minor lithologies will be included.

5.4a Metamorphism, M1

Throughout the area, evidence for this early metamorphic event is scarce due to the subsequent pervasive recrystallisation related to younger deformational phases. The assemblages for this first recognisable metamorphism have been deduced from relic F1 small scale fold hinges, and relic textures that are occasionally seen in the Banded Gneisses (biotite gneiss and biotite-hornblende gneiss). The fold hinges are usually defined by narrow aplite veins, or relic compositional banding, indicative of the S1 fabric. (section 4.5b)

The following features are characteristic of this M1 event in the Banded Gneisses and amphibolites. (The lack of recognisable M1 features in the quartz diorite gneiss is due to the homogeneous nature of the rock through time).

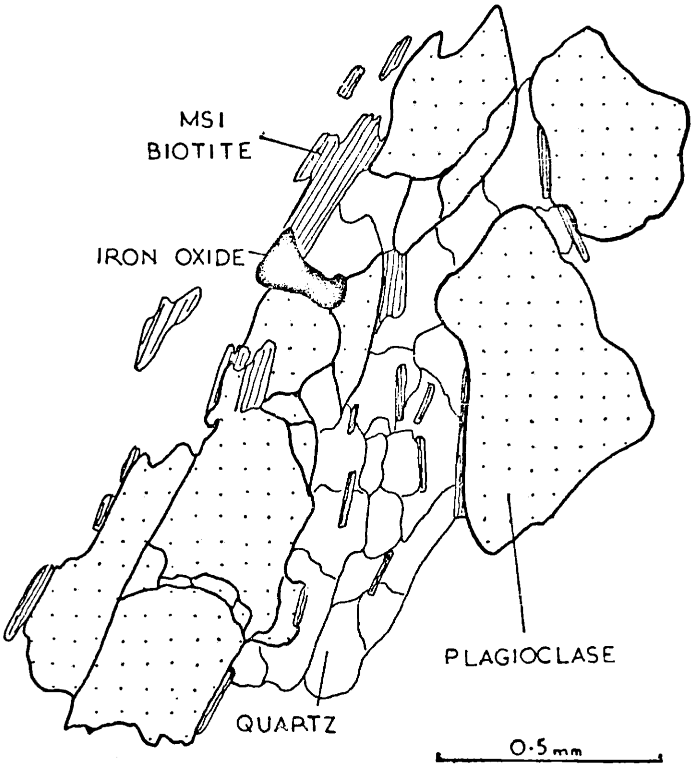
a) Quartz and plagioclase are coarser than that seen due to subsequent recrystallisation; the grains ranged in size from 1-2mm in the biotite-hornblende gneiss, and from 0.6-1mm in the biotite gneisses.

b) Quartz and plagioclase had an elongate granoblastic form that commonly had biotites confined at grain boundaries, forming a distinctive fabric (fig 113)

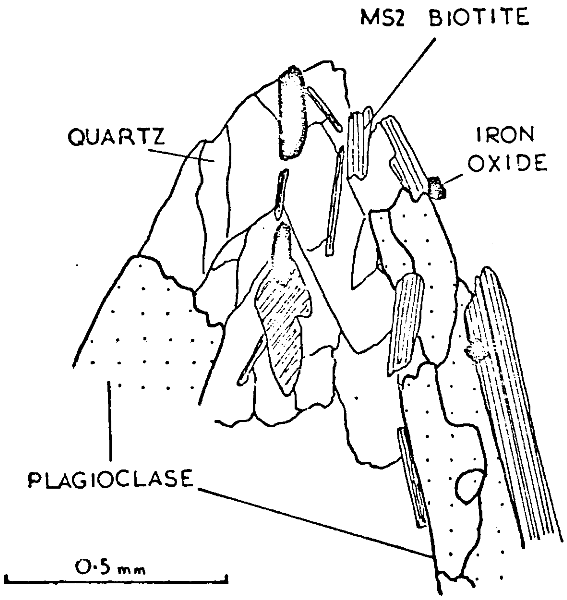
c) Euhedral hornblendes and biotites (up to 1.5mm in length) developed, with their shape fabrics parallel to that of the felsic fabric. Locally, the mafic minerals marginally included the quartz and feldspar. Together, the felsic and mafic components defined a strong gneissic foliation.

d) The plagioclase composition varies, depending upon the initial chemistry of the rock. In both the basic and intermediate biotite-hornblende gneisses, and in the amphibolites, the plagioclase was of mid-upper Andesine (An_{38} - An_{44}) composition,

FIG. 113.



tabular MS1 plagioclase and granulated MS1 elongate quartz, with grain boundary biotite; together, they define S1.



S1, defined by elongate MS1 quartz and plagioclase, isoclinally folded (F1) on a microscopic scale: recrystallisation in the hinge region, with the development of S2, as defined by MS2 biotite.

Both examples are of the biotite gneiss (Banded Gneiss), Lower Bergsdalen Nappe.

whilst the intermediate and acid biotite gneisses have plagioclase compositions within the range of upper oligoclase - mid andesine (An_{26} - An_{40}).

e) One specimen (no. AM 060/2a19) of biotite-hornblende gneiss contains a clinopyroxene (plate 95) as 5% of its modal value. It is invariably elongate, up to 1.5mm in length and is now parallel to the S1 fabric. The form is subhedral to euhedral, often with irregular margins, that include quartz, plagioclase and biotite. Hornblende and pyroxene are not seen in stable contact with each other, their instability reflecting a M2 feature.

The clinopyroxene is considered to be diopside from its optical properties; colourless in plane polarised light, interference colours of the upper second order, biaxial positive optical figure with a 2V of about 60^{o}, and a maximum recorded extinction angle ($C \wedge Z$) of 42^{o}. The plagioclase in contact with the diopside is andesine, with a maximum composition (determined optically) of An_{44}. However, one plagioclase within an augen has provided a composition of An_{50} (andesine/labradorite boundary).

The occurrence of diopside within only one recorded gneiss sample may reflect a local compositional variation to the normal biotite-hornblende gneisses. Comparison of the whole rock geochemistry of the diopside bearing sample, compared with the average biotite-hornblende gneisses, shows:

	Al_2O_3	Fe total
Diopside bearing biotite-hornblende gneisses:	13.56%	5.63%
Range for the biotite-hornblende gneisses:	15.77-17.83%	6.87-10.29%

This lower Al and total Fe content may be reflected by the preferential development of diopside, rather than almandine garnet; this is reported by Winkler (1976 p. 168) from labradorite/bytownite amphibolites of upper medium grade and high grade (equivalent to the upper amphibolite facies and granulite facies).

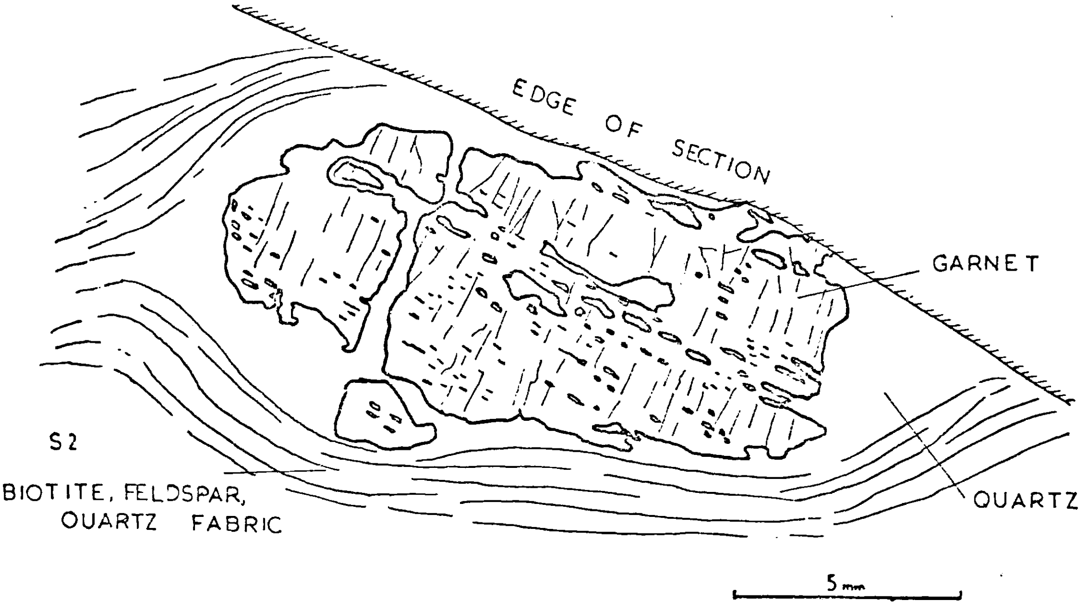
These features of M1 are indicative of synchronous deformation and recrystallisation (Spry 1969), and are therefore termed MS1.

In addition, the following minerals developed at a late stage in the crystallisation sequence, during a period of relaxed stress, and are termed MP1.

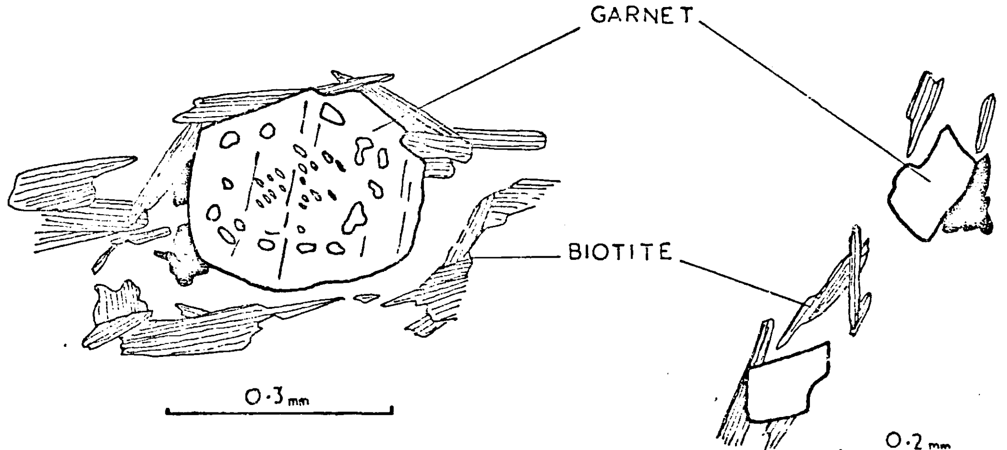
f) Dark red sub, and euhedral garnets up to 1mm (exceptionally 1cm) overgrow this S1 fabric. Commonly, the garnets are inclusion free, but some have rare planar orientated inclusions that are discordant to the subsequent external fabric. (fig 114)

g) Small subhedral apatites (0.2mm) and sphenes (0.1mm) often overgrow the S1 fabric.

FIG. 114



MP1 garnet with Si discordant to Se (S2)



Garnet showing composite crystallisation sequence. The inner, orientated inclusions are related to MP1, whilst the coarser outer zone of inclusions is MP2.

small, inclusion free garnets (MP1) overgrow S1.

These examples are taken from the Biotite gneiss (Banded Gneiss), Lower Bergsdalen Nappe.

Metamorphic grade of M1: the following parageneses are observed for M1:-

biotite gneiss: quartz + upper oligoclase/mid andesine plagioclase + biotite ± garnet

biotite-hornblende gneiss: quartz + mid/upper andesine (or labradorite) plagioclase + hornblende ± garnet ± diopside

Without regard to the evidence from the diopside bearing sample, the Banded Gneisses could be considered to have undergone metamorphism at mid-amphibolite facies, with the more basic gneisses being defined as andesine-amphibolites that lie in the middle of the medium grade of metamorphism (Winkler 1976 p. 169). However, the diopside bearing sample indicates that the metamorphic grade could have been higher; upper amphibolite or even granulite facies (Winkler op. cit). Further, a plagioclase of composition bordering the andesine/labradorite boundary is recognised in the same sample of gneiss, again indicating metamorphism at high grade.

To conclude, the M1 metamorphic event was typified by the generation of a medium/coarse grained metamorphic fabric (S1) that was derived under at least mid-amphibolite facies conditions.

5.4b <u>Metamorphism M2</u>

The S1 fabric generated during M1 is isoclinally folded by F1, with recrystallisation and the development of a schistosity (S2) that is defined primarily by MS2 biotite and hornblende (recognised in the Banded Gneisses, Quartz diorite and amphibolite).

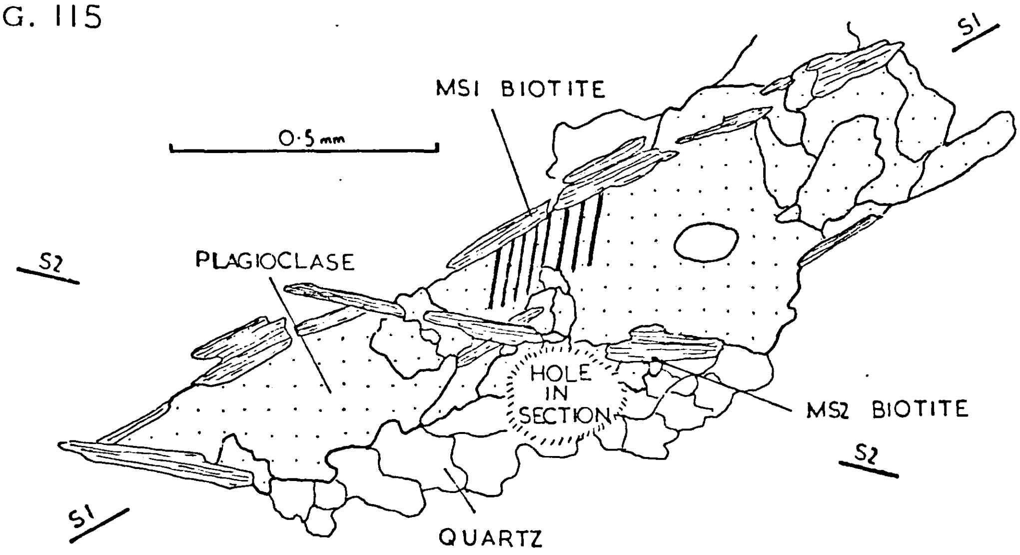
Therefore, the M1 texture is modified during M2, with the following characteristics:

a) The large tabular MS1 quartz and feldspar grains in the biotite and biotite-hornblende gneisses have undergone extensive dynamic recovery and recrystallisation in the MS2, resulting in the development of sub and new grains, often in discrete bands parallel to the S2 schistosity. Thus, there is a situation of grain size reduction, with the recrystallised grains typically < 0.5mm in size, compared with the coarse (1-2mm) MS1 grains. (figs 113, 115)

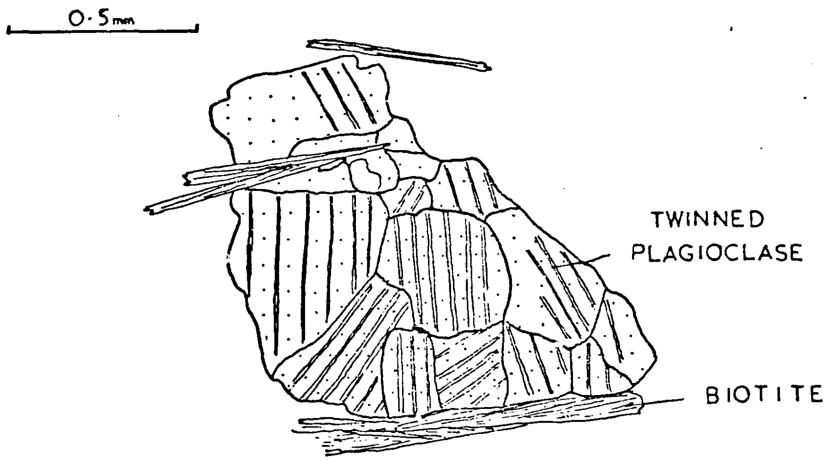
Relic coarse plagioclase grains, up to 4mm in length are seen to be broken down into several smaller (< 0.6mm) grains in the quartz diorite; this indicates a probable parallel line of development with the Banded Gneisses.

In all of the lithologies with at least a moderate felsic content, the coarse MS1 relic plagioclase and quartz grains, despite their breakdown into several smaller grains, can be identified by using the sensitive tint accessory plate.

FIG. 115



A relic tabular MS1 plagioclase, defining the S1 fabric; it is broken into two optically continuous grains by a zone of biotite recrystallisation and grain size reduction, which is parallel to the S2 fabric.
Example from the biotite-hornblende gneiss (BandedGneiss), Lower Bergsdalen Nappe.



MS1 plagioclase broken down into an aggregate of smaller grains during M2; from the gneissic quartz diorite, Lower Bergsdalen Nappe.

b) The recrystallised felsic grains form a granoblastic texture, that is locally elongate, parallel to S2.

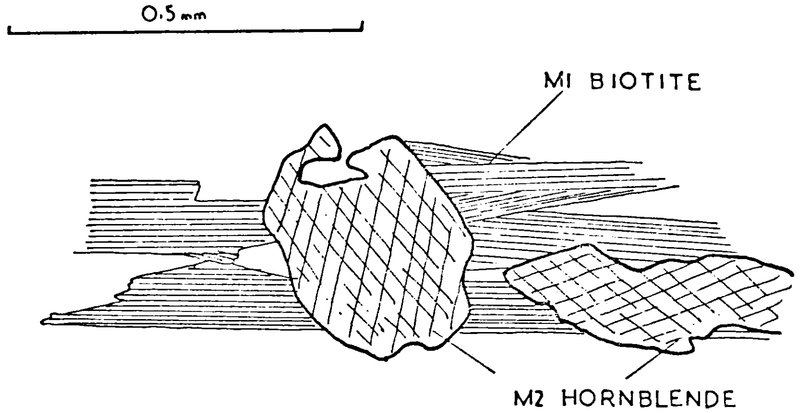
c) Some of the recrystallised MS2 plagioclases are twinned, on the albite and pericline laws. They are invariably fresh with occasional indications of reverse compositional zoning. MS2 plagioclase composition is no different from that of MS1, with the basic and intermediate rocks (including the metagabbros) containing mid-upper andesine plagioclases (An_{36} - An_{48}), and the more acidic rocks containing upper oligoclase - mid andesine plagioclase (An_{26} - An_{36}).

Some plagioclases contain in minor amounts, inclusions of biotite, hornblende and garnet.

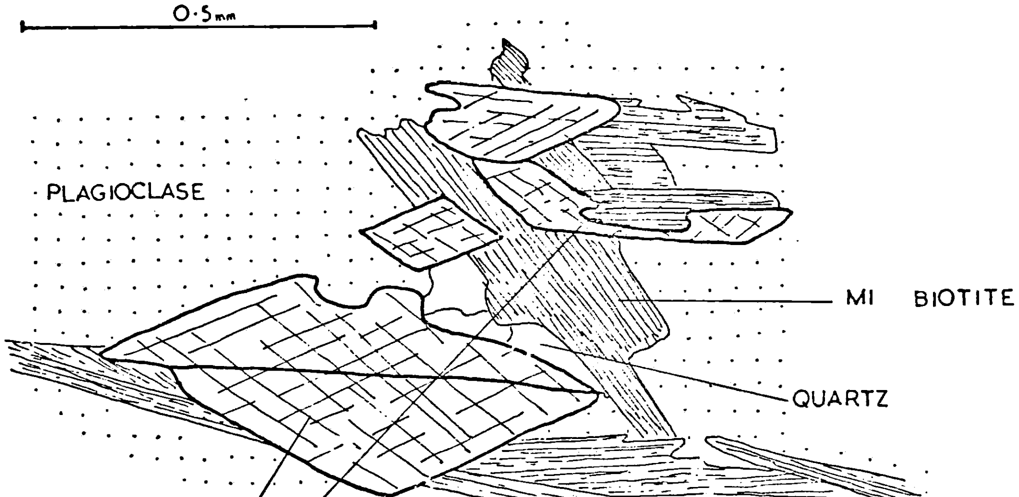
d) Biotite and hornblende recrystallise parallel to the S2 fabric (typically 0.5-1.0mm) and are locally seen to overgrow relic MS1 mafic components (fig 116). Both minerals partially overgrow and include the MS2 quartz and plagioclase grains. Hornblende also includes some biotite, and occasionally small inclusion free garnets (possibly MP1).

e) The MS1 diopside grains undergo minor replacement along their margins by hornblende during MS2. They occur as either small euhedral grains, or as irregular patches, growing into

FIG. 116



M2 hornblende overgrowing MS1 biotite , in a biotite-hornblende gneiss (Banded Gneiss), Lower Bergsdalen Nappe.



M1 biotite overgrown by MS2 biotite and hornblendes, in a gneissic quartz diorite, Lower Bergsdalen Nappe.

the diopside along cleavage planes. (fig 117a). For this reaction, Al must be added to the system:

diopside + Al + (OH) -- Hornblende.

f) In the more basic members, (especially the amphibolites), clinozoisite and zoisite is an important phase, being intergrown with and aligned parallel to, the biotite and hornblende S2 fabric. The clinozoisites and zoisites are derived from the hornblendes, and are consequently rimmed by iron oxides released by the breakdown of hornblende. (fig 112)

g) The MP1 garnets remain stable under M2 conditions, but do not appear to have grown whilst under stress. The MS2 biotites and hornblendes are locally flattened around the MP1 garnets; however, garnet growth does occur at a late stage (MP2) with the resulting inclusion of fine quartz and biotite grains, arranged in a ring in an outer zone of the garnet. Sometimes, the MP2 garnets are seen to overgrow the MS2 biotites (fig 118a)

From textural observations, the following reaction occurs:

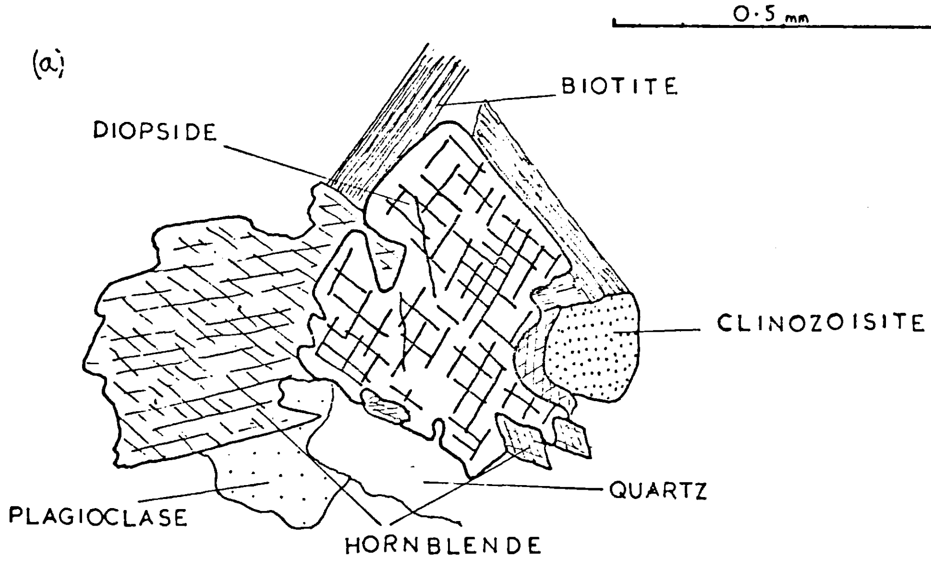
biotite + plagioclase -- garnet + quartz

Grade of metamorphism: The M2 metamorphic event is defined by the following parageneses:

biotite gneiss: quartz + upper oligoclase/mid andesine plagioclase + biotite $\pm$ garnet, K feldspar, iron oxides

FIG.117

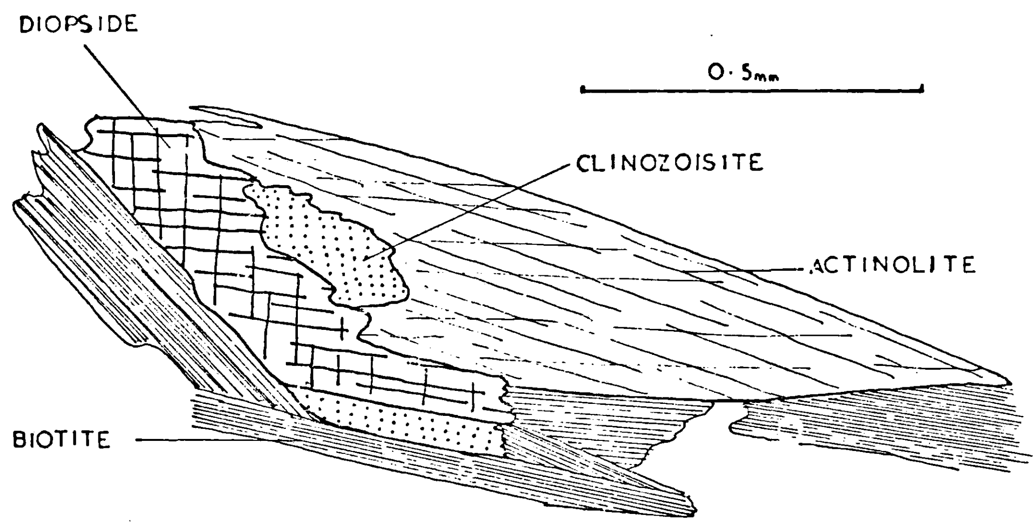
(a)



MS1 diopside being replaced by MS2 hornblende;

Both examples from a biotite-hornblende gneiss(Banded Gneiss) Lower Bergsdalen Nappe.

(b)



MS1 diopside being replaced by MS3 clinozoisite and actinolite.

Biotite-hornblende gneiss: quartz + mid/upper andesine plagioclase + biotite + hornblende ±garnet, clinozoisite

Amphibolite: hornblende + mid/upper andesine plagioclase ±biotite, quartz, zoisite, garnet

Gneissose quartz diorite: quartz + low/mid andesine plagioclase +hornblende + biotite

The presence of hornblende and andesine plagioclase in the more basic lithologies, places the grade of metamorphism at about mid-amphibolite facies (Winkler 1976, p.169).

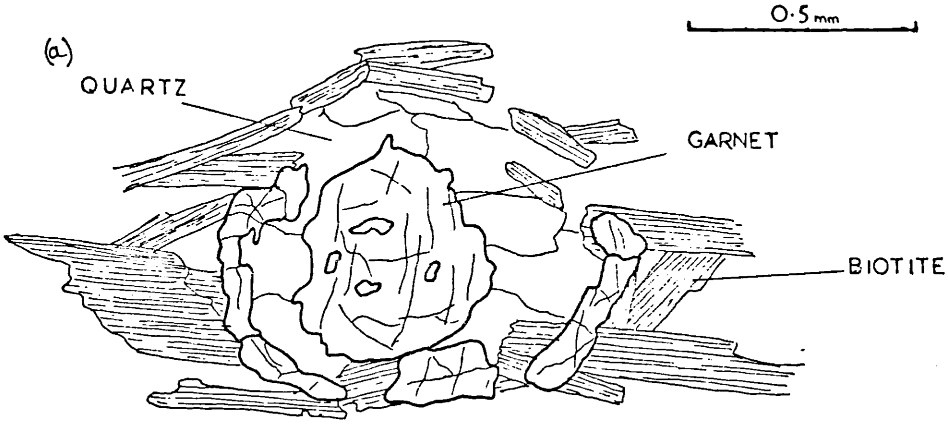
5.4c <u>Metamorphism, M3</u>

The M2 texture forms the regional foliation (S2) that is subsequently deformed by F2 structures, with which M3 is associated. The third metamorphic event is superimposed upon the M2 fabric with differing intensities - a new penetrative schistosity (S3) is developed in hinge regions of the tight F2 folds, whilst a composite foliation, based primarily on M2 textures, with some modification by M3 develops on the fold limbs. The foliation within the large bodies of gneissose quartz diorite is almost entirely a product of M3 due to its position in a tightly folded (F2) area within the Lower Bergsdalen Thrust zone.

The following features characterise the M3 event:

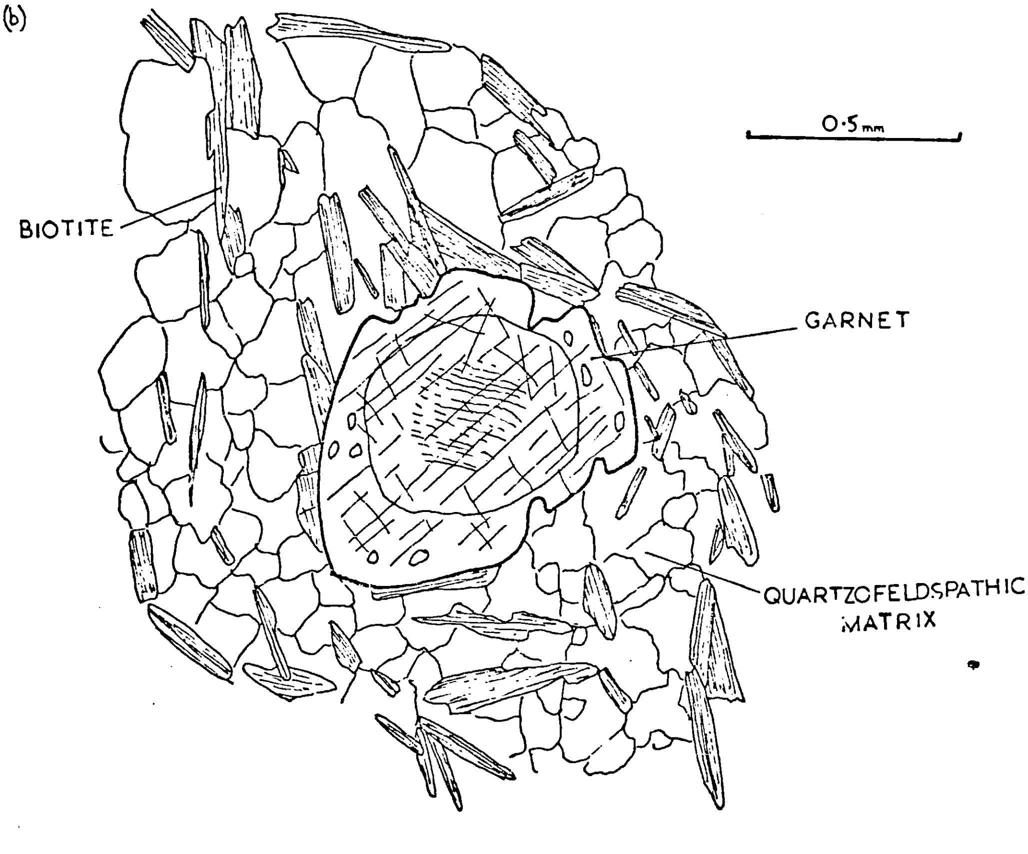
FIG. 118

(a)



MP1 garnet , with small inclusions, overgrowing MS2 biotites during MP2, leaving coarse incipient inclusions .

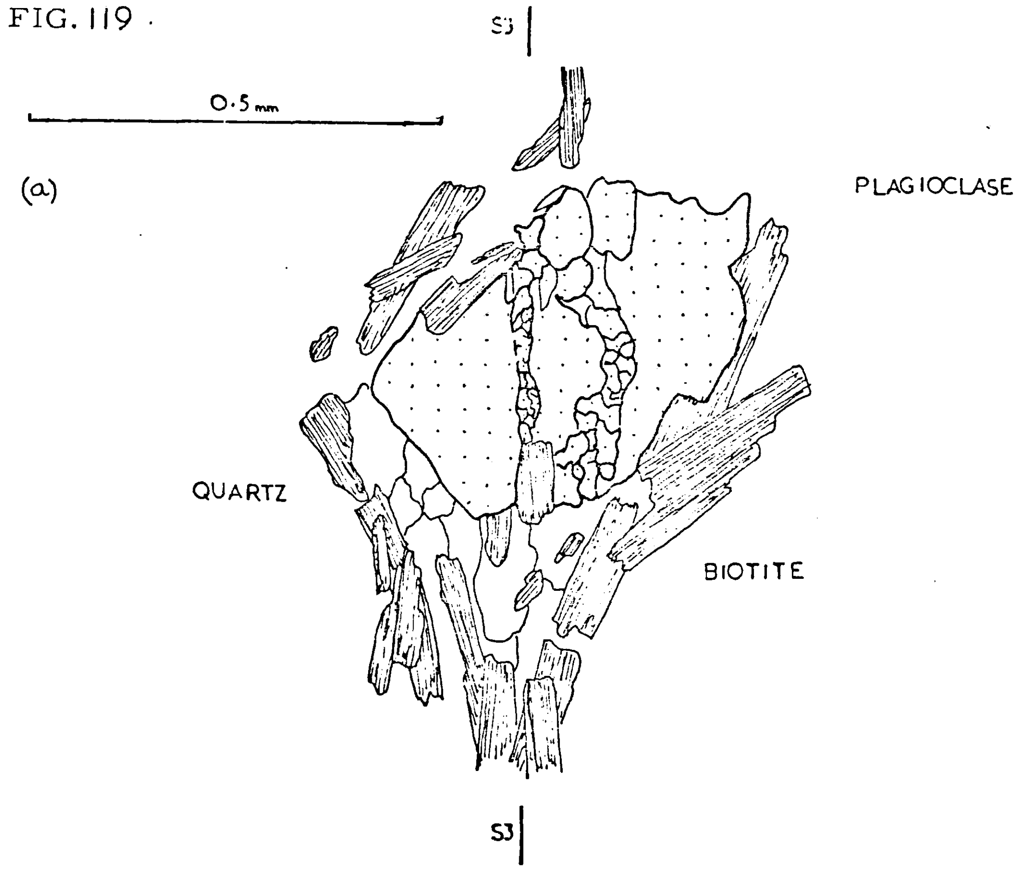
(b)



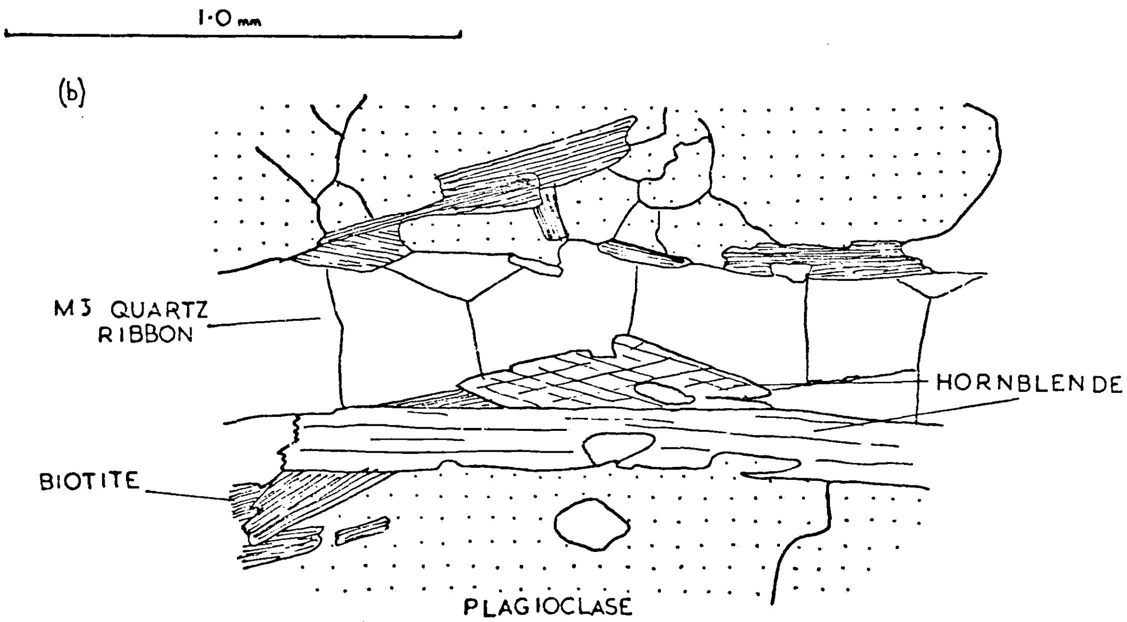
Zoned garnet with weakly rotated M1 inclusion trails, and post-tectonic idioblastic rim, overgrown by an MP2 rim with occasional inclusions. The biotite fabric is flattened around the garnet during M3.

Examples from the biotite gneiss (Banded Gneiss)

FIG. 119



M1/M2 plagioclase porphyroclast being augened and broken down into smaller grains, parallel to the S3 schistosity. From a biotite gneiss (Banded Gneiss), Lower Bergsdalen Nappe.



MS3 quartz ribbon overgrown along its margin by MS3 hornblende and biotite; from a gneissic quartz diorite. Lower Bergsdalen Nappe.

a) The MS2 quartz and feldspar grains undergo further grain size reduction by the process of dynamic recovery and recrystallisation (Bell & Etheridge 1975), with the resulting development of undulatory extinction, sub and new grains. In areas of high strain, such as the hinge area of F2 folds, the MS2 felsic grains are often broken into several smaller grains by discrete mylonite zones that pass through them (fig 119a). The net result of the straining is to reduce the felsic grain size in the Banded Gneisses to $<$ 0.3mm with only rare coarser porphyroclasts, and to $<$ 0.5mm in the gneissose quartz diorites. Locally, the felsic grains have an elongate form parallel to the S3 schistosity, although a granoblastic texture is more common.

b) Quartz ribbons, up to 4mm in length, and less than 0.5mm width, are occasional features within all of the gneisses, although are more pronounced in the gneissose quartz diorites. They cut across M2 textures, and are invariably aligned parallel to the S3 schistosity (or S3/S2 composite foliation). The ribbons are broken down into individual grains, rarely coarser than those of the matrix, with grain boundaries perpendicular to the ribbon margins. (fig 119b)

c) M3 plagioclase grains do not obviously contain more of the albite molecule than their predecessors, although there is some indication of minor retrogression, with localised patches of clinozoisite and quartz within the plagioclase.

d) Biotite and hornblende recrystallise in the hinge region of folds, to form a new schistosity (S3), grain size does not exceed that of M2. The quartz ribbons are marginally overgrown by the MS3 mafic components (fig 119b)

e) Biotite pressure solution strings are a distinctive feature, seen in both the biotite and biotite-hornblende gneisses, generated during M3. These are narrow (<0.05mm), continuous (up to 8mm) aggregates of biotite that cut across the M2 textures in hinge regions and are part of the composite fabric (S2/S3) on fold limbs. The biotite strings trail off into equally narrow ribbons of strained quartz, which continue to parallel the schistosity. Thin veins of iron oxide often follow the strings.

f) Locally, M2 hornblendes are altered to biotite in the hinge zones of F2 folds in the biotite-hornblende gneisses and gneissose quartz diorites. (plate 14). Hornblendes are only rarely altered in the amphibolites, usually just recrystallising.

The reaction, hornblende -- biotite implies mobility, on at least the small scale, of K and Ca.

g) In the fold limb regions, M2 biotite and hornblende undergo little alteration during M3. The M2 fabric (S2) is augened during M3 around clasts of felsic matrix, and garnet or coarser hornblendes if available. The mafic components undergo only slight recrystallisation around the augen.

h) The diopside in the biotite-hornblende gneiss is marginally retrogressed to actinolite (very pale green, and maximum extinction ($C \wedge Z$) of 18^{o} and clinozoisite (plate 96) and (fig 117b)

i) Clinozoisites are a common retrogressive feature from the M2 biotite and plagioclase. The biotites typically have a dark halo where they are in contact with the clinozoisite (fig 112) indicative of a high iron content, possibly due to the expulsion of iron from the clinozoisite as it grows.

j) Thrusting along discrete planes has generated its own distinct M3 characteristics that are described in section 4.6b

k) Garnets are stable under M3 metamorphic conditions, but do not themselves recrystallise.

Grade of Metamorphism: the parageneses associated with M3 is as follows:

biotite gneiss: quartz + plagioclase (oligoclase/andesine)
+ biotite + clinozoisite $\pm$garnet

biotite-hornblende gneiss: quartz + plagioclase (andesine) +biotite + hornblende ± clinozoisite, garnet, actinolite

amphibolites: plagioclase (andesine) + hornblende + clinozoisite ±biotite, quartz

gneissose quartz diorites: quartz + plagioclase (oligoclase/ andesine) + hornblende + biotite ± clinozoisite

The continuing stability of hornblende, garnet and plagioclase of composition between oligoclase and andesine is indicative of amphibolite facies metamorphism. However, the increase in clinozoisite content reflects a retrogression from the mid-amphibolite facies down to lower amphibolite facies. The lack of M3 chlorite indicates the lower amphibolite position, rather than Upper Greenschist. (Winkler 1976 p. 170).

5.4d Metamorphism, M4

The fourth metamorphic event, M4 did not generate pervasive changes to the earlier parageneses. It is associated with F3 folding in the nappe, which is restricted to the central and northern parts of the mapped area. Similarly, recognisable metamorphic effects are confined to the same areas.

Most of the metamorphic effects are restricted to granulation and recrystallisation with little new mineral growth to define a schistosity:

a) quartz and feldspar undergo only minor straining and recrystallisation, primarily with the development of undulose extinction and sub grains.

b) the M2/M3 plagioclases are often saussuritised (most commonly in mafic lithologies) and sericitised. The reduction in the anorthite content is confirmed where these plagioclases are seen to be breaking down to plagioclases of lower refractive index, along with quartz. The refractive index of the plagioclase may be either greater than or less than that of quartz, indicating a probable oligoclase composition.

c) biotite and hornblende undergo little modification, other than minor recrystallisation around fold hinges (plates 15, 97) and minor retrogression to chlorite. Locally, the biotite recrystallises parallel to the axial plane of the fold, defining a weak schistosity (S4). Muscovites (in phyllonites) react in a similar fashion.

d) clinozoisite and garnet remain stable, although clinozoisite very occasionally recrystallises parallel to the weak S4 biotite schistosity.

Metamorphic grade: the plagioclases are the only indicators of a change in metamorphic grade, with their breakdown characteristics. Otherwise, the mafic minerals generally remain stable, with only minor retrogression to chlorite, indicating that the grade of metamorphism is approximately Upper Greenschist facies (Winkler 1976 p. 168).

5.4e Metamorphism, M5

The fifth metamorphic event is related to the F4 northwest-southeast trending antiform that deforms all of the tectonic units at the margin of the Bergen Arcs. (section 4.10b) Consequently, the effects on all of the tectonic units will be described as one here.

Apart from minor recrystallisation of quartz and feldspar, M5 effects are restricted to retrogression of mafic minerals, (plates 98,99) with biotite, hornblende and garnet all retrogressed to chlorite, with the localised addition of sphene.

This is typical of metamorphism under mid greenschist facies conditions.

CONCLUSIONS (fig 120)

Several features stand out from the metamorphic investigations across the tectonic units:

a) In each unit, the regional foliation was generated under middle amphibolite facies conditions.

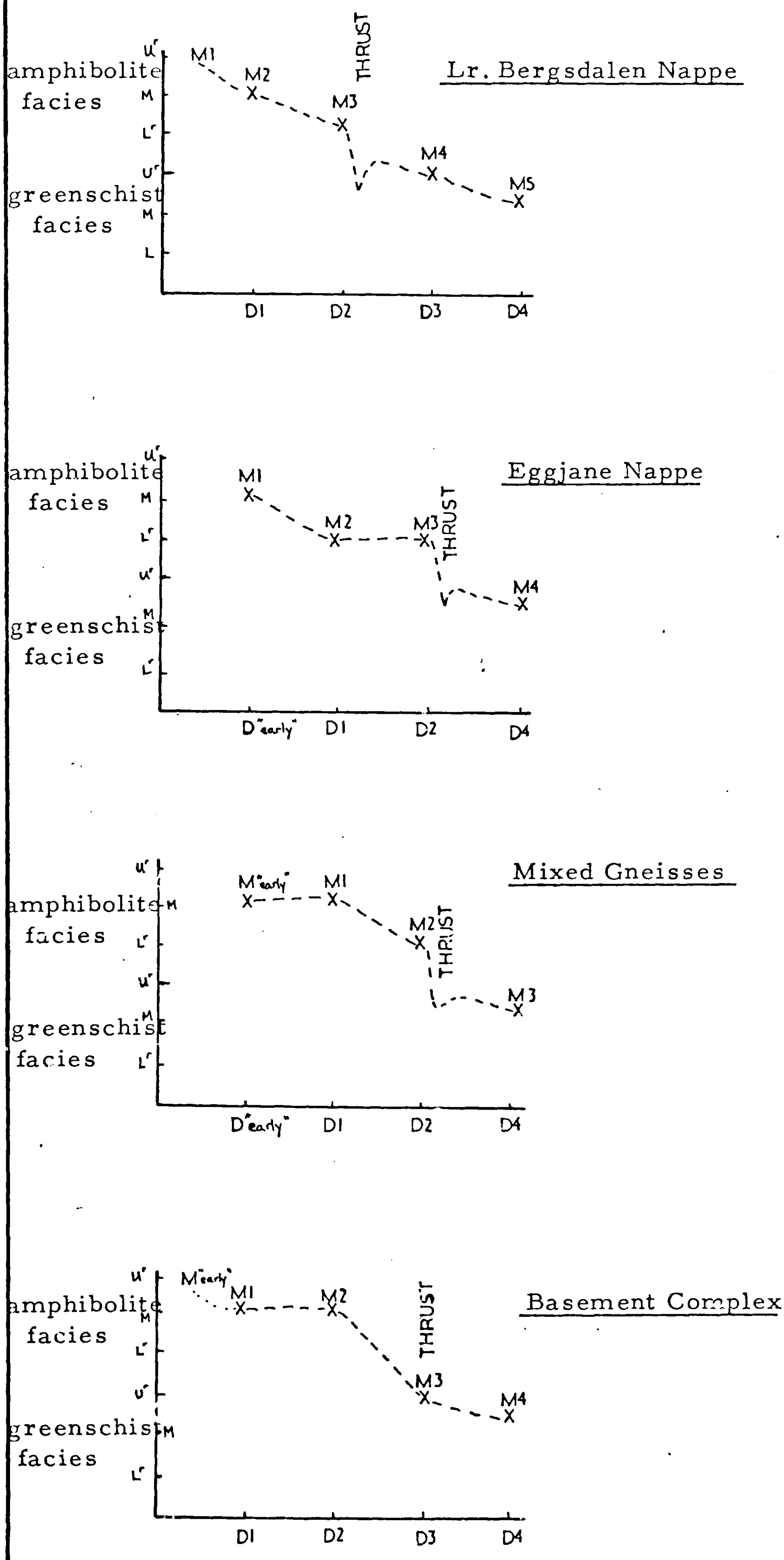
b) The metamorphic histories prior to the main phase of thrusting were very similar in each unit, with only the basement gneisses lying at a lower grade (upper greenschist facies cf. lower amphibolite facies) immediately prior to nappe emplacement.

c) Nappe emplacement (section 4.7) generated discrete planes of low grade metamorphism (mid greenschist) within higher grade tectonic blocks.

d) Within each tectonic unit, there has been a process of grain size reduction from that inherent from the first recognisable metamorphic event. In the case of the basement gneisses, this has reduced original grains 3-4mm in size, down to grains of less than 0.75mm. More extreme reduction occurred throughout the gneisses within the Lower Bergsdalen Nappe, with original grains up to 1.5mm in size reduced to grains of less than 0.3mm.

The process of grain size reduction is well reported in the literature in association with mylonite zones (i.e. White, 1973, 1976, 1977, Tullis et.al. 1973, Bell & Etheridge 1976, Hopper 1980).

FIG. 120 Summary of the metamorphic histories



Section 6 CALC-SILICATE & CALCITE BANDING

Thin bands containing calc-silicate and calcitic assemblages occur throughout the Lower Bergsdalen Nappe, and to a lesser extent, within the Mixed Gneisses. The bands are developed within all of the nappe lithologies, excepting the metasediments, the granitic and metagabbroic plutons, but including the quartz diorite plutons and amphibolites.

The following types of bands are recognised:

1. zoned calc-silicate/amphibolite bands (fig 121 and plate 100)
2. impure zoned calcareous bands
3. diopside and clinozoisite xenoliths within a granite pluton; these are included in this section due to their calc-silicate assemblage.

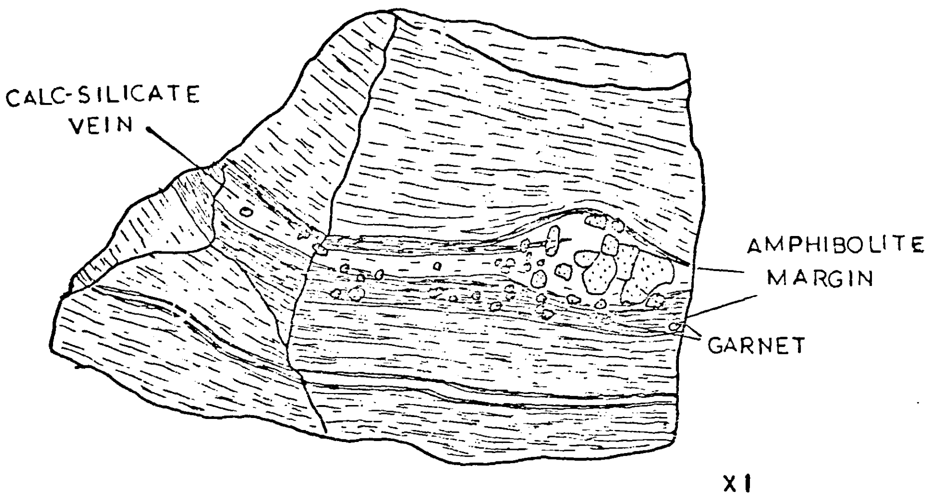
6.1 Zoned calc-silicate/amphibolite bands

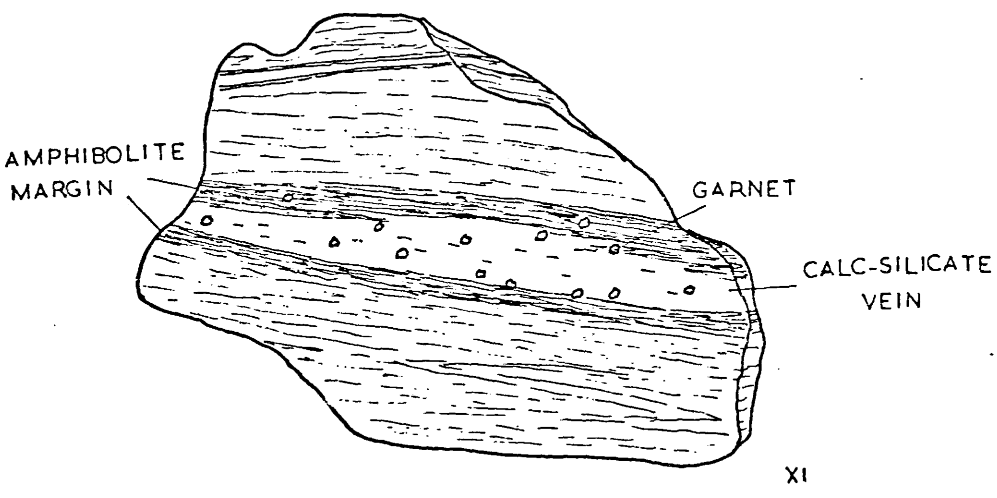
The amphibolite bands, with the characteristic central zone of leucocratic calc-silicates, are seen only within the biotite-hornblende gneiss and gneissose quartz-diorite lithologies.

The bands are always parallel to, and part of the gneissic foliation; however, the calc-silicate core is not invariably developed, dying out laterally to leave amphibolite bands indistinguishable from those of undoubted igneous origin.

The zonal arrangement of leucocratic calc-silicate core and green

FIG 121 Sketches of hand specimens of calc-silicate bands in Banded Gneisses of the Lower Bergsdalen Nappe





amphibole rich margins, form distinctive bands in both the pale coloured quartz diorite and biotite-hornblende gneisses. The ratio of the thickness of the amphibolite margin to that of the core is relatively consistent, lying in the range from 1:1 to 1:3. The calc-silicate core is nowhere greater than 4cm thick, and is itself occasionally compositionally banded, reflected by the concentrations of pale green clinozoisite. Brownish red garnets, up to 5mm diameter are often seen to overgrow both the calc-silicate core, and the amphibolite margins. (fig 121 and plate 49)

The bands predate the development of the S1 foliation in the Nappe, and are consequently seen to be intrafolially folded on a small scale (plates 48,49), with their limbs transposed, to form an integral part of S1. They are laterally impersistent, varying in thickness and ultimately dying out on outcrop scale.

At one location (GR 0334467183) along the Bergsdalen road, close to the Berg granite roadside outcrop, a zoned amphibolite band is seen to cross cut an indistinct small scale isocline in an axial planar fashion within homogeneous biotite-hornblende gneiss, (Banded Gneisses). A strong biotite and hornblende schistosity of S1 age cross cuts both fold and band. (fig 73) At the same location, concordant amphibolite-calc-silicate bands are seen to be cut by granite veins of D1 age. (plate 101)

Thus, the zoned calc-silicate bands are a D "early" feature, that have subsequently been subjected to at least 3 fold phases, two of which were isoclinal.

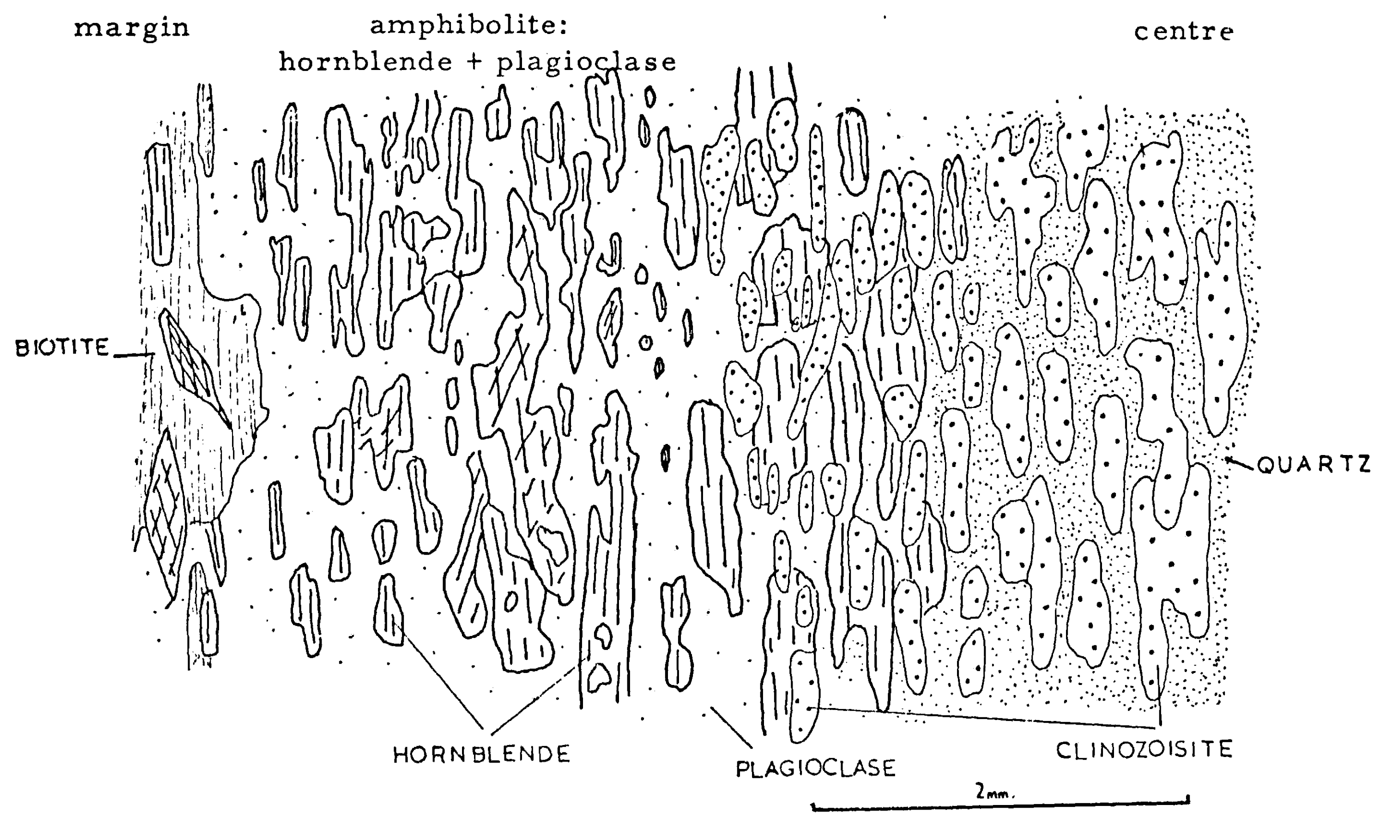
Calc-silicate/Amphibolite Band Petrology

a) Marginal amphibolite (plate 102, fig 122)

The contact between the biotite-hornblende gneiss and the amphibolite is sharp; the marginal amphibolite has a very simple, homogeneous mineralogy which is identical to that of the amphibolite horizons without the calc-silicate core. The two major components are hornblende and plagioclase, which occur in approximately equal proportions. (section 2.10). The plagioclase and quartz have very similar habits, with homogeneous grain sizes (0.3 - 0.5mm) evenly distributed throughout. Grain boundaries approximate to triple junctions where the plagioclase and quartz are polygonal. Elongate grains, with hornblende growing along their boundaries also occur. Quartz is often seen as small inclusions within the hornblende.

Twinning on the albite law is quite common, although some is suspected of being strain induced where the twins wedge out across the body of the grain. The plagioclase composition has been determined to lie in the range mid-upper andesine (An_{36} - An_{44})

FIG 122 Section through a zoned calc-silicate band



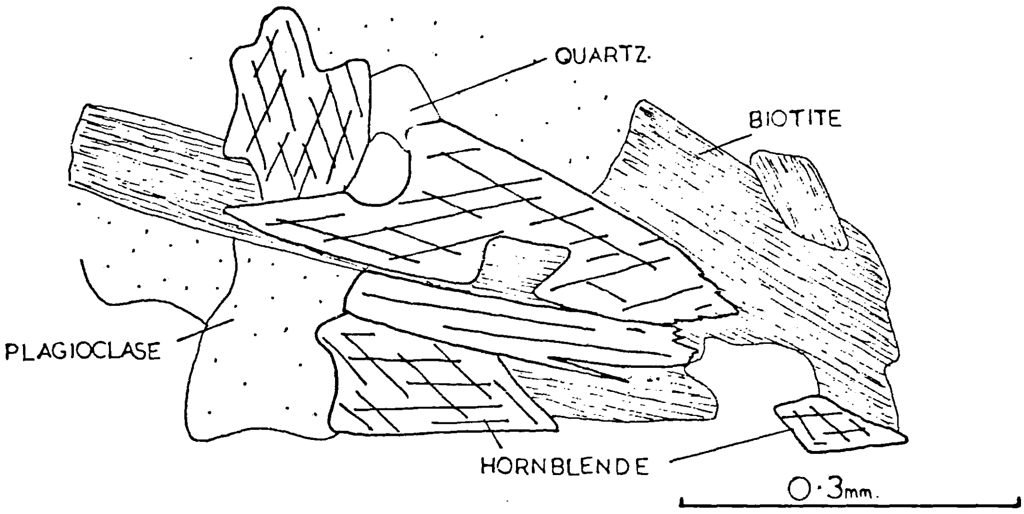
using the Michel Lévy test. Some plagioclases have reverse zoning with margins enriched in the anorthite molecule. The hornblende is sub to euhedral, with a pleochroic scheme from pale green to green. The maximum extinction angle (C$\wedge$Z) is 26^{o}, although commonly it lies in the range 14^{o} - 18^{o}. Grain size is homogeneous in individual specimens, yet variable from sample to sample. The total range is from 0.2 - 2mm. Hornblendes locally contain inclusions of sphene and iron oxides, along with the quartz. Otherwise, the hornblende margins show little embayment. Occasional biotites attest to their replacement by hornblende in the presence of plagioclase, releasing minor quartz. (fig 123) and (Plate 103). The hornblendes are strongly aligned, with their prism faces defining a good fabric. Subsequent deformation has caused local retrogression of the hornblende to chlorite.

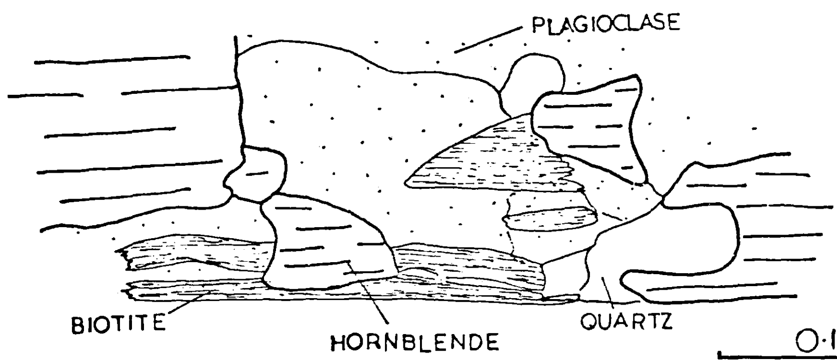
b) Calc-silicate core (fig 122)

The marginal amphibolite passes into the clinozoisite rich core across a transitional zone of about 1mm. Within the transitional zone, clinozoisite is seen to variably replace both the hornblende and the plagioclase. (table 6) and(fig 124)

Within the core zone proper plagioclase is not common, and occurs only as small aggregates ($\ll$0.3mm) usually enveloped by clinozoisite. Occasional fresh plagioclases are seen, but generally they are altered to either irresolvable tiny opaque

FIG. 123 Examples of hornblende overgrowing and replacing biotite from the amphibolite margins to calc-silicate bands, within Banded Gneisses of the Lower Bergsdalen Nappe.





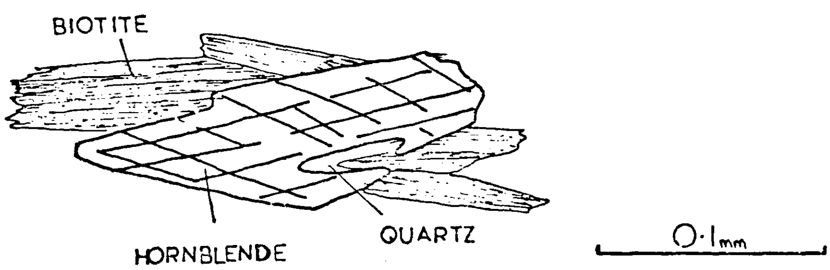
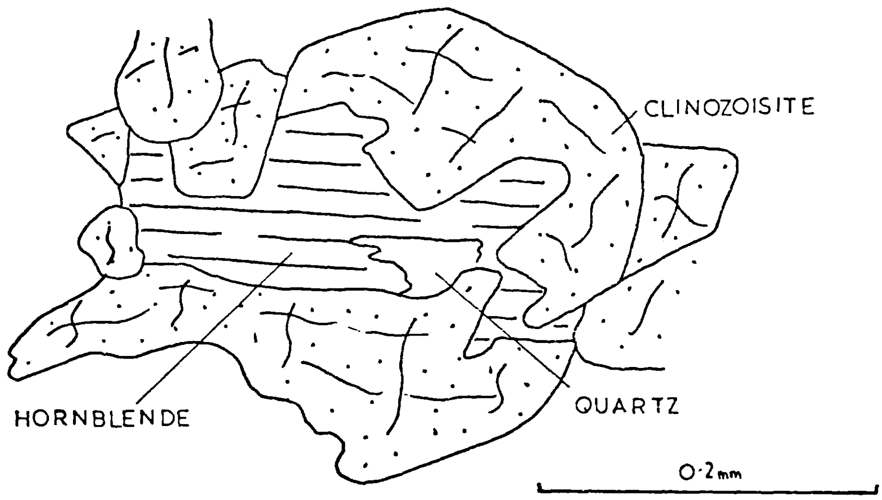
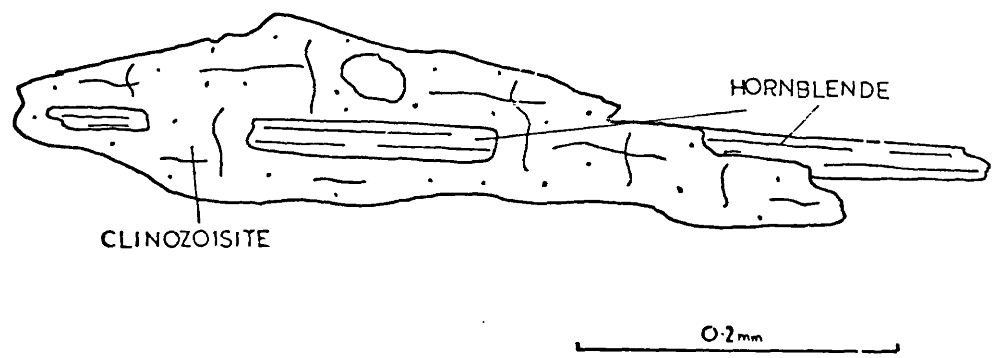


FIG. 124 Examples of clinozoisite replacing hornblende in the central zone of calc-silicate bands; Lower Bergsdalen Nappe.





grains or to calcite and clinozoisite. Relic albite twinning can be seen, but are rarely suitable for the determination of An. composition. The maximum composition obtained was An_{54}. (Labradorite).

The hornblende is pleochroic from pale green to bluish green, with a maximum extinction angle of 25° (γ :Z). Typically, the hornblende has a very eroded form, being replaced by clino- zoisite. (plate 104). Commonly small (< 0.3mm) ragged inclusions of hornblende are seen within large aggregates of clinozoisite, although an occasional coarse (~ 0.8mm) hornblende may remain.

Biotite is absent from the core zone, apart from very occasional small ragged forms that are overgrown by clinozoisite.

Pale green chlorites with anomalous brown and dark blue inter- ference colours are sometimes seen to replace the hornblendes. Quartz occurs in two forms - as small grains associated with the breakdown of plagioclase to clinozoisite, and as elongate tabular grains, with both hornblende and clinozoisite growing along the grain boundaries. The quartz grains are only rarely greater than 0.3mm in size.

Chemistry of the Calc-Silicate Zone

No detailed geochemistry of the calc-silicate bands has been undertaken. However, one analysis of a leucocratic, calc-silicate core to a typical zoned band has been made.

This analysed calc-silicate (3cm thick) (specimen MD 7) was composed of quartz-plagioclase-hornblende-zoisite-garnet, and had an amphibolite margin on either side. It occurred in a biotite-hornblende gneiss which had no distinctive features. The analysis for this calc-silicate core can be compared with the average analysis obtained from the intermediate biotite-gneisses. (Table 7). It can readily be seen that the differences between both the major and trace element values for the calc-silicate and biotite-hornblende gneiss are very small. Of the major elements, the calc-silicate is enriched in CaO, and depleted in K_2O and Na_2O. Trace element data is virtually identical, apart from Rb which is significantly depleted in the calc-silicate vein. This depletion probably reflects the loss of K_2O, with which Rb is associated.

Origin of the Zoned Calc-Silicate Bands

Two possible origins can be considered for the calc-silicate bands:

1. limited deposits of impure calcareous sediments
2. metasomatic bands due to the introduction of a volatile phase.

Table: 6

Modal Analysis of the Zoned Amphibolite/Calc-Silicate bands:

Sample No:	Y4.4		Y4.5	
	Amphibolite margin	Calc-Silicate Core	Amphibolite margin	Calc-Silicate Core
Plagioclase	42.6%	5.2%	41.0%	6.8%
Hornblende	45.4%	24.0%	48.2%	15.8%
Chlorite	0.8%	0.7%	0.4%	2.0%
Quartz	10.5%	14.8%	10.0%	18.6%
Clinozoisite	trace	55.1%	-	55.3%
Zircon	trace	trace	trace	trace
Sphene	trace	0.2%	0.3%	1.1%
Apatite	trace	trace	trace	trace
Ore	trace	trace	0.2%	0.7%

Table: 7

Chemical analysis for a calc-silicate band (spec.MD7) compared to that for the average intermediate biotite-hornblende gneisses

	MD7 %	av.int.bi-hb gn.%
SiO_2	59.73	56.42
Al_2O_3	16.40	16.69
MgO	2.35	3.32
MnO	0.15	0.13
FeO	5.50	5.49
Fe_2O_3	0.84	1.91
TiO_2	0.51	0.67
CaO	10.00	5.45
K_2O	0.32	1.98
Na_2O	1.84	3.88
P_2O_5	0.21	0.22
	97.85%	96.16%
Sr	483 ppm	449 ppm
Rb	3	67
Y	14	21
Zr	78	93
Th	0	2
Nb	2	4

The lensoid, foliation parallel appearance, and mineralogy of the bands (assuming that the zoning could be a secondary metamorphic feature) might reflect local sedimentary deposition during a break in volcanic activity. (section 3.5)

However, the second alternative is preferred on the strength of:

1. the bands always occur within either moderately homogeneous biotite-hornblende gneiss (interpreted as basaltic andesite/andesite), or gneissose quartz diorite, with no other possible sedimentary lithology in association.

2. rare calc-silicate bands are cross cutting to early structural features.

3. the mineralogy, although being a calc-silicate assemblage, is very homogeneous from band to band. Sedimentary calc-silicates have a noticeable mineralogical inhomogeneity (D. Powell pers. comm.) from outcrop to outcrop.

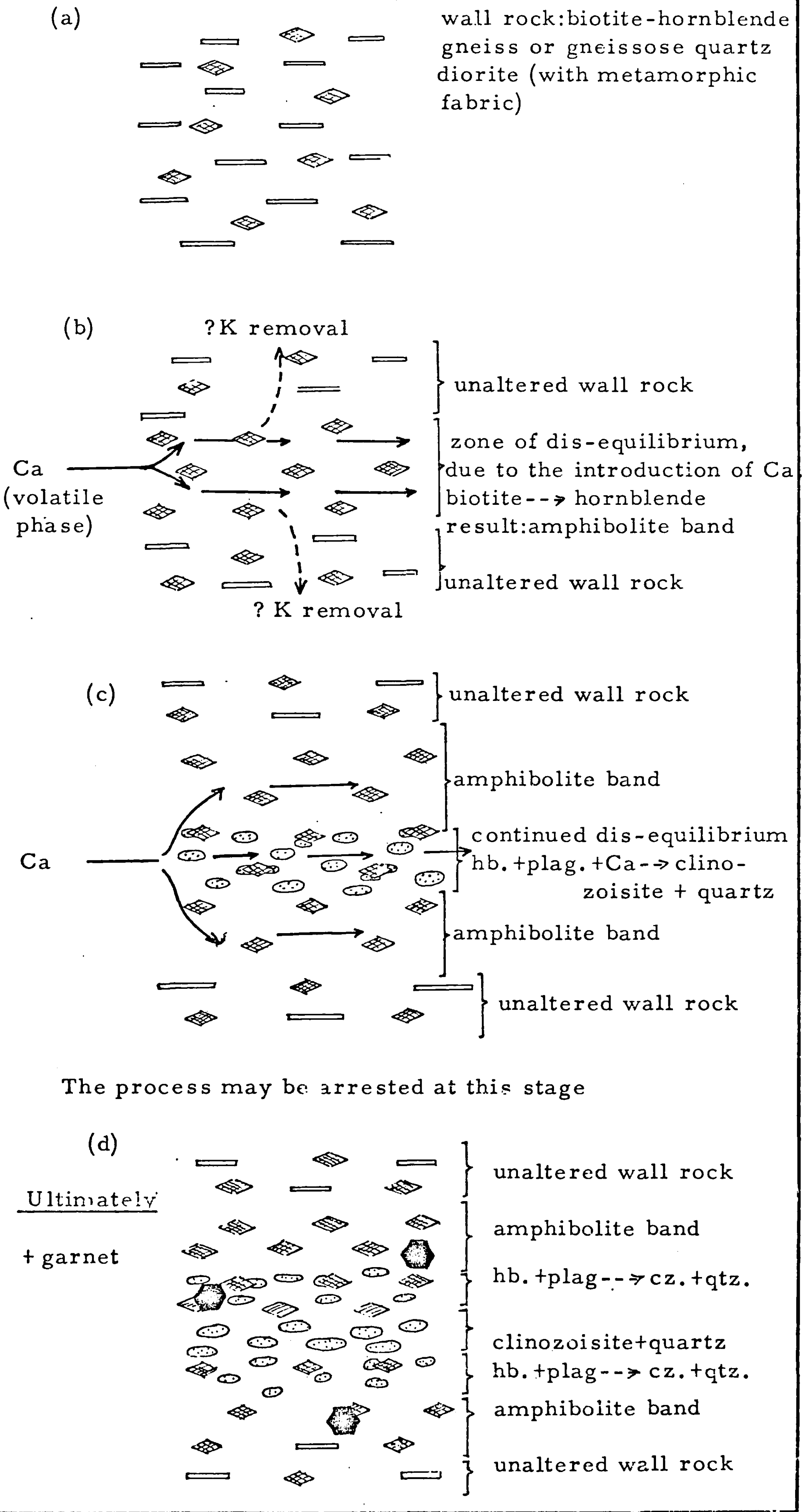
4. minimal geochemical evidence suggests a very close chemical affinity between calc-silicate bands and the biotite hornblende gneisses. This is perhaps not too surprising if the band is considered to be of sedimentary origin of very local derivation. However, the similar chemistry can also be easily explained in a model involving metasomatic processes:

From the limited geochemical data obtained for a zoned calc-silicate band (including the amphibolite margin), it is assumed that reactions originate due to the introduction of Ca as a volatile phase, along with the coeval removal of K and Na. Other than this mobility, the reactions are considered to be isochemical on the scale of the vein system. This view accepts the possibility of local small scale mobility of elements within the veins. Thus, the following simplistic model is postulated (fig 125) to explain the zoned calc-silicate assemblage, utilising observed reactions; the wall rock is assumed to be in a metamorphic state, with the main components being biotite, hornblende, plagioclase and quartz. A Ca rich phase is introduced and diffuses along defined channels, possibly parallel to the tectonic fabric (explaining the lack of cross-cutting relations). The introduction of a Ca rich phase destroys the equilibrium of the wall rock, (Vidale 1969, Carswell et.al. 1974) resulting in the following initial reactions, leading to in situ replacement:

(i) biotite + Ca --- hornblende + Na + K
(ii) increase in anorthite content of plagioclase lower andesine (An_{30-36}) + Ca --- mid/andesine (An_{36} - An_{44}) + Na

The hornblende of the wall rock remains in equilibrium with the volatile phase. The result is an amphibolite band, with the components hornblende, plagioclase ± quartz, while Na + K are

FIG. 125 Postulated model for the generation of zoned calc-silicate banding.



removed from the system.

Continued introduction of calcium as a volatile phase along the central zone would create further conditions of dis-equilibrium, with the resulting reaction:

hornblende+plagioclase+Ca -- clinozoisite+quartz±garnet, iron oxides, sphene (fig 124 and plate 104)

andesine plagioclase + Ca -- labradorite plagioclase

The excess Fe, Mg liberated by the breakdown of hornblende, must pass into solution, being incorporated in local sites for the nucleation of garnets and iron oxides.

Ultimately, the breakdown of hornblende and plagioclase will be complete, leaving a central zone of clinozoisite, quartz ± garnet and iron oxides.

Thus depending on how far the reactions have gone, an amphibolite band, with or without a calc-silicate core is metasomatically produced. The zonation therefore reflects depth of diffusion and amount of calcium introduced. Further deformation, augens the amphibolite around the calc-silicate, accentuating the lensoidal nature.

An alternative origin, under the general heading of "metasomatic" may be envisaged. Hydrothermal fluids passing through a rock pile may deposit the necessary elements, possibly in zonal form, that on subsequent metamorphism would combine to give rise to the calc-silicate mineralogy observed today. Without geochemical evidence it would be impossible to reach a conclusive answer as to which mechanism was operative. However, it is more likely that hydrothermal vein deposits would concentrate certain elements rather than mirror the geochemistry of the host rock, with only specific anomalies, as proposed here.

Thus, when reaching a conclusion as to the origin of these calc-silicate bands, the importance placed upon only a single geochemical sample must be realised. Further geochemistry should be undertaken before any confident conclusion may be reached.

6.2 Zoned Calcite Bands

Thin (0.5-4cm) laterally impersistent calcite bands form distinctive yellowish brown weathering horizons within the biotite gneisses of the Lower Bergsdalen Nappe. Although not densely distributed, one or two bands may be spotted in most large outcrops. The bands are invariably concordant to the gneissic foliation, and are often seen to be intrafolially folded (plate 106) Macroscopically, the calcite bands have a weak zonation with margins enriched in mafic minerals (biotite and garnet in particular). A weak zonation of calcite content is also suspected from the variable intensities of the brown weathering across the band.

This zonation across the calcite band is confirmed when studied microscopically. Only five bands have been investigated, but all have a very similar zonal arrangement of mineral assemblages, parallel to the band margins, that are moderately symmetrical about the centre of the band:

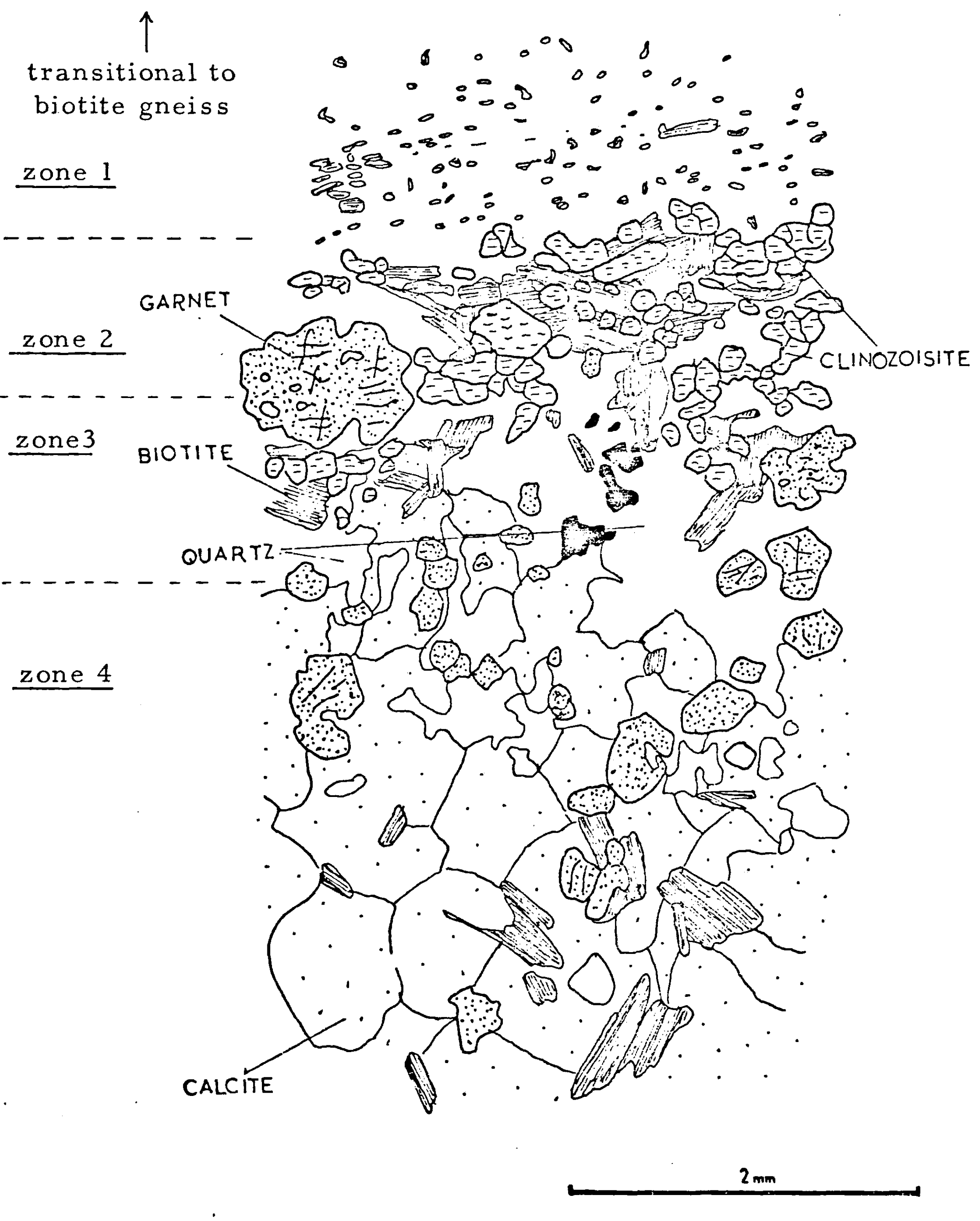
(fig 126) host gneiss:		quartz-feldspar-biotite±muscovite (biotite gneiss)
margin	zone 1	quartz-feldspar±biotite
	zone 2	biotite-clinozoisite-garnet-iron oxides ±quartz, plagioclase
	zone 3	quartz-garnet-calcite-biotite±plagioclase
	zone 4	calcite-garnet-biotite-quartz±clinozoisite, plagioclase
core	zone 5	calcite-clinozoisite-biotite-chlorite ±quartz, plagioclase

Of these zones, 5 and 3 are not invariably developed.

Zone 1 (fig 127)

This outermost zone is difficult to separate from the host gneiss, being its equivalent except for a decrease in amount and reduction in grain size of biotite. This biotite reduction may be pronounced or weak, although it is transitional to the biotite gneisses. The

FIG. 126 The zoning between a biotite gneiss and a calcite band, from the Lower Bergsdalen Nappe



zone never exceeds a width of greater than 3mm, and additionally is slightly enriched in plagioclase compared with the average biotite gneiss. The plagioclases are often almost completely replaced by sericite and tiny, dusty irresolvable inclusions. Where seen, the fresh twinned plagioclases have a composition of An_{36} - An_{40} (mid andesine).

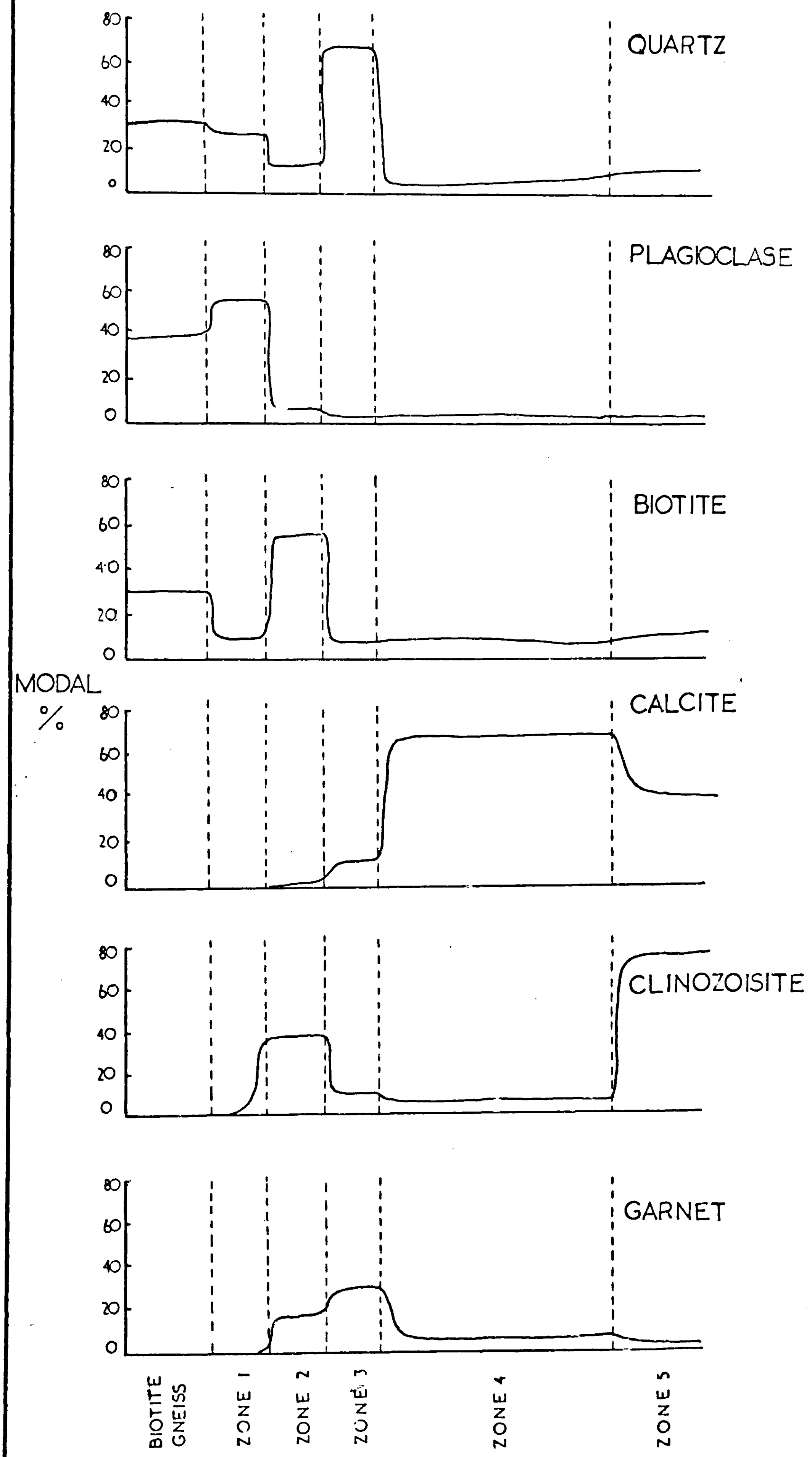
mineral ranges:	zone 1	average biotite gneiss
quartz	20-35%	25-37%
plagioclase	40-60%	27-40%
biotite	8-16%	20-36%
iron oxides	trace - 2%	traces
clinozoisite	traces	traces

Zone 2 (figs. 126, 127)

This zone is characterised by an enrichment in mafic phases, typically biotite, clinozoisite, garnet and iron oxides. The zone is invariably present, but never exceeds 2mm in width. The junction with Zone 1 is sharp and forms an obvious outer line for the calcite band as a whole. In contrast to Zone 1, this zone is depleted in quartz, and may have a variable plagioclase content:

range of mineralogies:		
	quartz	2-17%
	plagioclase	1-35%
	biotite	22-46%
	garnet	4-16%
	clinozoisite	6-34%
	iron oxides	trace - 5%
	calcite	trace
	chlorite	trace
	sphene	trace

FIG. 12.7 Modal content across a zoned calcite band (sample no. Y4.10)



The plagioclase and clinozoisite contents are inversely proportional with the clinozoisite replacing the plagioclase, which has a composition of mid-andesine (An_{38} - An_{42}). The clinozoisites occur as both individual grains (<0.4mm in size) and in aggregates up to 1mm in size. They overgrow the biotite aggregates, often with a rim of iron oxides. (fig 128c)

Sub and euhedral garnet grains up to 2mm in diameter include biotite, clinozoisite and calcite (fig 128 a, b)

<u>Zone 3</u> (fig 126, 127)

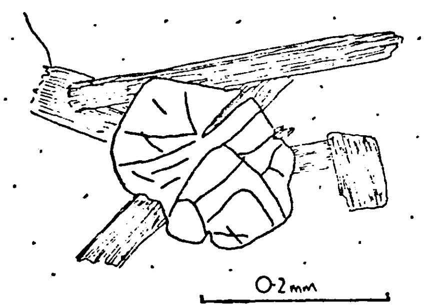
This zone is characterised by an abundance of quartz, and relative depletion of calcium. The zone is narrow (0.5 - 1mm) and is well developed in only 3 of the five samples studied, although it is poorly developed in the fourth. Where Zone 3 is only poorly developed, it appears as a quartz rich transition zone between the mafic zone 2 and the calcitic zone 4

Usually, however, the junction with Zone 2 is moderately abrupt, although some garnet tends to cross the boundary. (fig 126)

Range of mineralogies:		
	quartz	48-75%
	plagioclase	trace - 5%
	garnet	8-27%
	biotite	4-15%
	clinozoisite	trace - 3%
	calcite	0-16%
	iron oxides	trace - 4%

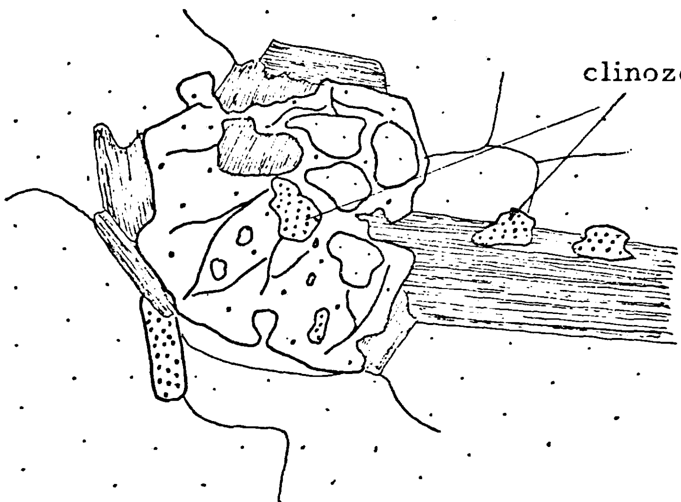
FIG. 128 Examples of reactions within the calcite bands of the Lower Bergsdalen Nappe.

(a)



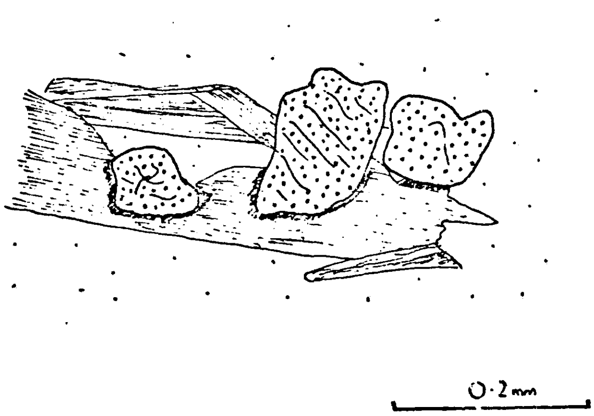
Garnet overgrowing biotite in a groundmass of calcite

(b)



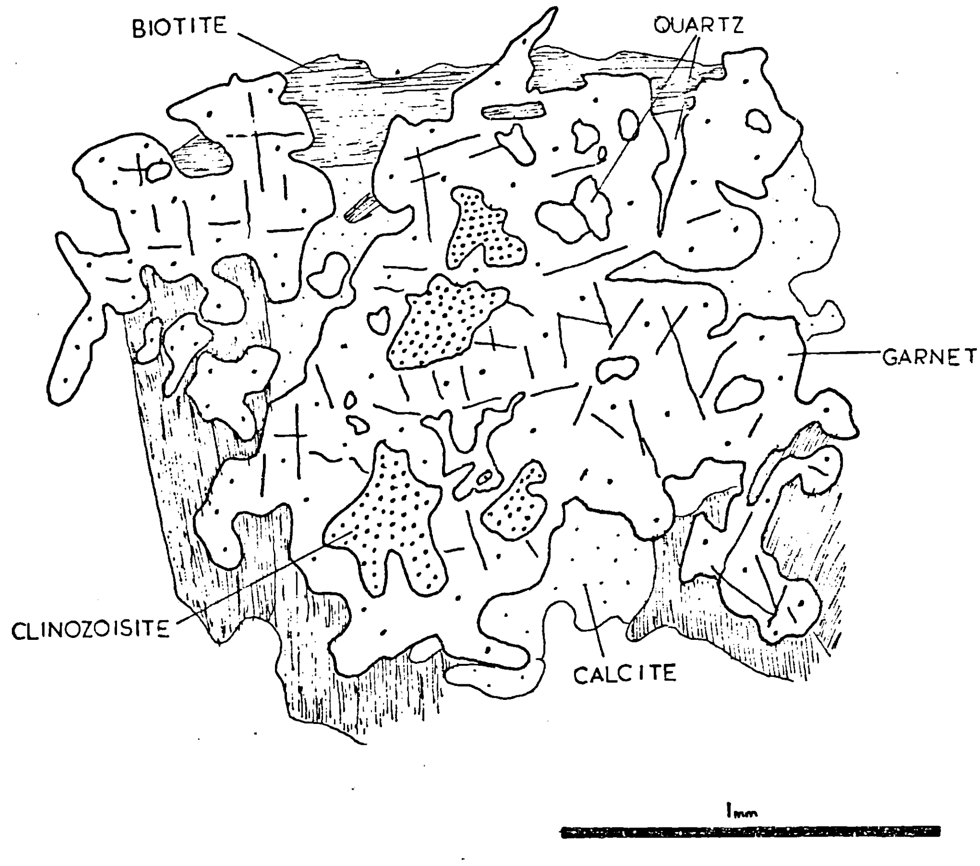
Garnet with inclusions of biotite, calcite and clinozoisite

(c)



Clinozoisite overgrowing biotite, with the local development of an Fe rich halo in the biotite

FIG. 129 Porphyroblastic garnet overgrowing calcite, clinozoisite, quartz and biotite in zone 2 of a calcite band



Quartz occurs as granoblastic aggregates with a maximum grain size of<0.5mm. The aggregates are intergrown with all of the other phases of the zone, especially calcite (when present). Other than quartz, subhedral garnet is the most common phase; it is fine grained (<0.5mm) and has only rare inclusions, although they may be of either biotite, quartz, clinozoisite or calcite. Biotite occurs principally as fine, individual grains (<0.4mm) distributed either along quartz - quartz grain boundaries, or as inclusions within the other phases.

Clinozoisite is rare, but where seen it occurs as small (<0.2mm) grains in contact with biotite or altered plagioclases.

Iron oxides form at a late stage in the development of the zone, including all of the previous phases.

Zone 4

This zone is observed in all of the samples studied, forming the main body of the calcite band; maximum thickness is 1.5cm. In contrast to the marginal zones that are depleted in free calcite, Zone 4 is characterised by a high calcite content. In addition, garnet and biotite are the important mafic phases. The boundary between Zone 3 and Zone 4 tends to be rather diffuse, with a transitional decline in the calcite content (figs. 126)

The full range of mineralogies:

calcite	64-71%
garnet	8-14%
biotite	10-14%
clinozoisite	2- 5%
quartz	0.8-5%
plagioclase	trace - 2%
iron oxides	1-2%

The calcite occurs as a granoblastic groundmass, with grain size rarely exceeding 0.5mm, that is in contact with all of the other phases. Of these, subhedral garnet occurs as both groundmass (<0.5mm) and as porphyroblasts (<4mm). The groundmass garnets are rarely free of inclusions, especially calcite. However, biotite and clinozoisite are also included. (plate 108) Many of the smaller garnets and all of the porphyroblasts show symplectic intergrowths with the calcite. (fig s 128b, 129)

The appearance, and breakdown features of biotite, clinozoisite, quartz and plagioclase in Zone 4 is the same as that in Zone 5, and will be described in that part.

Zone 5

This innermost zonal assemblage is not always developed (observed in 3 of the 5 samples); where seen, it can be of a variable nature, with extreme ranges in the calcite, clinozoisite and quartz contents. The most significant difference between Zones 4 and 5 is the decrease in the garnet phase, and the allied increase in clinozoisite. The junction between the two zones is diffuse.

Range of mineralogies:		
	calcite	8-75%
	clinozoisite	6-66%
	garnet	trace - 2%
	quartz	trace - 25%
	biotite	8-13%
	plagioclase	0-1%
	iron oxides	trace - 2%
	chlorite	0-1.5%
	muscovite	0-1%

The three major variables are calcite, clinozoisite and quartz. The calcite/clinozoisite ratio is approximately inversely proportioned, whilst the maximum quartz content occurs where there is approximately equal developments of calcite and clinozoisite. The lowest quartz content occurs with the maximum of calcite.

In samples where calcite is the dominant phase, it is granoblastic with a maximum grain size of 0.5mm. Subhedral clinozoisite (<0.3mm) typically occurs either along calcite-calcite grain boundaries, or as inclusions within the calcite. Where traces of plagioclase are seen, clinozoisite is invariably an associated replacement phase, along with calcite:

plagioclase -- calcite + clinozoisite + quartz

Plagioclase composition, determined on only 3 grains, indicates a position on the andesine/labradorite boundary (An_{46} - An_{52}).

Some plagioclase have reverse zoning, with more anorthite rich margins.

Biotites occur as individual grains (<1mm) with a pleochroic scheme from pale brown to brown, and are orientated parallel to the regional foliation. They occur along calcite-calcite grain boundaries, with some included by the calcite. Locally, the biotites have dark pleochroic halos around included, and overgrowing clinozoisites, indicative of the following reaction: (fig 128c)

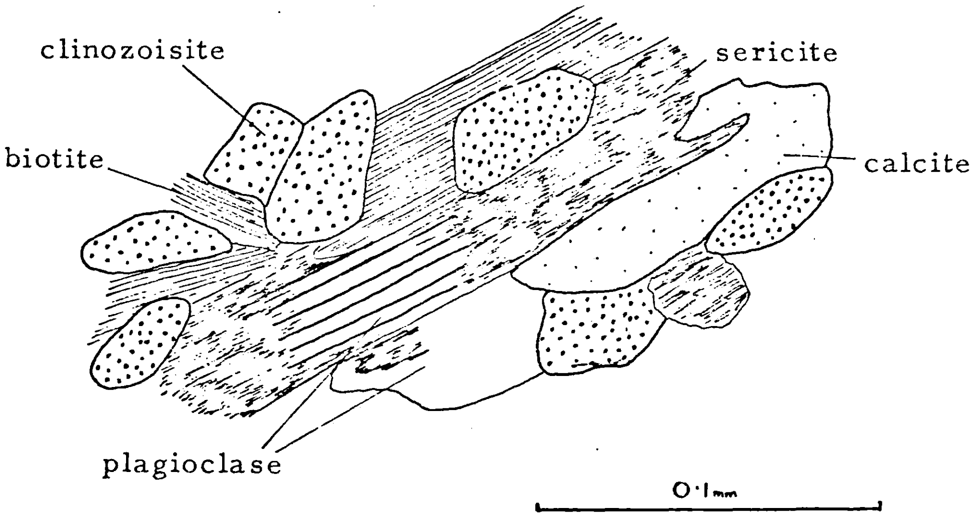
biotite + calcite -- clinozoisite + Fe + K + CO_2

Quartz is rare in the calcite rich sample; where it does occur, it forms as small (<0.2mm) discrete grains enclosed by calcite.

The clinozoisite rich facies of Zone 5 is very distinctive, with some similarity to the diopsidic xenoliths described below (section 6.3) Muscovite, sometimes in the form of sericite is present in small amounts, whilst garnet is absent.

The characteristic feature of the zone is the rarity of plagioclase; traces can be seen within patches of clinozoisite, calcite and sericite (fig 130). Patches of sericite and clinozoisite attest to the complete alteration of the plagioclase elsewhere in this zone. Otherwise, the clinozoisites occur as both knotty aggregates, up to 1mm in diameter that are intergrown with calcite and quartz,

FIG. 130 Alteration of plagioclase to sericite along twin planes; from zone 5 of a calcite band



and have sericite and biotite swinging around them, or as an equigranular ($< 0.3mm$) granoblastic matrix with intergrown calcite.

The biotites are commonly being replaced by a pale green chlorite, with deep blue anomalous interference colours, suggesting the variety penninite.

<u>Origin of the zoned calcite bands</u>

The calcite bands within the biotite gneisses may be interpreted in two ways:

a) they are of metasedimentary origin, and represent an impure calcareous horizon

b) they are of secondary, hydrothermal origin, and represent calcite veining from a phase early in the history of the gneisses.

The gneissic environment of the bands sheds no light on the origin, with some bands occurring in association with thin metasedimentary horizons within the biotite gneisses (muscovite-biotite schists) whilst others occur within homogeneous tracts of the biotite gneiss, that have been interpreted as dacites and rhyolites (section 3.5).

At the present state of knowledge, the origin must remain unknown.

Mineral zonation at the contact of limestones and pelites has often been recorded in the literature (Vidale 1969, Thompson 1974).

The zonation has been ascribed to metasomatic reactions across the contact, and has been studied experimentally by Vidale (1969). It was shown that the compositional difference between limestone and pelite resulted in a chemical gradient across the contact. Components are able to diffuse down the chemical activity gradient in the presence of fluid phases, under metamorphic conditions, resulting in a sequence of mineral assemblages controlled by the available migrating elements (fig 131)

The basis for zonation is thus present in this situation with the calcareous band juxtaposed against a biotite gneiss, compositionally equivalent to a marble/pelite contact. Thus, the zonation will be looked at in the light of element mobility, although it must be borne in mind that the present assemblages and zonation reflect the effect of several metamorphic episodes (section 5.4) that have probably altered the primary zonal features. Consequently, an attempt is made to estimate the primary assemblages, and interpret them in terms of element mobility along chemical gradients.

From textural observations, it can be seen that clinozoisite and garnet replace earlier assemblages; clinozoisite replaces plagioclase (labradorite) and overgrows biotite, while garnet occurred late on in the recrystallisation story, including calcite,

FIG. 131

Experimental zonation sequence obtained by Vidale (1969) for a single pelite/marble contact, held at 2kb. for 28 days.

↓				calcite
↓	Si			calcite-wollastonite
↓	↑	Mg		calcite-wollastonite-diopside
↓	↑	↑		diopside-tremolite-quartz-(anorthite)
↓	↑	↑		tremolite-quartz-(anorthite)
Ca	↑	↑	K	tremolite-phlogopite-quartz-(anorthite)
	↑	↑	↑	phlogopite-quartz-(anorthite)
	↑	↑	↑	phlogopite-quartz-sanidine-(anorthite)
	↑	↑	↑	muscovite-phlogopite-quartz-sanidine-(anorthite)

biotite and clinozoisite.

Thus, the following simple primary assemblages are postulated, where the first named mineral is modally of greatest importance:

Zones 4 & 5	calcite + biotite + plagioclase $\pm$ quartz
Zone 3	Quartz + biotite + calcite
Zone 2	biotite + plagioclase + quartz
Zone 1	plagioclase + quartz + biotite

A simple sequence of element mobility, perpendicular to the band margins, can be postulated, (fig 132) with Ca migrating outwards from the calcitic core, with a limit of effect at zone 1. Si, K, Fe, Mg, Al migrate inwards, leaving a biotite enriched zone (Zone 2) which acts as a buffer to all of the elements except Si, which is able to migrate further inwards, forming a quartz rich zone adjacent to the calcite band (Zone 3)

This simple zonal pattern is subsequently modified by later metamorphisms which retrogress the assemblages (mainly plagioclase -- clinozoisite) and creates further small scale mobilities, resulting in the development of garnet.

6.3 Calc-Silicate Xenoliths

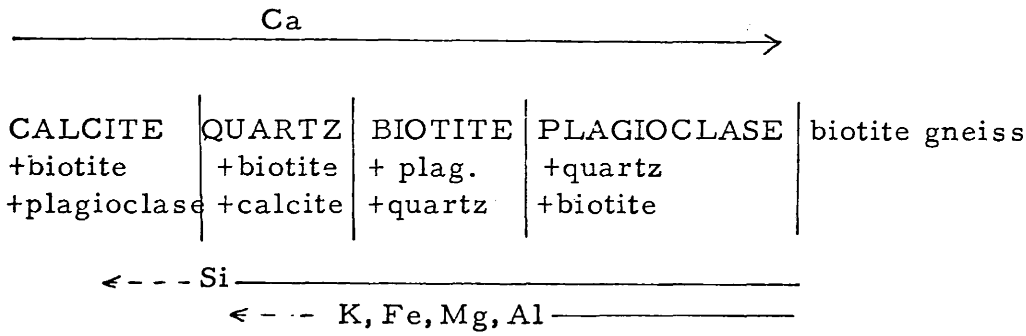
Pale green xenoliths with a calc-silicate assemblage occur within a net veined complex at the western margin of the Berge granite (Lower Bergsdalen Nappe (fig 27)) exposed in a new road cutting

FIG. 132 Postulated model of element mobility for the development of the zoned calcite bands

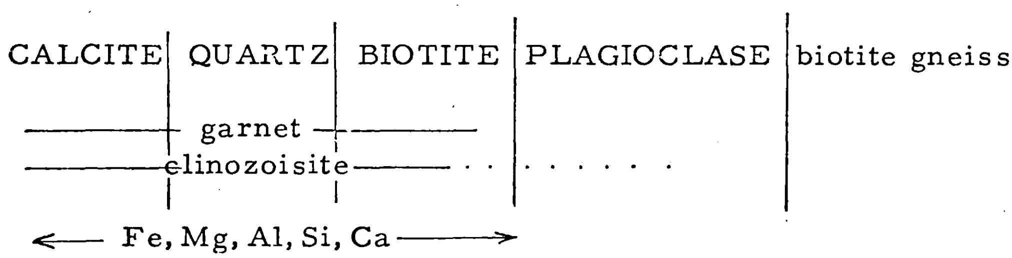
(a) Initial mineral distribution at the contact between calcite band and biotite gneiss

"impure marble"	biotite gneiss = "pelite"
calcite	quartz
biotite	plagioclase
plagioclase	biotite
	± k feldspar

(b) Preferential migration of elements, in both directions across the original calcite/biotite gneiss contact.



(c) There is additional mobility of elements, and modification of the assemblages, due to retrogressive metamorphism



along the Dale-Voss road (GR 0334467183). The net veining is confined to two bands, each approximately 2-3 metres in thickness, separated by a four metre section of Banded Gneisses (plate 50). The exposure is folded by a F3, medium scale (10-15 metres amplitude) structure.

The Banded Gneisses in this area comprise biotite-hornblende gneiss and amphibolite, with minor intercalations of a clinozoisite enriched biotite gneiss. These biotite gneisses are chemically indistinguishable from other biotite gneisses containing clinozoisite, in that the CaO content is greater than those without clinozoisite. (average biotite gneiss ~ 2% CaO cf clinozoisite biotite gneiss ~ 4% CaO - see appendix).

Immediately adjacent to the net veined xenolithic complex, rare patches of pale green calc-silicate occur within the clinozoisite bearing biotite gneiss; the calc-silicate/gneiss contact is transitional, indicating progressive compositional change. Similarly, a progressive visual change is recorded from Banded Gneisses at the margin of the intrusion, through to green calc-silicate xenoliths within the granite (plate 109)

Within the net veined complex, the pale green xenoliths have their longest axes (which range from 3-35cm in length) parallel to the gneissic foliation in the adjacent Banded Gneisses; a weak biotite defined fabric is also generated in the intrusive granite. Although some of the xenoliths are pale green with no obvious macroscopic fabric, instead having a fine grained (<0.3mm) sugary texture, others have a darker colour due to the presence of inhomogeneously distributed biotites (<3mm in length) that define a macroscopic fabric. The variable biotite occurrence must reflect compositional changes in the original, pre-net veined body, that has been disrupted by the intrusion of the granite. The result is a varied array of xenoliths, some biotite free, some with a partial biotite content (confined to well defined bands within the xenolith) and others with a complete biotite fabric (plate 110). The biotite fabric is invariably parallel to that of the granite and Banded Gneisses (S2).

Mineralogy of the calc-silicate xenoliths

The xenoliths within the net veined complex are characterised by the presence of diopside; the following mineralogical ranges are estimated visually:

diopside	33-48%
actinolite	trace - 2%
plagioclase	40-46%
quartz	2-8%
clinozoisite	2-3%
biotite	2-21%
sphene	trace - 1%
apatite	trace
iron oxides	trace
chlorite	0-1.5%
hornblende	0-0.5%

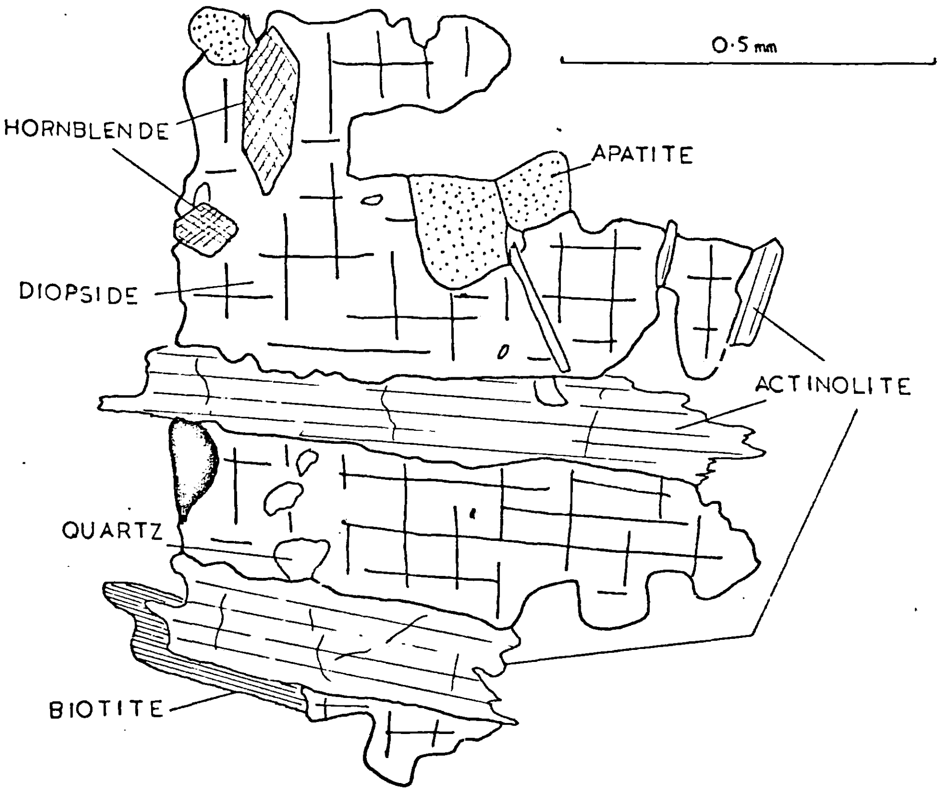
The green body colour of the xenoliths is due to the high concentration of diopside, which in thin section has a pleochroic scheme from colourless to very pale green. It is optically identified by its moderate 2V, positive optical figure and maximum extinction angle up to 42^{o} ($C \wedge Z$). The identification was confirmed using X-ray diffraction techniques on separated samples (appendix). The diopsides have a subhedral to anhedral form, and are almost unimodal in grain size (0.2mm) with no size difference in zones of high biotite development. In only one specimen were grains up to 2mm in size recorded, and these poikilitically enclosed quartz, plagioclase, sphene, biotite and small euhedral (<0.2mm) hornblendes (figs 133, 134a)

Although not obvious in hand specimen, the diopsides, along with the other minerals have a shape orientation, with their longest axes parallel to the regional fabric.

Plagioclase is moderately fresh, with an oligoclase composition (An_{24} - An_{28}), locally replaced by clinozoisite. Grain size is approximately the same as the diopsides, together having a granoblastic texture (plate 111)

The biotites are pleochroic from pale yellowish brown to reddish brown, and are often seen to be overgrown by the diopsides.

FIG 133 Examples of diopside with inclusions of hornblende being retrogressed to actinolite, from the calc-silicate xenoliths



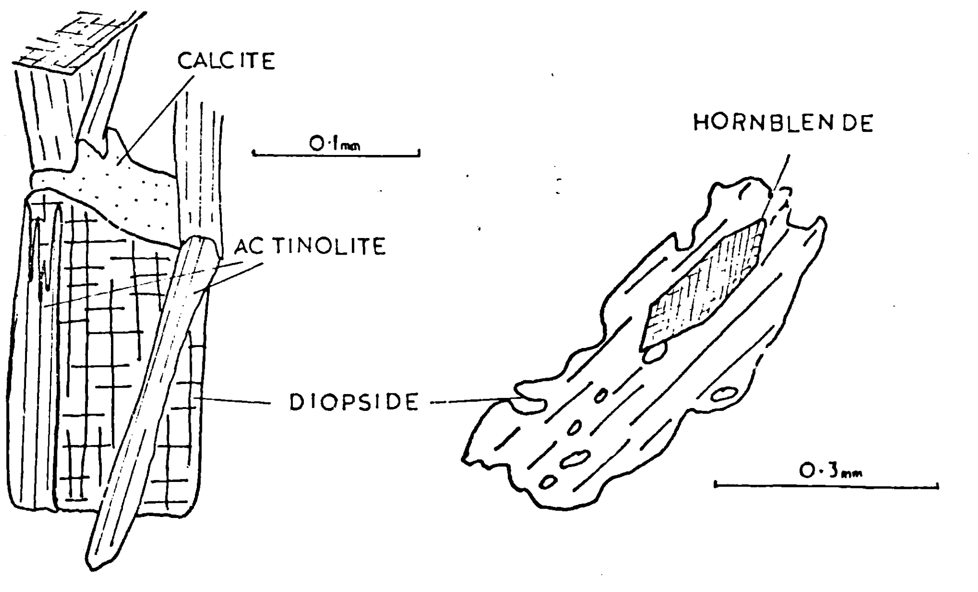
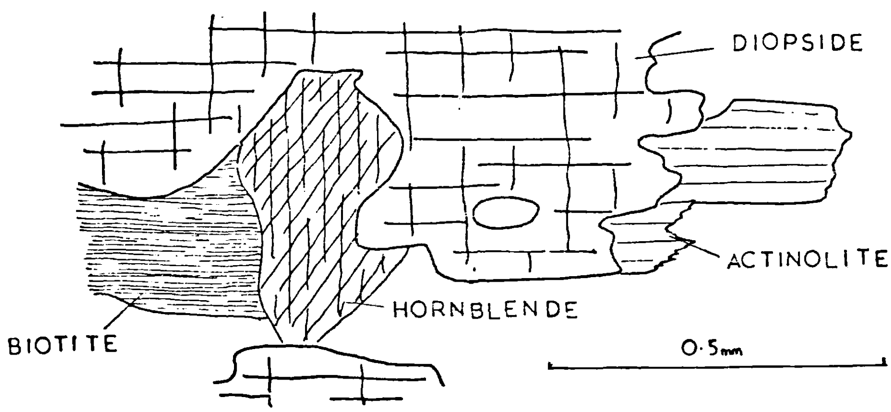
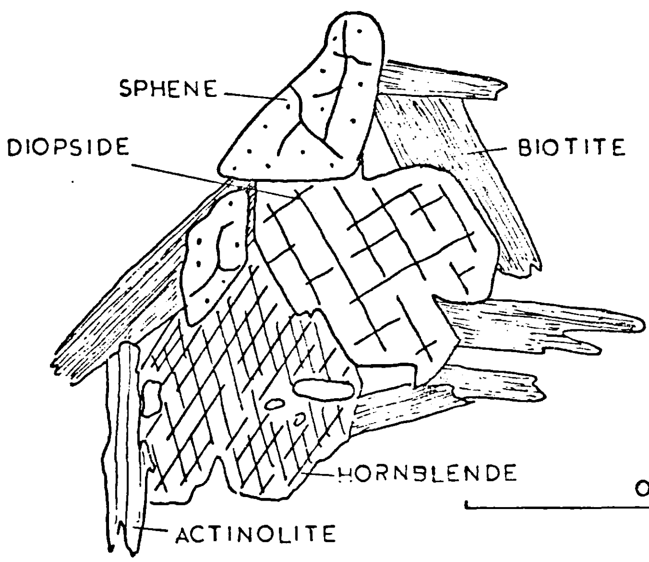


FIG. 134 The form of diopside from a calc-silicate xenolith





Their grain size varies from 0.2-2mm, whilst their modal content is also extremely variable.

A stable assemblage is recognised:

diopside - oligoclase plagioclase - biotite - quartz
± hornblende

However, this assemblage has been retrogressed, with diopside, and very occasionally hornblende being replaced by a pale green amphibole, with a maximum recorded extinction angle of 18° (C∧Z):

diopside -- actinolite ± calcite (plate 112) and (fig 133)

In addition, other retrogressive reactions seen:

plagioclase -- clinozoisite + quartz
biotite -- chlorite

Discussion of the calc-silicate xenoliths

The calc-silicate xenoliths present a problem in interpreting their origin. From the field data, it would seem that the calc-silicates have some transitional association with the clinozoisite bearing biotite gneisses and the biotite-hornblende gneisses (Banded Gneisses)

Thus, the calc-silicates represent a Ca enriched horizon within the Banded Gneisses; however, it is unknown as to whether this Ca enrichment is primary i.e. of sedimentary or volcanic origin, or secondary, due to the introduction of a Ca rich phase into a normal Banded Gneiss sequence.

An additional "coincidence" is the location of the calc-silicates within, and immediately adjacent to, the D1 granitic net veining. These calc-silicates are not recognised at any other location, thereby suggesting that the granite and calc-silicate horizon are intimately associated.

This association with the D1 granite might reflect the following:

1. Purely coincidental location of the granite intrusion into the calc-silicates

2. If the calc-silicate assemblage is a secondary, metasomatic feature, then the calc-silicates might lie along a pre-defined weakness that acted as a channel for the initial metasomatism; the subsequent granite intrusion has re-utilised the weakness, thereby being intruded into the previously altered calc horizons.

3. The calc-silicate assemblage could represent Banded Gneisses that have been altered by the granite intrusion, which induced element mobility and recrystallisation. This again implies a secondary origin for the calc-silicates.

This final suggestion is considered more likely, due to the immediate proximity of Banded Gneisses and calc-silicates at the margin of the net veined complex (plate 109) and the apparent "fortuitous" occurrence of calc-silicates only within an area of extensive granitic net veining.

Thus, the following sequence of events is postulated:

a) The Banded Gneisses, comprising dominantly biotite-hornblende gneiss and amphibolite, along with some biotite gneiss are invaded by a volatile phase, resulting in the disruption of the gneissic banding and the intrusion of granite in a net vein form. This intrusion occurred during the first deformational phase (D1) recorded in the Lower Bergsdalen Nappe, under regional metamorphic conditions at mid amphibolite facies (section 5.4b).

b) The volatile phase was enriched in Ca, as suggested by the presence of free calcite in the granite, and encouraged local element mobility within the invaded gneisses.

c) Under suitable temperatures, total fluid pressures (CO_2 and H_2O) and partial pressure ratios (ratio of CO_2 to H_2O = mole fraction X_{co2}), reactions occur that are dependent upon element mobility, thereby changing the mineral assemblages of the assumed Banded Gneiss xenoliths within the net veining complex. The conditions suitable for these reactions are placed within the amphibolite facies by Winkler (1976 p. 122).

hornblende + Ca + quartz -- diopside + Al + Fe

Reported reactions normally involve tremolite/actinolite to release diopside (Winkler 1976 p. 112); however, if one considers that the systems would be open due to the introduction of a volatile phase, then the proposed mobility of Al + Fe might be considered feasible.

Textural evidence for the reaction is derived from the one sample that contains diopsides with inclusions of hornblende (figs 133, 134) The Fe released by the reaction may be utilised in the recrystallisation of biotite, the nucleation of iron oxides or possibly removed from the system completely. Excess Al may be postulated to facilitate further growth of plagioclase, by using the free quartz that is available as a phase from the Banded Gneisses:

Ca + Al + quartz -- plagioclase

thereby partially explaining the reduction in the quartz content of the calc-silicates compared with the Banded Gneisses. In addition, excess Al may also be incorporated in further recrystallisation of biotite.

Thus a new assemblage is created:

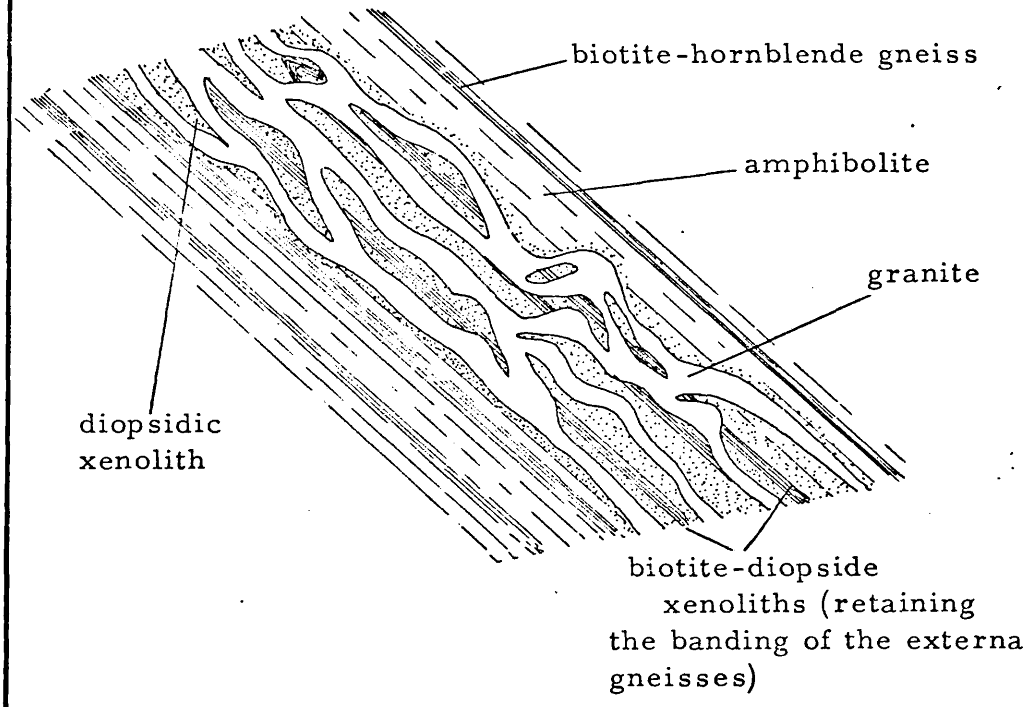
diopside - plagioclase - biotite - quartz $\pm$ hornblende

Structural evidence suggests that the granites were intruded into country rock under regional stress and underwent continued deformation as they crystallised (section 4.5b). The alignment of the minerals defining the new calc-silicate assemblage probably reflects this applied stress.

d) The original compositional variation in the Banded Gneiss i.e. biotite-hornblende gneiss and amphibolite could be reflected in the varience in biotite content of the calc-silicate xenoliths, with the biotite free amphibolites being altered to the pure diopside-plagioclase rocks. (fig 135)

e) Whatever origin is considered for the calc-silicate xenoliths, the late stages in their history are well documented, with the retrogression of the higher grade assemblages to one at Greenschist facies, involving primarily actinolite, clinozoisite/epidote and chlorite.

FIG 135 Granite veining including xenoliths of diopsidic rock (altered amphibolite bands) and diopside-biotite rock (altered biotite-hornblende gneiss) in the Banded Gneisses of the Lower Bergsdalen Nappe.



SECTION 7 MODEL FOR THE DEVELOPMENT OF THE BERGSDALEN AREA.

A model incorporating the data obtained from the Bergsdalen area is postulated to account for the present configuration of lithologies and tectonic units: (fig 136).

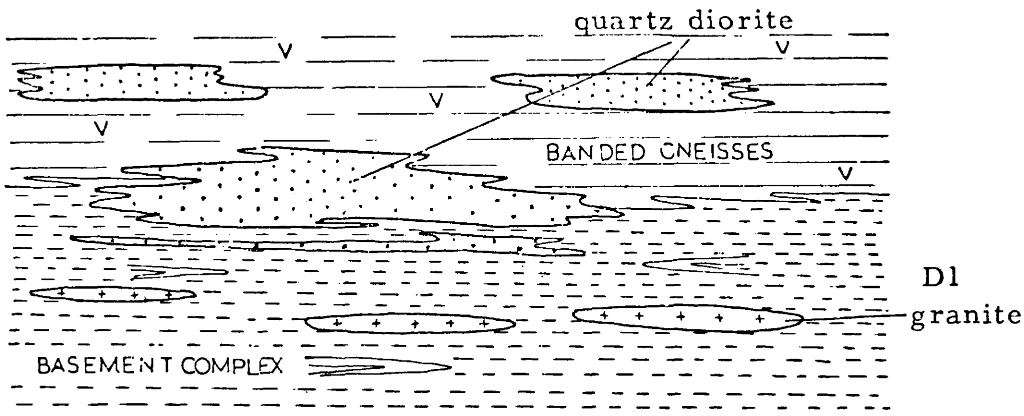
a. Svecofennian - post Svecofennian Phase (fig 136a)

The initial relationship between the two elements, Basal gneisses and Bergsdalen complex, that eventually form the basement cover situation as seen at the present time, is unknown. Rb/Sr whole rock investigation of the basal gneisses indicates that they have a possible age of origin at ~ 2070ma (Gray 1978) and underwent their first recognisable deformation at 1855 $\pm$ 242ma, subsequently being deformed and intruded by granites at about 1500ma. (Gray 1978) However, no dating of early events has been done within the Lower Bergsdalen Nappe; all that is known is that at some period prior to 1274ma (the age of the Hernes granite pluton, Pringle et. al 1975) the precursors to the Banded Gneisses with calc-alkaline geochemistry were deposited, intruded by quartz diorite plutons, and folded at least at mid-amphibolite facies.

A similar sequence of volcanic rocks are recognised in both the northwest Basal Gneiss area (the Fjordane complex, Brhyni 1977) that are dated between 1900-1500ma (Brhyni et. al 1971, Brueckner

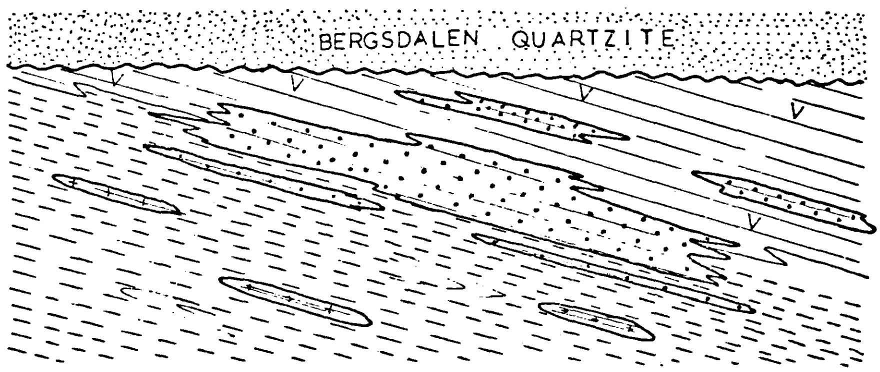
FIG. 136 Model for the development of the Bergsdalen Area

(a) ca 1500 ma



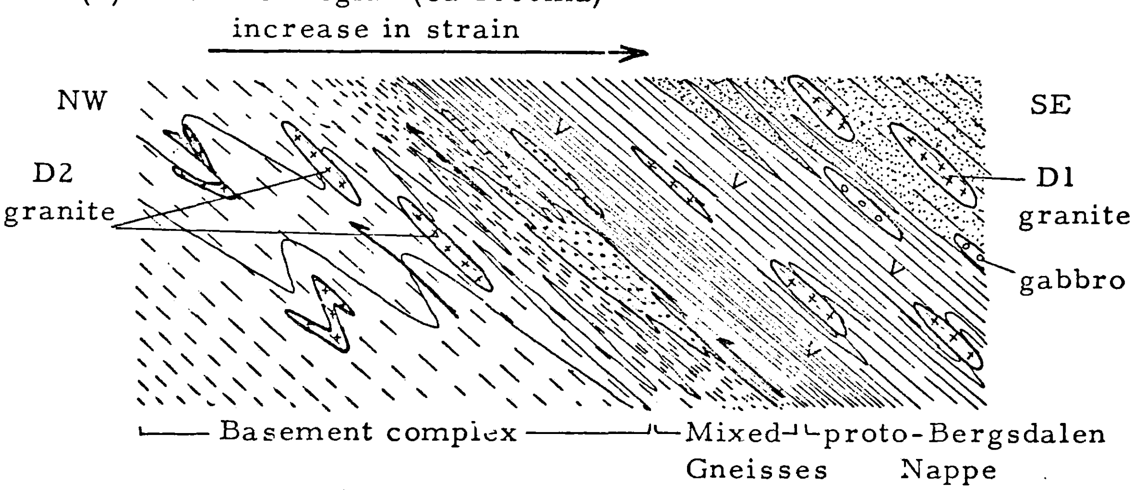
proto-Bergsdalen Nappe volcanic sequence (the Banded Gneisses) forms a cover to a basement complex; quartz diorite is intruded into both sequences, whilst granites are intruded into the basement.

(b) early Sveconorwegian (ca 1200ma)



Uplift, and deposition of the Bergsdalen quartzites

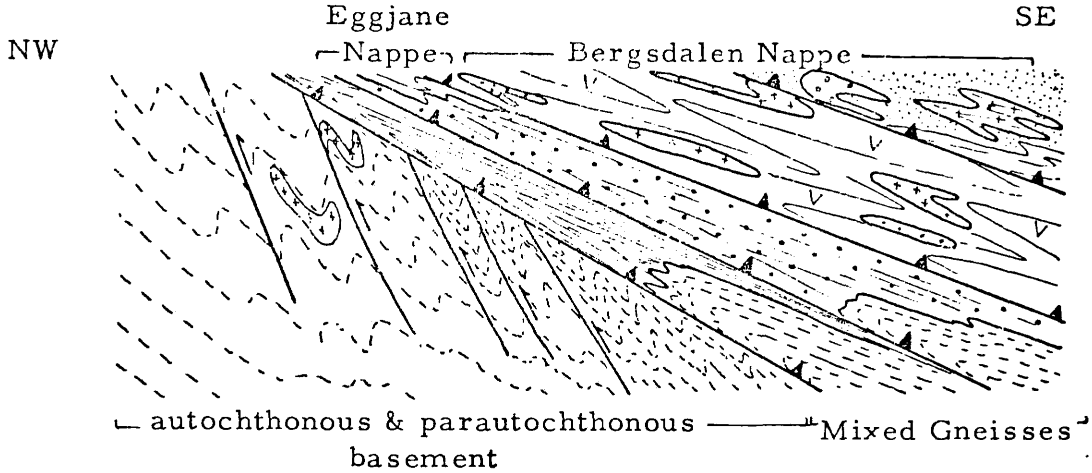
(c) Sveconorwegian (ca 1000ma)



D2 granites (D1 in Nappe) are intruded synchronously with deformation; generation of the Mixed Gneisses-a zone of intense infolding of basement and cover.

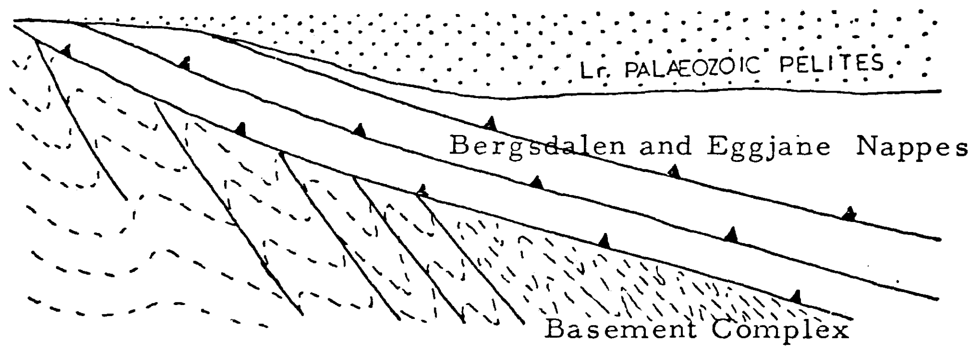
FIG. 136 (cont.)

(d) ?950-600ma <u>Nappe emplacement</u>



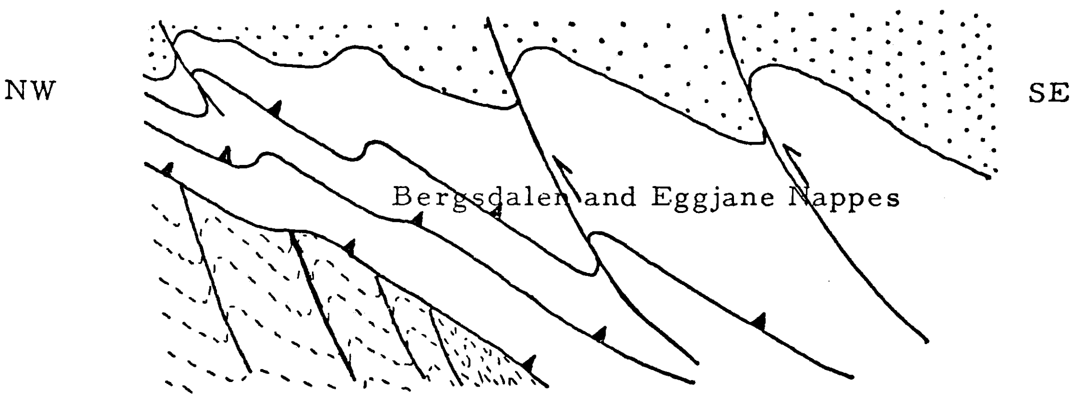
The proto-Bergsdalen Nappe is further deformed and uplifted with associated thrusting;this results in the highly strained Bergsdalen Nappe being emplaced upon an extension of its own basement.

(e) ca 600ma-400ma <u>Cambro-Ordovician</u>



Uplift and erosion;deposition of the precursors to the Voss phyllites

(f) <u>Caledonian</u>



Folding (F3 in the Nappe) of the higher structural levels, with associated thrusting, incorporates the Cambro-Ordovician pelites, and restacks the Lower Bergsdalen Nappe

1972, 1979, Abdel-Monem and Brhyni 1979, Lappin et. al 1979), and also in the Telemark area, where Svecofennian basement is unconformably overlain by the Rjukan Group (a calc-alkaline volcanic sequence) deposited between 1750-1400ma (Dons 1960, Martin 1968). The Bergsdalen metavolcanics have previously been correlated (Kvale 1960, Brhyni and Grimstad 1970) with both the Telemark vocanics and the Fjordane complex, therefore indicating an age of deposition for the Bergsdalen metavolcanics, within the time span 1900-1400ma.

The possibility is raised that the Svecofennian basement beneath the Bergsdalen Nappe complex could represent part of the original basement to the volcanic sequence. Some indirect evidence for this is provided by the interbanding of an epidote gneiss, that is very similar in appearance to the gneisses of the Eggjane Nappe (which are of probable quartz diorite origin) with the quartzofeldspathic basement gneisses immediately beneath the Nappe complex. In addition, Gray (1978) reported the presence of quartz-diorite gneisses within the basement immediately to the north of the Dale area. Meanwhile, Hopper (1980) has equated some infolded kyanite grade metasediments within the Osterøy basement (~10km northwest of the Dale basement) with the Fjordane complex.

This points to the Basal gneisses having acted as basement to a cover sequence, and for them having been involved in some calc-alkaline activity, perhaps related to that within the Bergsdalen complex.

It is therefore suggested that the metavolcanics, although not now in an autochthonous position, are not exotic to the Basal gneisses, having been deposited elsewhere on their equivalents.

Deformation deep in the crust (at least mid amphibolite facies) affected both Basal gneisses and the Bergsdalen metavolcanics, but not necessarily at the same time or same place. This stage of the evolution of the basement/cover complex ended by the uplift of the metavolcanics and the accumulation of sedimentary deposits.

b. Early Sveconorwegian uplift and erosion (fig 136b)

The sequence: uplift of the metavolcanics, followed by the unconformable deposition of the Bergsdalen quartzites is very similar to that seen in the Telemark suite, where the Rjukan Group is overlain unconformably by the quartzitic Seljord Group (Dons 1960, Singh 1969).

c. Sveconorwegian Deformation (fig 136c)

Gabbroic bodies and amphibolites were intruded into both the volcanic sequence and the Quartzites during the early part of this stage, or at the conclusion of the previous stage. The timing of the subsequent deformation is well known from the presence of granitic plutons intruded synchronously with deformation into both the basement and cover. The cover sequence suffered intense deformation during this stage, with a regional mylonitic foliation produced at mid-amphibolite facies (as defined by an overall grain size reduction). In addition, a foliation was imparted upon the intrusive granites and gabbros.

The basement complex underwent deformation at lower amphibolite facies, at this stage as well, with the intensity of folding increasing towards the southeast, so that immediately beneath the present nappe complex, the basement has a superimposed flaggy foliation. Granitic plutons, dated at 1050ma were intruded synchronously with the folding and shared the superimposed foliation.

Thrusting, directed towards the northwest (Hopper 1980) was also a feature of the basement response to the deformation.

It is postulated on the basis of correlatable subsequent deformation across the basement/nappe interface that the cover sequence, as seen today, was effectively emplaced during this stage. The contact is represented by the Mixed Gneisses, which is a zone of flattened gneisses containing elements of basement, quartz diorite gneiss (Eggjane Gneisses) and Banded Gneisses (Bergsdalen cover sequence). It is suspected, from the presence of a slide at the base of the Mixed Gneisses (section 4.3b) that simple shear translation occured, deriving the cover from a deeper structural environment, rather than juxtaposition of basement and cover purely through flattening.

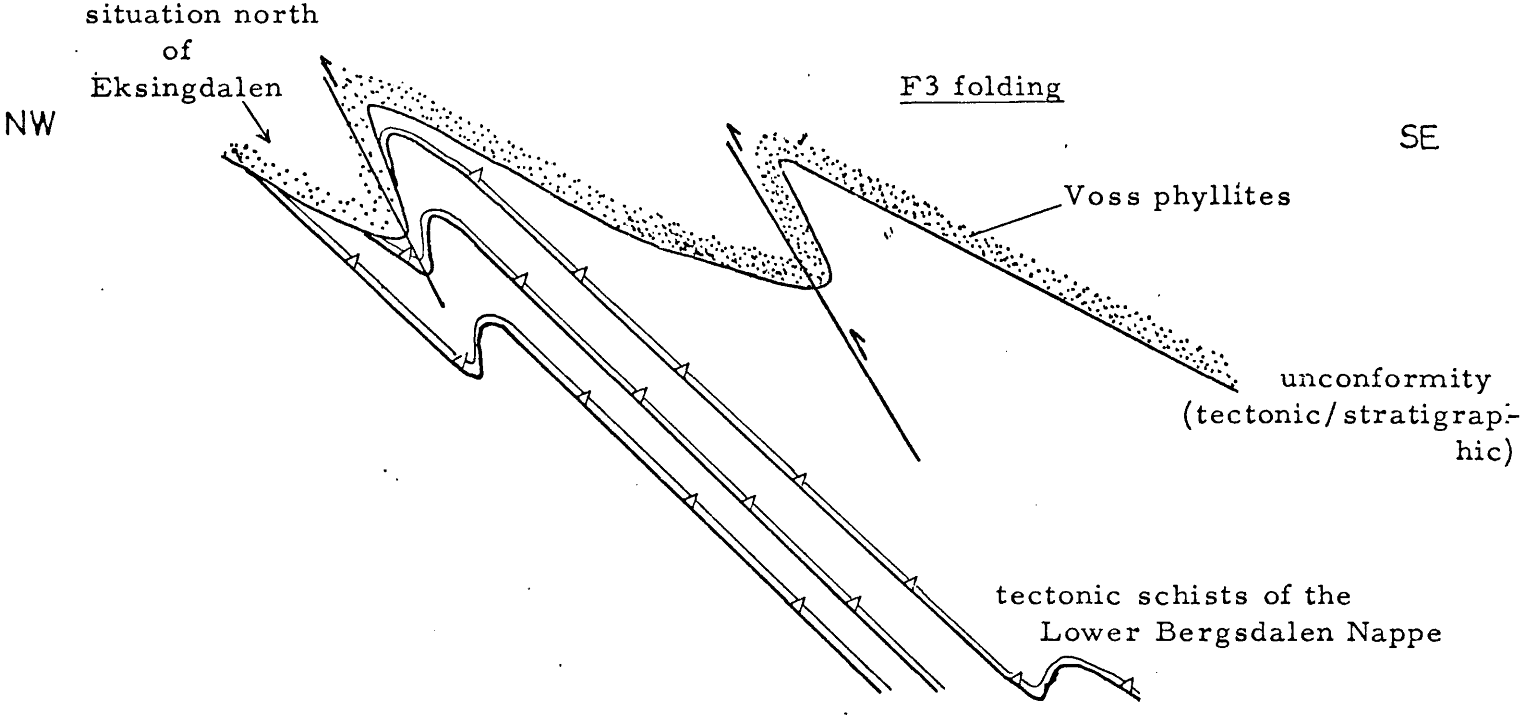
The juxtaposition of mid-amphibolite facies cover against lower amphibolite facies basement indicates a minimum translational distance of approximately 6kms. Certainly, the presence of granites such as Dystingen granite (section 2.2a) and Fosse granite (Gray 1978) of both the same age and appearance in cover and basement, indicates some spatial proximity of the two units during the Sveconorwegian orogeny.

d. <u>Late Sveconorwegian</u> (fig 136d)

Deformation coaxial to that of the previous stage persisted into this stage, with the resulting uplift of the Bergsdalen cover complex and folding at lower amphibolite facies. This was then thrust over slightly lower grade basement, with the generation of greenschist facies mylonitic and phyllonitic zones along the thrust planes and the creation of the four separate structural units recognised in this report.

The amount of movement during this stage is unknown, but is not suspected to have been extensive, due to the similarities between parautochthonous and allochthonous lithogical units.

FIG. 137 Schematic section indicating the possible relationship between the Voss phyllites, and the tectonic schists of the Lower Bergsdalen Nappe



However, the age of the nappe translation is debatable. A critical factor is whether the Voss phyllites are incorporated in this phase of thrusting. The recognition of the mica schists in the Bergsdalen thrust complex as being tectonic schists (phyllonites) derived from the Precambrian gneisses, rather than Cambro-Ordovician schists, equivalent to the Voss phyllites (Kvale 1946) removes the previously applied constraint on the age of nappe transport in the Bergsdalen area. Elsewhere within the Caledonian nappe complex of southwest Norway (fig 2) the Voss phyllites and their equivalents are incorporated in thrust movements (Sturt and Thon 1978). Kvale (1946) and Gray (1978) consider the Lower Bergsdalen Nappe as having been transported on a horizon of the Voss phyllites, therefore defining the age of movement as Caledonian. However, Gray (1978) reports that the phyllites were deposited unconformably on amphibolite facies folds, that are correlated with F2 in the Bergsdalen area (fig 92) and that the sediments only attained a maximum of Upper Greenschist facies metamorphism (Sturt and Thon 1978).

This work has shown that thrusting and F2 fold generation at amphibolite facies were closely associated in the Bergsdalen area (section 4.7), thus the post F2 deposition of the phyllites, as reported by Gray (1978), along with their low grade of metamorphism indicates that the phyllites were not involved with the D2 thrusting. The suggestion is therefore made that the Lower Palaeozoic sedimentation post dates the D2 thrusting, thereby placing the movement within the Precambrian.

Contrary to this suggestion of Precambrian nappe transport, is the recognition that the Bergsdalen tectonic schists (phyllonites) can be traced laterally into the Voss phyllites (Kvale 1946, Gray 1978), thus seemingly indicating a Caledonian age for the tectonic schists.

However, it may be incorrect to consider the Bergsdalen tectonic schists and the Voss phyllites as being of equivalent age. If, as postulated here, the tectonic schists were derived in the Precambrian then subsequent unconformable deposition of pelites on the tectonic schists, along with Caledonian deformation and thrusting, could create a mixed zone of phyllite and tectonic schist that links the two horizons of different ages (fig. 137).

Hopper (1980) concluded that the initial nappe transport within the Bergen Arcs was Precambrian in age; he suggested a date of 800ma based on an Rb/Sr isochron from a granite at the margin of the Arcs.

Evidence from the northwest margin of the Lower Bergsdalen Nappe indicates that the sense of translation was towards the northwest (section 4.7), the opposite direction to that traditionally envisaged (Strand and Kulling 1972).

(e) Caledonian (fig. 136e)

The Lower Palaeozoic pelites (phyllites) were unconformably deposited upon the deformed and thrust basement/cover complex.

(f) <u>Caledonian deformation</u> (fig. 136 f)

By correlation with deformations within the Bergen Arcs (section 4.11), where fossiliferous strata is present, the structurally higher units of the Bergsdalen Nappe (and also basement gneiss further north, Gray 1978) are reworked during the Silurian.

Restacking of the Nappe occurs along thrusts that replace the steep limbs of the F3 folds with movement again directed towards the northwest.

The phyllites are deformed and tectonically incorporated in these thrusts, thereby creating planes of easy translation for further movement. It is these thrust planes that are most readily recognised within the Bergsdalen Nappe complex (fig. 2).

The Bergsdalen area is further modified by the late Devonian generation of cross folds, one of which downfolds upper units of the Bergsdalen Nappes, and the Bergen Nappe, into the Bergen Arc structure.

Therefore, in conclusion, the geology of the Bergsdalen area reflects a continual process of orogenic development, from the Svecofennian phase, through the Sveconorwegian phase that created the protobasement/nappe complex, and its modification in late Sveconorwegian times, into an end Silurian Caledonian event that restacked the Precambrian nappes, leaving them in their present state. The periphery of the area was further modified by late Devonian deformation that created the Bergen Arc structure.

APPENDIX

Geochemical Techniques

The following samples have been analysed for both major and trace elements; their locations are recorded on fig. 27.

Index no.	Sample no.	Description of rock
1	MD4	medium grained biotite gneiss
2	X3	fine grained biotite-garnet gneiss (major oxides only)
3	AM060/2a 13	fine grained biotite-garnet gneiss
4	BG4	" " biotite gneiss
5	A7.7	" " biotite-garnet gneiss
6	A6.18	" " biotite-garnet gneiss
7	A15.7	" " biotite-garnet gneiss (trace elements only)
8	A15.5	" " biotite gneiss (thrust zone)
9	X1a	" " biotite-garnet gneiss
10	X1b	medium grained biotite schist
11	AM060/2a 17	fine grained biotite-garnet gneiss
12	AL059/1e 2	" " biotite gneiss
13	AL058/1b 17	" " biotite gneiss
14	M2	" " biotite gneiss
15	M8	" " biotite gneiss
16	AL058/1b 16	" " biotite-clinozoisite gneiss
17	A9.20	" " biotite-clinozoisite gneiss
18	A15.15	" " biotite-clinozoisite gneiss
19	AL058/1b 9	" " biotite-garnet gneiss
20	BG5	" " biotite gneiss
21	BG6	" " biotite-garnet-muscovite gneiss
22	AM060/2a 19	" " pyroxene-biotite-hornblende gneiss(major oxides only)
23	A7.8	" " biotite-hornblende gneiss (trace elements only)
24	A7.2	" " biotite-hornblende gneiss
25	BG2	" " biotite-hornblende gneiss
26	A16.6	" " biotite-hornblende-garnet gneiss
27	A16.4	" " biotite-hornblende gneiss
28	A16.1	" " biotite-hornblende-garnet gneiss
29	A15.9	" " biotite-hornblende-garnet-clinozoisite gneiss
30	A15.1a	" " biotite-hornblende gneiss

Index no.	Sample no.	Rock description	
31	A15.2	fine grained	biotite-hornblende gneiss
32	A16.7	" "	biotite-hornblende-garnet gneiss
33	A15.10	" "	biotite-hornblende-garnet gneiss
34	A15.22	" "	biotite-hornblende-garnet clinozoisite gneiss
35	A15.18a	" "	amphibolite (hornblendite)
36	A15.18b	" "	amphibolite (hornblendite)
37	A15.18c	" "	amphibolite (hornblendite)
38	A15.18d	" "	amphibolite (hornblendite)
39	A15.18e	" "	amphibolite (hornblendite)
40	A15.11	" "	amphibolite (hornblendite)
41	A16.11	" "	amphibolite (hornblendite)
42	AL058/1b 14	" "	amphibolite (hornblendite)
43	A16.10	" "	amphibolite (hornblendite)
44	A16.8	" "	amphibolite (hornblendite)
45	Z1	" "	amphibolite
46	Z2	" "	amphibolite
47	A15.1b	" "	amphibolite
48	A15.16	" "	amphibolite (hornblendite)
49	A15.20	" "	amphibolite (trace elements only)
50	AM060/2a 21	" "	amphibolite
51	M1	medium grain	amphibolite (hornblendite)
52	M3	" "	amphibolite (hornblendite) trace element only
53	M4a	" "	amphibolite (hornblendite)
54	M4b	" "	amphibolite (hornblendite) + biotite
55	D1	" "	amphibolite (hornblendite)
56	D2	" "	amphibolite (hornblendite)
57	MD2	fine grained	calc-silicate xenolith
58	MD3	" "	calc-silicate xenolith
59	MD5	" "	calc-silicate xenolith
60	MD7	" "	calc-silicate band
61	MD9	" "	calc-silicate xenolith
62	MD10	" "	calc-silicate xenolith
63	M12a	" "	calc-silicate xenolith
64	M12b	" "	calc-silicate xenolith

The fresh samples were reduced to powder form using a roll jaw crusher and tungsten carbide tema, both of which were thoroughly washed and dried after each sample to prevent contamination.

The powdered samples were prepared in two ways, one for the major element analyses and one for the trace element analyses.

For major elements, the powder was initially dried in an oven at 100 °c for at least 12 hours; 0.4 gms. of the powder was then weighed with 2.4gms. of Johnson Matthey spectraflux 104, in a platinum gold crucible and fused at 1000°c in a furnace. Duplicate samples were made up in each case.

The fusion was then formed into a bead while molten, using a former and press, heated to 200°c. The beads are hydroscopic, therefore are cooled in a desiccator and analysed as soon as possible after preparation.

Ferrous iron was determined titrimetrically, employing potassium dichromate. No analyses were made for CO_2, F, H_2O^+, H_2O^-, accounting for the low totals in some cases.

Trace elements were determined using powdered samples pressed into pellets : 6 gms. of the powder were mixed with 1 gm. of PF Bakerlite resin, and together they were pressed into pellets at 15 tons. Finally, they were hardened for 20 mins. at 105°c in an oven.

X Ray fluorescence analyses were made using a Phillips PW 1212 X Ray spectrometer in the Geology Department, Bedford College (London University).

The X Ray diffractometer was used in one case, to identify diopside. Grains of the suspect mineral were picked out from a powdered sample, crushed, and placed on a pinhead mount. X Ray powder photographs were taken with a Phillips114.6mm diam. Debye-Scherrer camera, with a Staumanis film mounting, in Ni filtered Cu (k_α) radiation.

GEOCHEMICAL ANALYSIS OF THE BANDED GNEISSES AND AMPHIBOLITES, LOWER BERGSDALEN NAPPE

(a) Biotite ± garnet gneisses.

	Index Nos:	1	2	3	4	5	6	7	8	9	10	11
weight %	P_2O_5	0.2	0.2	0.1	0.3	0.1	-	-	0.1	0.1	0.3	0.1
	SiO_2	56.6	58.4	67.5	53.2	72.8	76.7	-	71.5	68.9	57.0	72.9
	Al_2O_3	16.4	16.6	14.7	19.5	14.0	12.7	-	13.9	14.6	15.9	12.7
	MgO	3.3	3.4	1.5	2.4	1.2	0.6	-	1.4	1.4	3.1	0.7
	MnO	0.1	0.1	0.1	0.1	0.1	0.1	-	0.1	0.1	0.2	0.1
	FeO	5.9	6.2	5.1	6.4	2.1	2.0	-	2.9	4.0	7.9	3.2
	Fe_2O_3	0.7	0.9	0.5	0.5	1.1	0.1	-	0.6	0.9	1.1	0.7
	TiO_2	0.6	0.7	0.5	0.7	0.6	0.2	-	0.5	0.6	1.0	0.4
	CaO	4.4	6.7	3.4	4.1	2.2	1.4	-	1.2	2.5	3.6	3.2
	K_2O	3.0	1.3	2.2	2.4	2.0	3.3	-	3.8	2.0	3.1	2.5
	Na_2O	3.8	4.0	3.6	5.8	4.4	3.7	-	4.1	4.6	4.9	4.3
	Total	95.0	98.5	99.2	95.4	100.6	100.8	-	100.1	99.7	98.1	100.8
ppm	Nb	3	-	9	2	6	11	9	8	4	5	10
	Y	24	-	31	16	15	24	20	23	35	33	40
	Sr	359	-	278	538	291	209	274	243	288	270	174
	Rb	138	-	59	83	66	61	171	76	43	93	83
	Zr	89	-	123	58	132	144	122	133	135	119	181
	Th	2	-	4	1	5	10	3	2	-	5	1

(a) Biotite ± garnet gneisses (cont.)

	Index nos :	12	13	14	15	16	17	18	19	20	21
weight %	P_2O_5	0.2	0.2	0.1	0.1	0.1	0.1	0.3	0.2	0.1	0.1
	SiO_2	64.2	65.2	64.0	75.1	69.6	70.8	62.5	65.3	67.9	70.0
	Al_2O_3	16.8	17.0	15.6	12.6	15.0	13.4	15.1	15.0	14.4	13.9
	MgO	2.4	2.0	2.5	1.3	1.3	1.3	1.8	1.8	1.5	1.3
	MnO	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	FeO	3.8	3.7	3.9	2.3	3.2	2.6	5.1	4.0	4.7	3.9
	Fe_2O_3	1.0	0.7	1.1	0.6	0.4	1.1	1.1	2.1	0.6	1.2
	TiO_2	0.6	0.6	0.5	0.3	0.4	0.5	0.7	0.6	0.5	0.6
	CaO	3.2	3.8	2.8	2.8	4.8	3.7	4.9	3.9	2.1	1.8
	K_2O	2.2	3.2	2.2	1.3	1.9	2.2	1.7	3.0	3.7	4.0
	Na_2O	5.0	3.6	5.7	3.9	2.8	3.8	3.3	3.7	3.7	2.2
	Total	99.5	100.1	98.5	100.4	99.6	99.6	96.6	99.7	99.3	99.1
ppm	Nb	7	9	2	3	9	9	6	3	7	9
	Y	18	28	17	13	28	42	25	25	29	35
	Sr	303	419	374	412	307	192	354	697	323	205
	Rb	92	108	72	46	59	64	74	80	82	90
	Zr	162	168	101	77	174	167	91	96	108	143
	Th	2	5	1	-	5	4	-	2	7	4

(b) Biotite-hornblende gneisses

	Index nos:	22	23	24	25	26	27	28	29	30	31	32	33	34
weight %	P_2O_5	0.1	-	0.2	0.3	0.3	0.2	0.2	0.2	0.4	0.2	0.2	0.2	0.2
	SiO_2	57.0	-	50.7	55.1	54.1	54.3	46.7	58.9	47.7	50.7	54.4	50.4	57.2
	Al_2O_3	13.6	-	14.5	17.8	16.4	17.1	14.2	17.0	13.1	16.3	15.8	14.6	16.5
	MgO	2.8	-	5.0	4.7	3.0	3.3	3.8	3.2	3.8	4.4	3.3	3.6	3.2
	MnO	0.1	-	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1
	FeO	4.3	-	5.2	6.6	3.7	4.1	5.5	4.8	6.7	6.2	3.7	6.1	5.3
	Fe_2O_3	0.8	-	2.1	3.0	2.6	2.6	1.4	2.4	2.6	2.7	2.8	1.6	1.5
	TiO_2	0.5	-	0.8	0.9	0.7	0.6	0.6	0.7	1.2	0.8	0.6	0.7	0.7
	CaO	4.7	-	7.6	5.9	4.0	6.1	6.0	6.2	6.3	6.2	4.9	6.4	5.7
	K_2O	2.2	-	1.5	2.6	2.2	1.7	1.6	1.6	1.7	2.3	1.5	1.5	2.0
	Na_2O	3.6	-	2.5	3.4	4.5	4.0	3.4	3.6	4.1	2.9	3.9	3.2	3.5
	Total	89.7		90.3	100.4	91.6	94.1	83.5	98.7	87.8	92.8	91.2	88.4	95.9
ppm	Nb	-	5	5	5	7	5	4	0	13	4	6	5	5
	Y	-	19	25	20	17	19	17	20	38	20	18	19	22
	Sr	-	404	392	430	431	492	446	546	555	560	426	464	566
	Rb	-	59	79	70	57	53	45	65	101	61	43	37	83
	Zr	-	105	86	89	126	99	78	83	195	80	101	80	94
	Th	-	2	8	1	5	2	4	3	2	4	6	1	3

(c) Amphibolites

	Index nos:	35	36	37	38	39	40	41	42	43	44	45
weight %	P_2O_5	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.2	0.3	0.2
	SiO_2	47.3	49.3	44.4	46.2	47.3	47.0	44.9	45.3	47.9	48.8	56.3
	Al_2O_3	15.9	15.9	14.7	17.2	15.3	13.9	15.9	15.8	14.9	15.7	8.7
	MgO	5.1	5.2	9.4	6.3	8.5	10.1	7.7	6.6	9.0	5.3	4.6
	MnO	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.2
	FeO	5.7	8.0	9.3	7.1	8.2	8.8	8.8	11.0	7.9	7.3	5.5
	Fe_2O_3	2.6	o.9	3.6	3.5	2.7	1.6	1.8	3.4	3.7	3.7	2.8
	TiO_2	1.1	0.9	1.3	1.1	1.1	1.0	1.1	2.4	1.2	1.6	0.8
	CaO	14.7	11.2	11.6	14.6	13.8	13.6	12.5	9.6	11.0	12.6	6.7
	K_2O	0.8	0.6	1.7	0.6	0.5	0.7	0.7	0.6	0.9	0.9	1.6
	Na_2O	3.9	3.4	1.7	1.5	1.8	1.4	2.1	3.0	2.4	2.1	3.2
	Total	97.6	95.8	98.1	98.5	99.6	98.5	95.9	98.3	99.3	98.5	90.6
ppm	Nb	7	2	3	1	3	3	3	7	3	6	5
	Y	20	20	20	23	17	18	18	42	17	23	22
	Sr	547	526	168	471	409	339	406	274	278	567	556
	Rb	10	2	43	0	4	24	7	5	23	22	18
	Zr	79	51	37	53	37	30	32	150	52	95	82
	Th	0	2	3	3	3	0	4	0	0	0	4

(c) Amphibolites (cont.)

	Index nos:	46	47	48	49	50	51	52	53	54	55	56
weight %	P_2O_5	0.2	1.3	0.3	-	0.1	0.2	-	0.2	0.2	0.2	0.2
	SiO_2	55.0	44.0	47.0	-	47.8	43.7	-	47.7	49.4	44.6	47.2
	Al_2O_3	17.2	12.1	16.8	-	14.6	12.7	-	12.9	13.5	13.8	15.7
	MgO	4.5	4.6	5.6	-	9.6	9.4	-	10.5	11.2	10.1	7.9
	MnO	0.2	0.3	0.2	-	0.2	0.4	-	0.3	0.3	0.3	0.2
	FeO	6.1	12.5	8.1	-	8.4	9.3	-	7.5	9.5	8.2	6.7
	Fe_2O_3	3.2	3.3	3.1	-	2.8	3.3	-	3.4	1.4	2.9	4.3
	TiO_2	0.8	3.4	1.3	-	0.6	1.1	-	1.0	1.0	1.2	1.0
	CaO	8.4	8.7	12.5	-	13.7	12.1	-	11.8	10.8	12.1	11.2
	K_2O	0.8	3.0	0.7	-	0.7	1.5	-	1.4	2.2	1.5	1.0
	Na_2O	2.9	1.8	2.3	-	1.0	1.6	-	2.1	1.4	1.4	2.6
	Total	99.3	95.0	97.9		99.5	95.3		98.8	100.9	96.3	98.0
ppm	Nb	2	16	8	2	4	3	1	1	1	3	6
	Y	18	86	25	18	14	15	17	9	15	14	20
	Sr	468	159	462	392	447	95	219	177	165	199	379
	Rb	12	179	0	57	8	30	26	39	78	51	21
	Zr	73	531	80	72	53	35	34	33	36	31	86
	Th	5	0	3	0	0	0	1	3	6	4	1

GEOCHEMICAL ANALYSIS OF THE CALC - SILICATE XENOLITHS
LOWER BERGSDALEN NAPPE

	Index nos:	57	58	59	60	61	62	63	64
weight %	P_2O_5	1.2	1.3	1.2	1.2	1.2	0.2	1.3	1.2
	SiO_2	52.6	53.2	49.8	49.8	53.4	59.7	55.1	52.1
	Al_2O_3	12.2	11.5	10.9	12.7	13.2	16.4	10.0	10.5
	MgO	6.6	5.9	7.0	7.2	5.7	2.4	6.0	7.2
	MnO	0.1	0.2	0.2	0.1	0.1	0.2	0.2	0.2
	FeO	4.7	4.1	3.2	5.6	5.5	4.1	4.8	3.8
	Fe_2O_3	1.8	0.7	0.5	1.1	0.8	2.6	0.2	1.2
	TiO_2	1.4	1.3	1.4	1.5	1.6	0.5	1.3	1.2
	CaO	5.8	16.1	12.7	5.7	5.8	10.0	14.0	9.8
	K_2O	8.5	0.5	2.6	8.0	6.7	0.3	0.9	5.6
	Na_2O	1.3	4.2	3.5	1.5	2.6	1.8	5.5	2.7
	Total	96.2	99.0	93.0	94.4	96.6	98.2	99.3	95.5
ppm	Nb	20	20	23	19	18	2	34	20
	Y	28	26	27	30	33	14	33	29
	Sr	1041	1660	824	1653	1939	483	1028	1236
	Rb	10	355	133	494	321	3	21	261
	Zr	565	439	604	615	560	78	588	537
	Th	19	26	18	20	15	0	21	21

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VOLUME II - Plates

Basement/Cover Relationships of the Bergsdalen Area, Central South West Norway

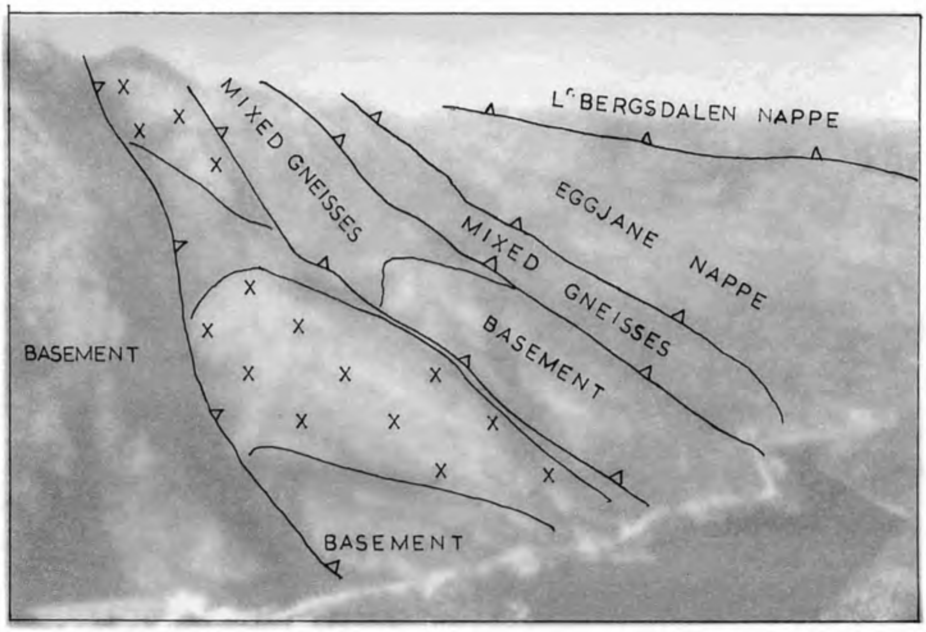


plate 1
view to the northeast across the basement /nappe contact above Fosse (Bergsdalen), with Dystingen granite (D2) body prominent, sitting above a D3 basement thrust

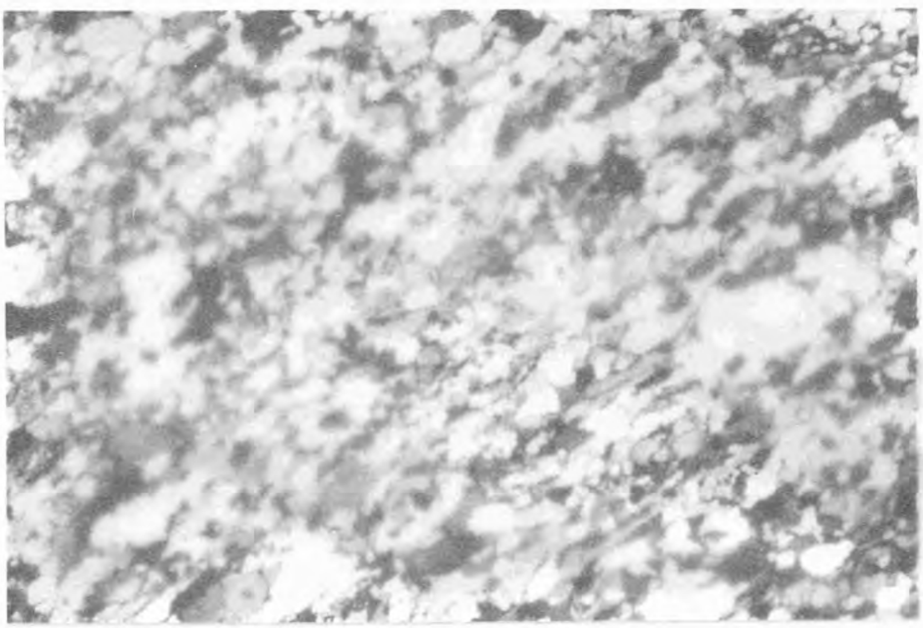


plate 2
photomicrograph of a quartzofeldspathic gneiss;biotite defines S2. (cross polarized light, x 12.5)

plate 1
view to the northeast across the basement /nappe contact above Fosse (Bergsdalen), with Dystingen granite (D2) body prominent, sitting above a D3 basement thrust

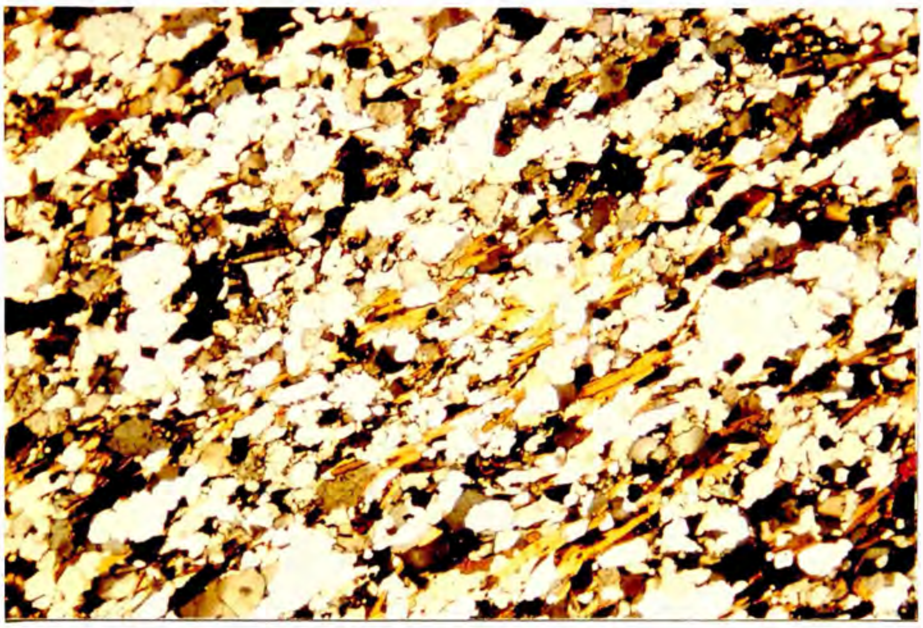


plate 2
photomicrograph of a quartzofeldspathic gneiss;biotite defines S2. (cross polarized light, x 12.5)

plate 3
quartzofeldspathic schlieren augened within a weakly deformed hornblende quartzofeldspathic gneiss.
(lens cap diameter : 5. 8cms)

plate 4
tightly folded (F2) pegmatite bodies within the Mixed Gneisses. (outcrop height ca. 20m)

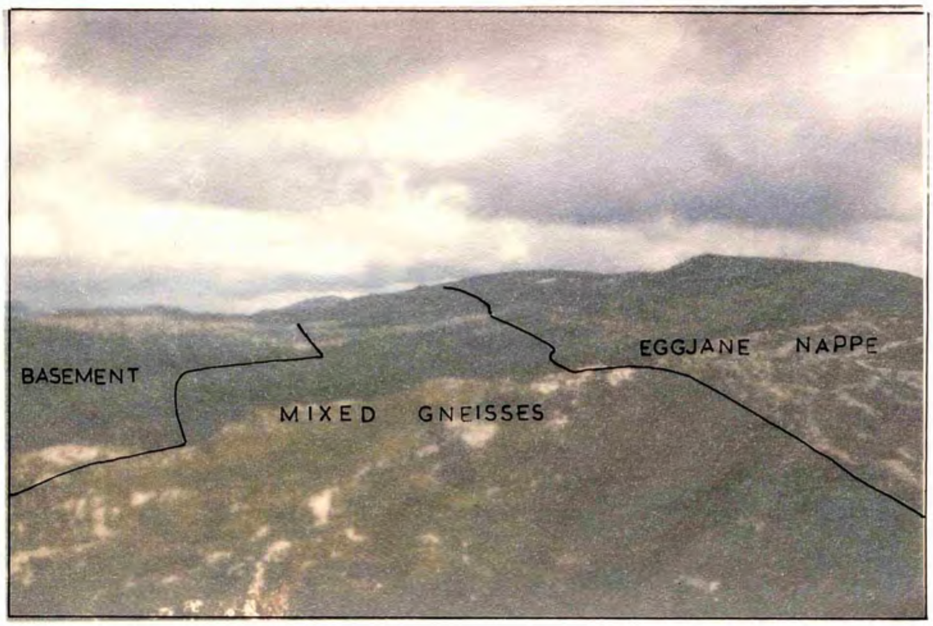


plate 5
view to the northeast across the plateau;exposure of the basement gneisses, Mixed Gneiss and Eggjane Nappe.

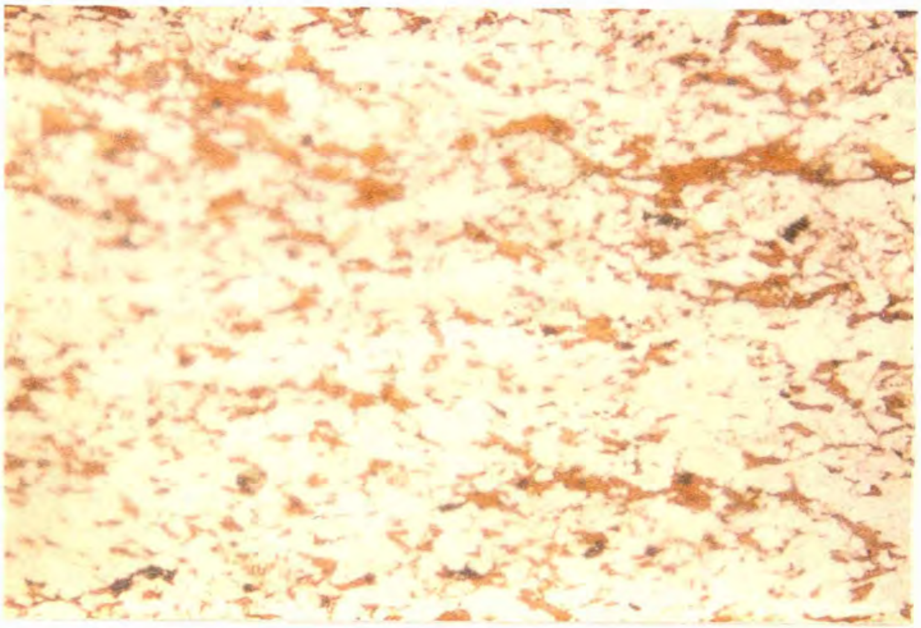


plate 6
photomicrograph of biotite gneiss from the Mixed Gneisses;the fabric defined by the biotite is S_1.
(plane polarised light, x 12.5)

plate 5
view to the northeast across the plateau;exposure of the basement gneisses, Mixed Gneiss and Eggjane Nappe.

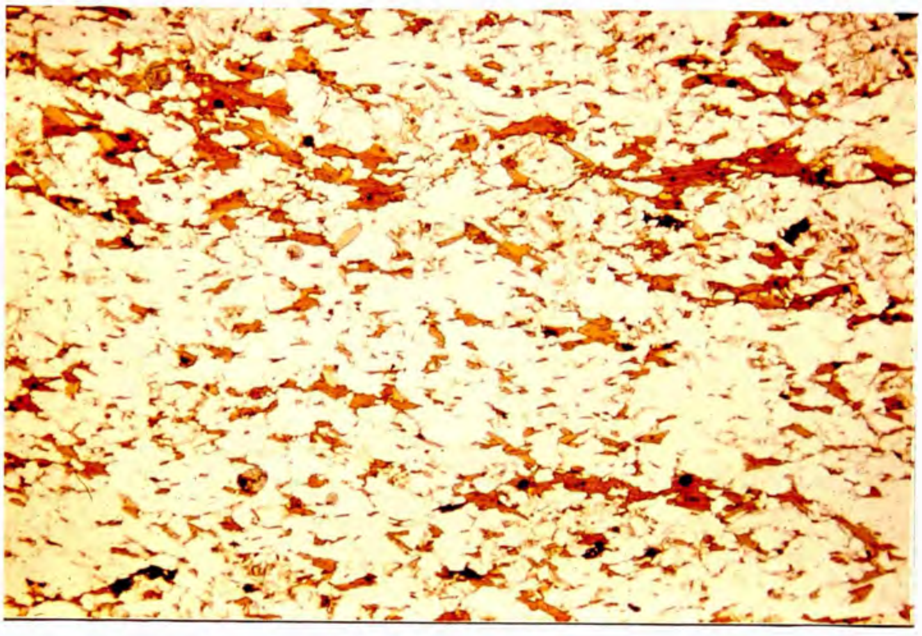


plate 6
photomicrograph of biotite gneiss from the Mixed Gneisses;the fabric defined by the biotite is S_1.
(plane polarised light, x 12.5)

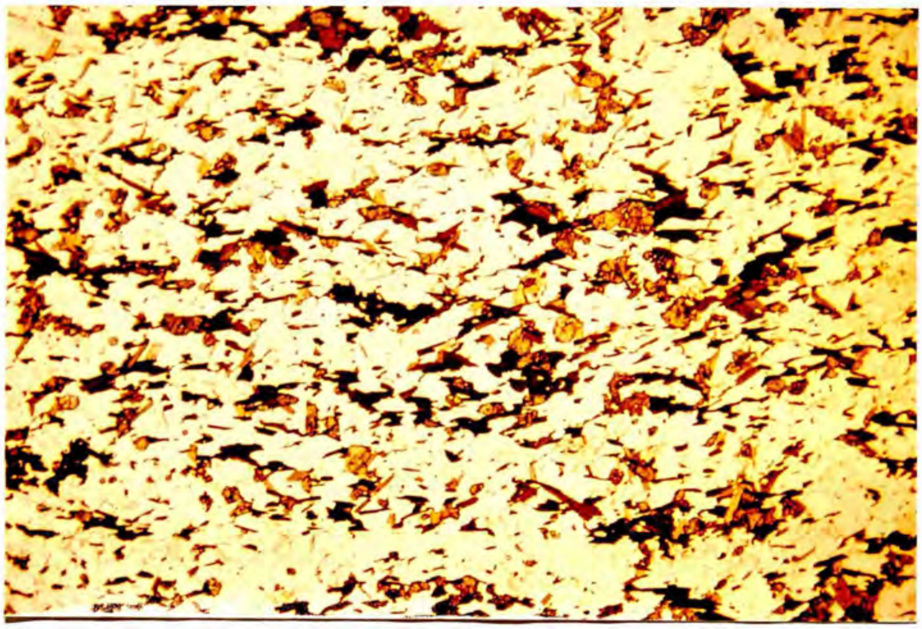


plate 7
photomicrograph of the biotite-epidote-hornblende gneiss, from the Mixed Gneisses;the mafic minerals define S1.
(plane polarised light, x 12.5)

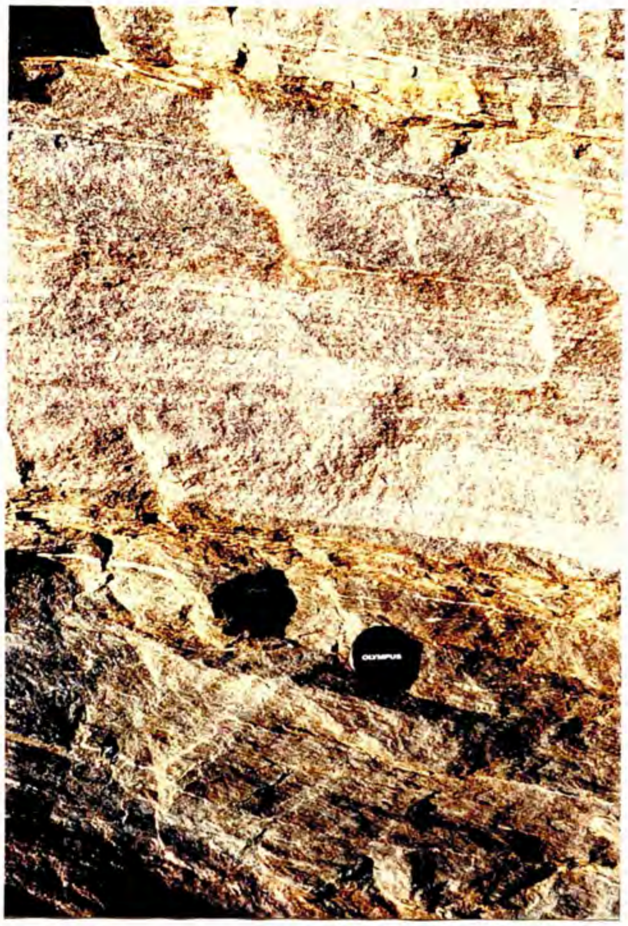
plate 8
photomicrograph of the biotite-epidote gneiss (Eggjane Gneiss) with biotite defining both S1 and S2.

(plane polarised light, x 12.5)

plate 9
view to the southwest, across Sedalen (2 km northeast of Vaksdal) indicating the poorly exposed ground beneath the tree line.

plate 10
Banded Gneisses, including biotite schist, from the Lower Bergsdalen Nappe.
(lens cap diameter, 5.5 cm.)

plate 11
Banded Gneiss, including biotite gneiss, biotite - hornblende gneiss and amphibolite; Lower Bergsdalen Nappe



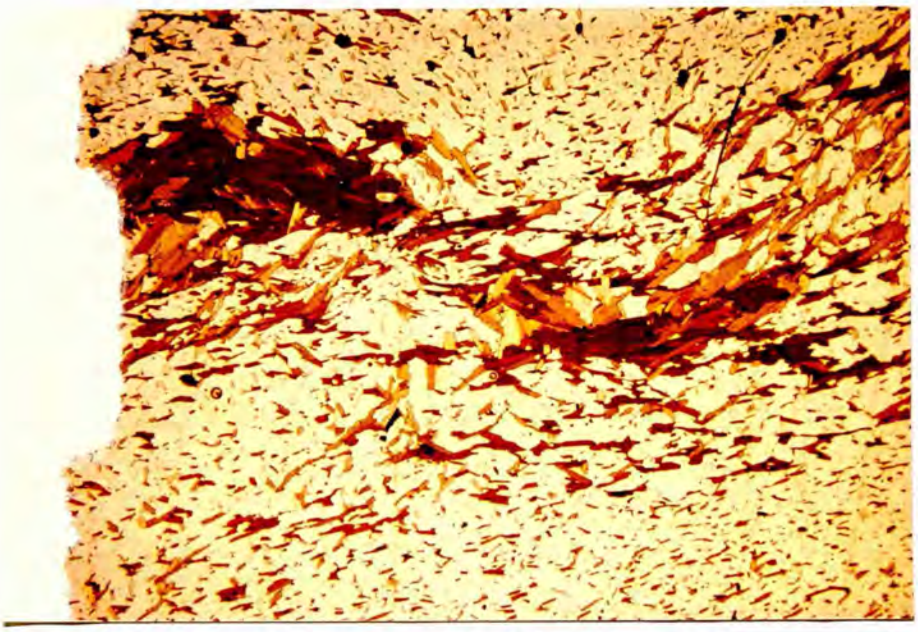


plate 12
photomicrograph of a band of biotite schist within biotite gneiss; Banded Gneisses, Lower Bergsdalen Nappe.
(plane polarised light, x 12.5)

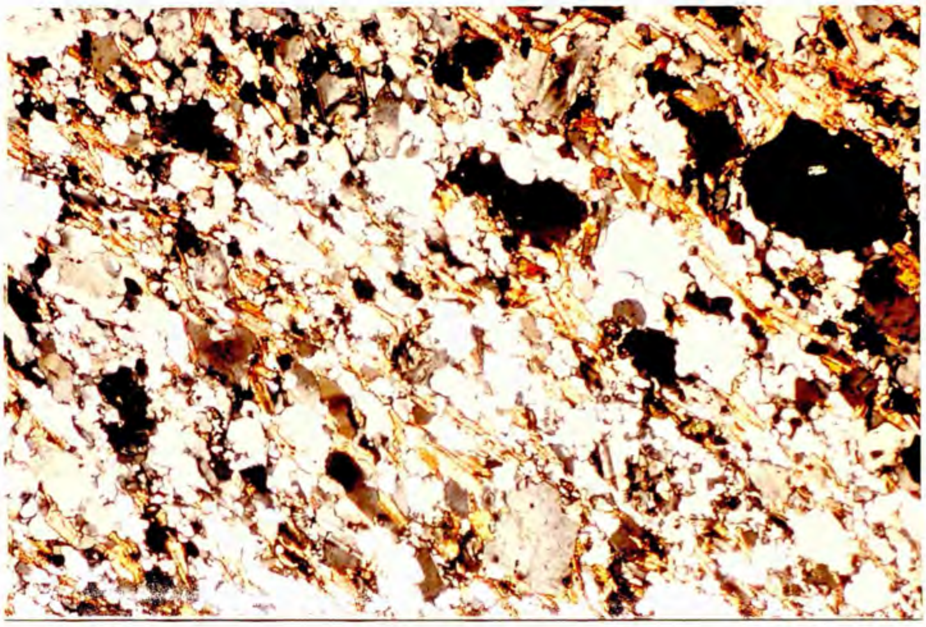


plate 13

photomicrograph of biotite-garnet gneiss;Banded Gneisses, Lower Bergsdalen Nappe. Note the granulated quartzofeldspathic matrix. (M3) (cross poarised light, x 32)

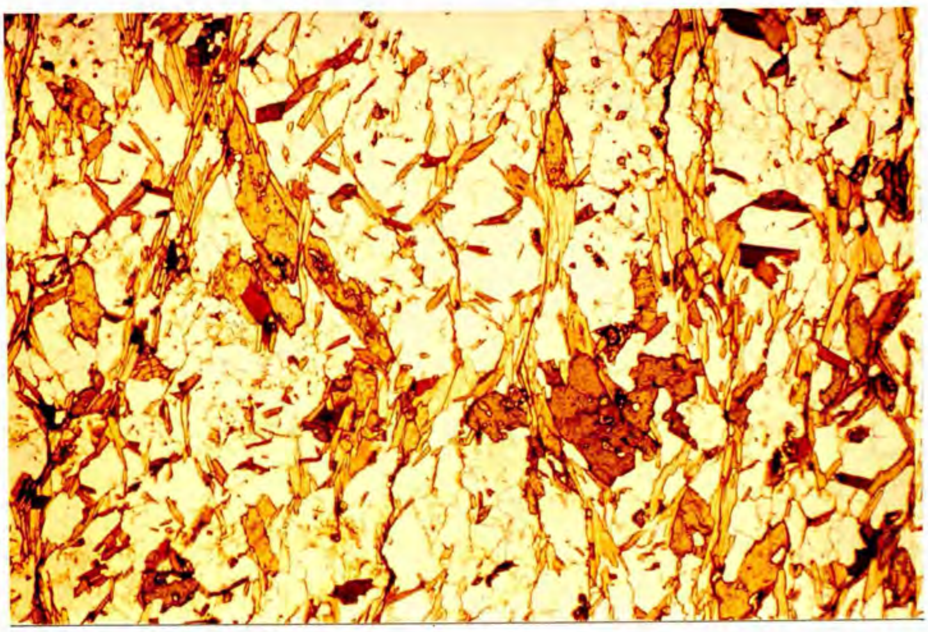


plate 14

photomicrograph of biotite-hornblende gneiss;Banded Gneiss, Lower Bergsdalen Nappe. Note the S1 hornblendes being overgrown by S2 biotite.

(plane polarised light, x 32)

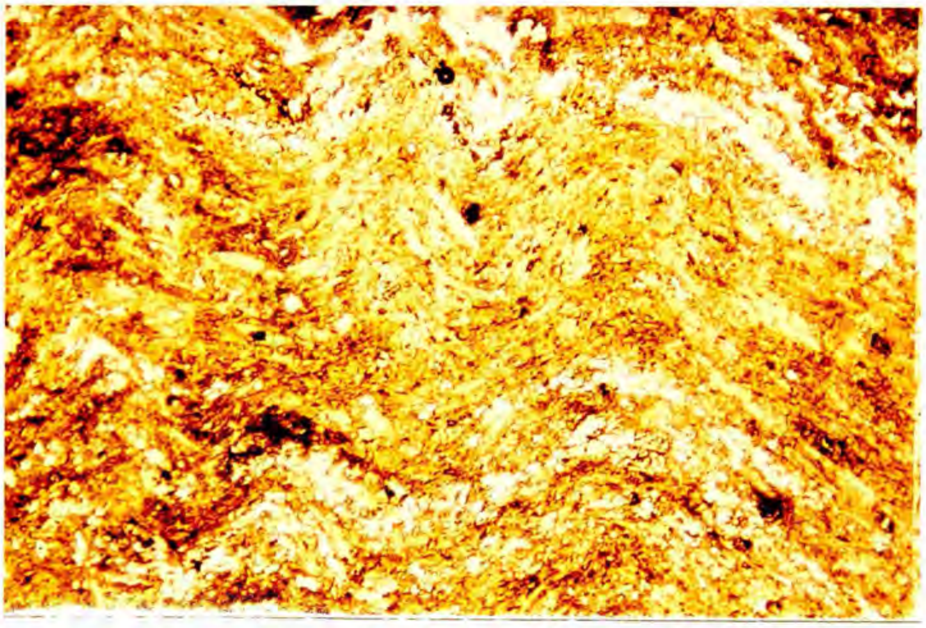


plate 15
photomicrograph of crenulated (F3) amphibolite (hornblendite); Banded Gneiss, Lower Bergsdalen Nappe.
(plane polarised light, x 12.5)

plate 16
gneissose quartz diorite, with a thin zoned calc-silicate band; Lower Bergsdalen Nappe.
(diameter of coin: 2.5 cms.)

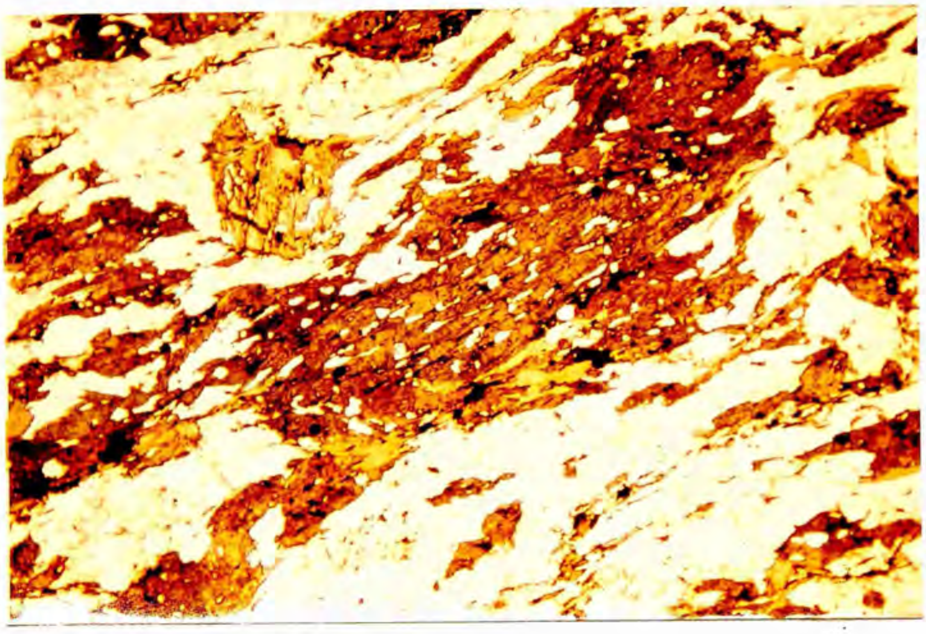


plate 17
photomicrograph of gneissose quartz diorite;Lower Bergsdalen Nappe. Note the marginal replacement of hornblende by chlorite.
(plane polarised light, x 12.5)

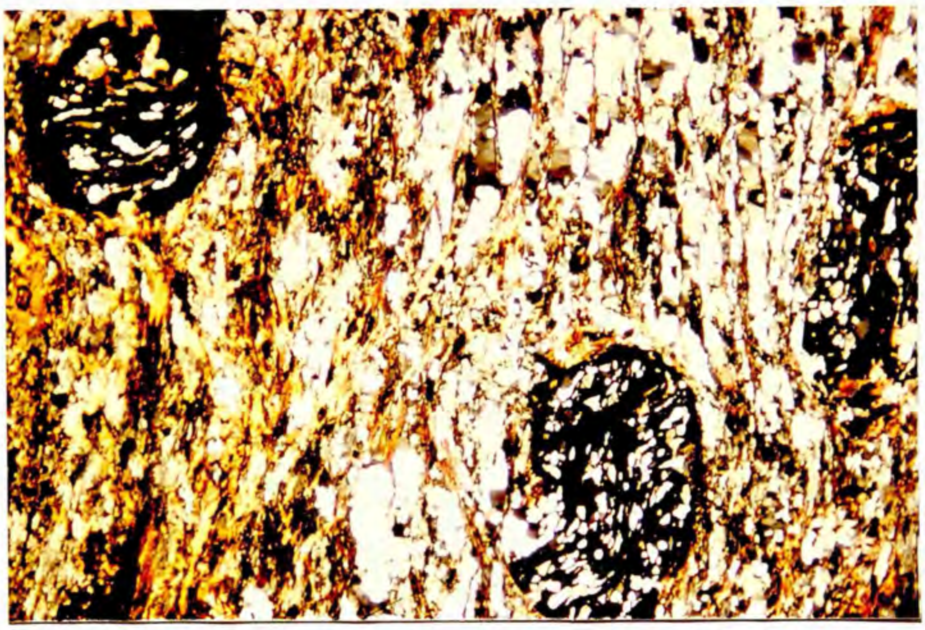


plate 18
photomicrograph of garnet-mica schist from the thrust block between the Lower Bergsdalen Nappe and the Bergen Arcs. Note the rotational Si fabric in the garnet.
(cross polarised light, x 12.5)

plate 19
D "early" amphibolite intruded by isoclinally folded/flattened aplitic veining.
(length of hammer head : 21 cms)

plate 20
D "early" rootless isoclines within the quartzofeldspathic basement gneiss.
(diameter of lens cap : 5.8 cm.)

plate 21
D2 granite veins axial planar to F2 folds that deform S1 in quartzo-feldspathic gneiss. Note the strong foliation in the granite (S2).
(diameter of coin : 1.5 cms)

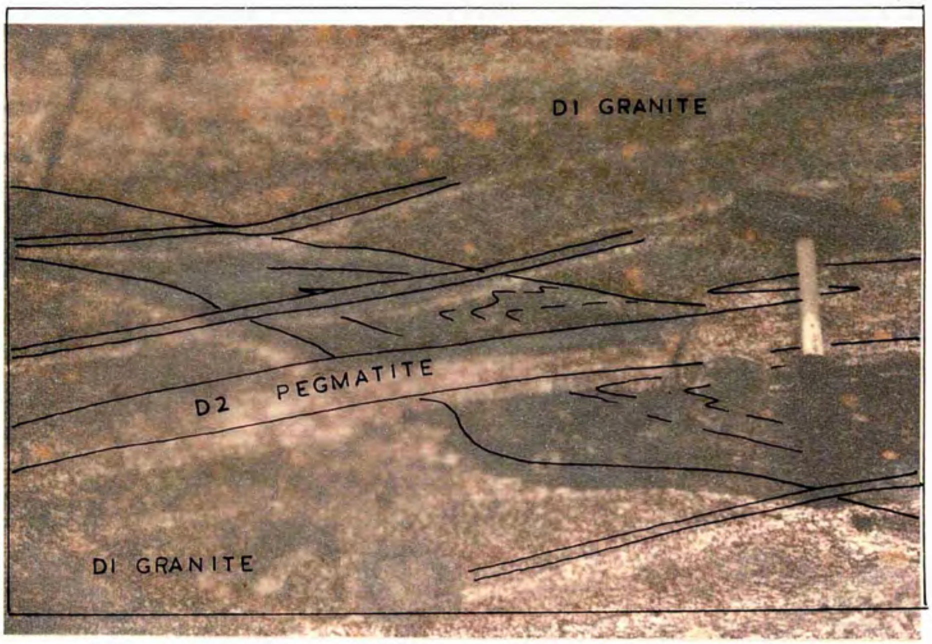


plate 22
F1 fold, defined by thin aplitic bands in hornblende quartzofeldspathic gneiss (basement gneiss), cut by a D1 granite body; both are cut by D2 pegmatites. (length of hammer shaft : 42 cm.)

plate 21
D2 granite veins axial planar to F2 folds that deform S1 in quartzo-feldspathic gneiss. Note the strong foliation in the granite (S2).
(diameter of coin : 1.5 cms.)

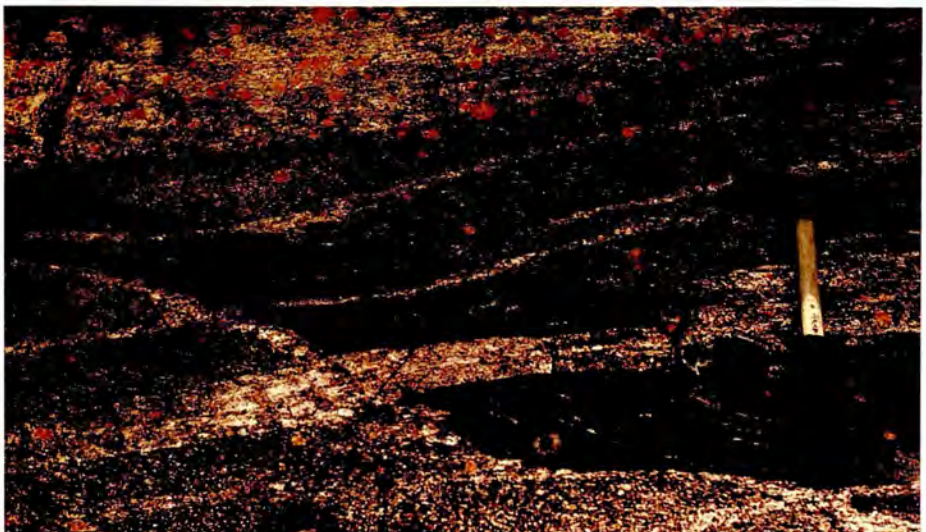


plate 22
F1 fold, defined by thin aplitic bands in hornblende quartzofeldspathic gneiss (basement gneiss), cut by a D1 granite body; both are cut by D2 pegmatites. (length of hammer shaft : 42 cm.)

plate 23
late D1 amphibolite intrusive into the quartzofeldspathic basement gneiss. (amphibolite body is 1.2 m. thick)

plate 24
schistosity (S2) overprinting S1 with internal isocline , in the hornblende quartzofeldspathic basement gneiss.
(length of pencil : 16 cm)

plate 25
a D2 pegmatite axial planar to a F2 fold within hornblende quartzofeldspathic basement gneiss. Note the development of S2 within both the pegmatite and the gneiss .

plate 26
xenolith of isoclinally folded quartzofeldspathic basement gneiss within a D2 granite.
(xenolith ca. 50cm. thick)

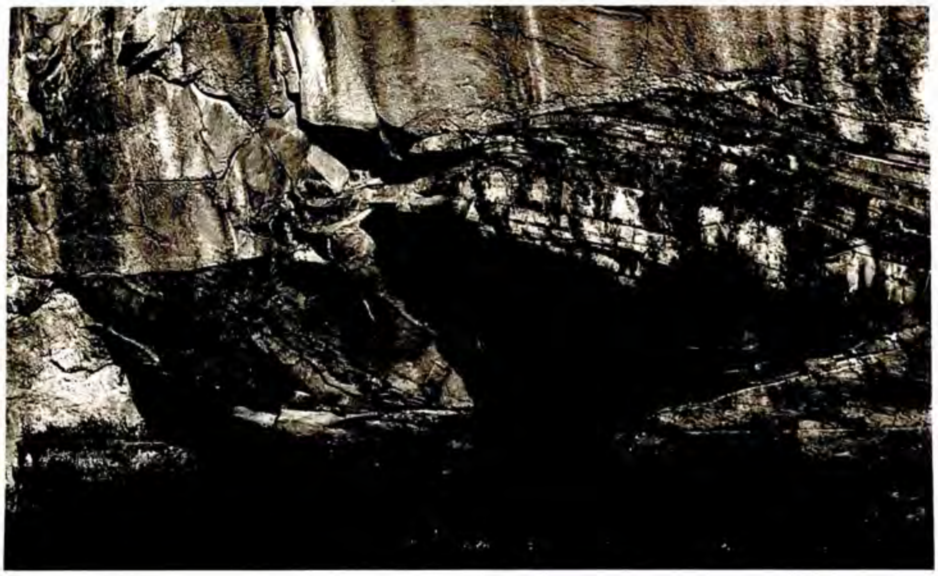


plate 27
the D2 granite body of plate 26, intrusive into quartzofeldspathic basement gneiss with the S1 foliation.
(height of face ca. 5m)

plate 28
flaggy basement quartzofeldspathic and epidote quartzofeldspathic gneiss with enhanced S2 foliation.
(length of hammer shaft :42 cms)

plate 29
F2 isoclines with axial planar D2 granite veins within flaggy basement quartzofeldspathic gneiss.

plate 30
a D2 thrust, utilising a retrogressed mafic body, cuts out a F2 fold in quartzofeldspathic basement gneiss.
(length of notebook : 16cm.)

plate 31
type 2 (Ramsey 1967) interference pattern produced by the refolding of F2 by F3 in the quartzofeldspathic basement gneiss. (mapping case width :31 cm.)

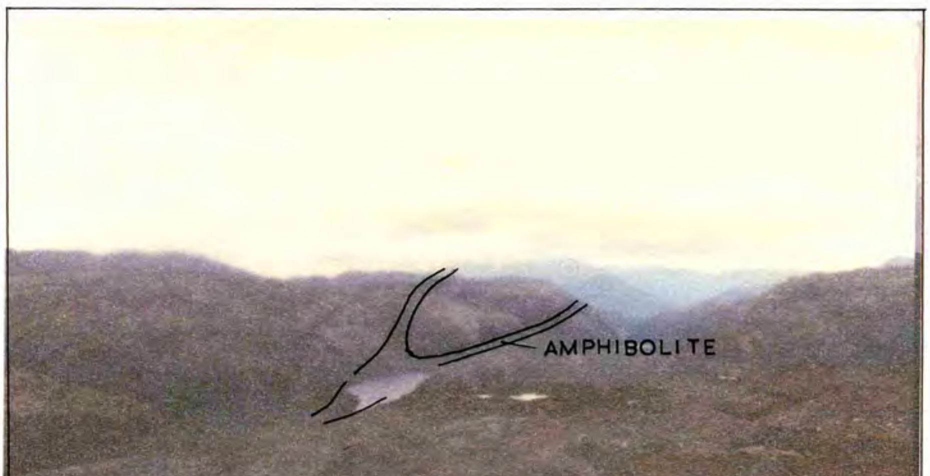


plate 32
view to the southwest across the basement gneisses showing a large scale F3 synform defined by an amphibolite body.

plate 31
type 2 (Ramsey 1967) interference pattern produced by the refolding of F2 by F3 in the quartzofeldspathic basement gneiss. (mapping case width :31 cm.)

plate 32
view to the southwest across the basement gneisses showing a large scale F3 synform defined by an amphibolite body.

plate 33
F3 folding of quartzofeldspathic basement gneiss, viewed towards the northeast.

plate 34
Banded Gneisses from within the Mixed Gneiss tectonic unit;a F1 isocline folds D "early"aplites, and is itself cut by D1 axial planar pegmatites;crenulated by F4.
(height of face : 50cm.)

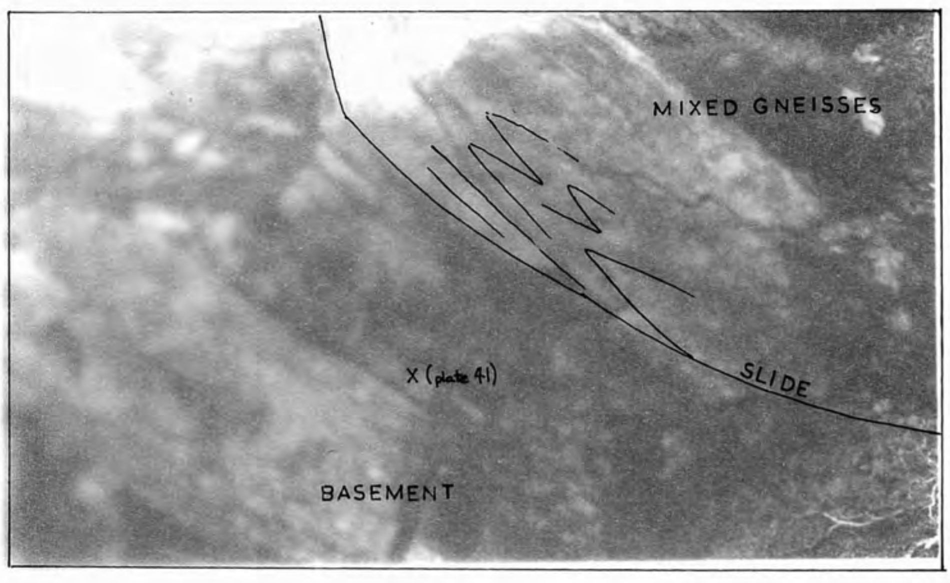
plate 35
Banded Gneisses with the S "early" foliation, from within the Mixed Gneiss tectonic unit, folded by F1, with an intrusive D1 pegmatite along the axial plane.

plate 36
xenolith of quartzofeldspathic basement gneiss within a D1 granite within the Mixed Gneiss tectonic unit. Note the S1 fabric in both granite and wall rock. (lens cap diameter: 5.8cms)

plate 37
an irregular body of D1 granite intruded into flattened basement gneiss within the Mixed Gneiss tectonic unit. Note that the vein running from the granite is flattened into the S1 gneissic fabric.
(length of pencil : 12 cms)

plate 38
a D1 granite vein, axial planar to a F1 fold in Banded Gneisses within the Mixed Gneiss tectonic unit;note the S1 fabric in both granite and gneiss.
(length of pencil :12 cms.)

(S1) within basement gneisses of the Mixed
unit.



...ing basement gneisses and Banded Gneisses
...neiss tectonic unit.
...of hammer shaft : 42 cms.)

plate 39
mylonitic foliation (S1) within basement gneisses of the Mixed Gneiss tectonic unit.

plate 40
a D1 slide juxtaposing basement gneisses and Banded Gneisses within the Mixed Gneiss tectonic unit.
(length of hammer shaft : 42 cms.)

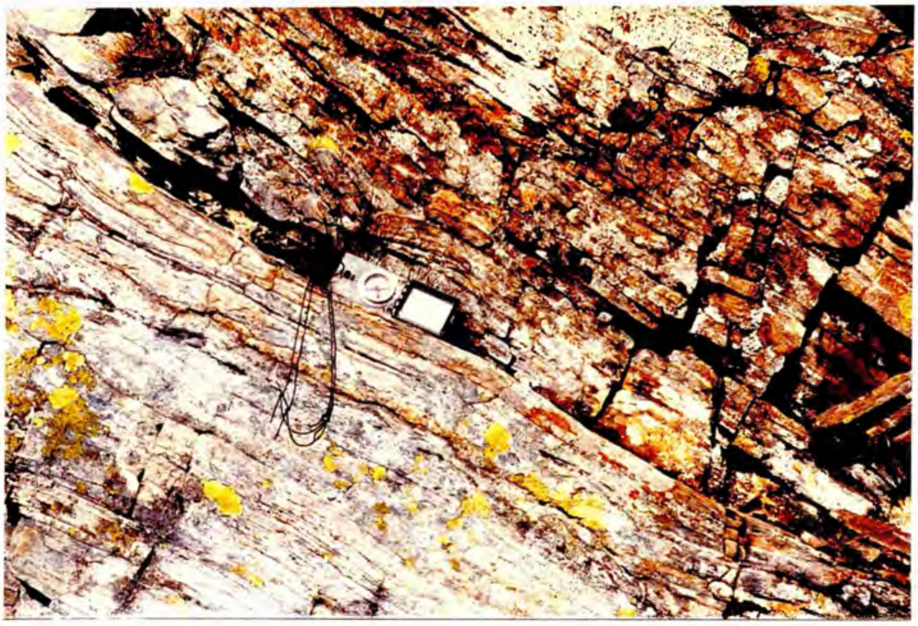


plate 41
point X (plate 40): basement gneiss develops a flaggy parting and rusty weathering within the D1 slide zone.

plate 42
F2 fold mullion lineation (L2) in the biotite-epidote-hornblende gneiss of the Mixed Gneisses.

plate 43
S1 schistosity in a D1 granite, boudinaged during D2;in the Banded Gneisses within the Mixed Gneiss tectonic unit.

plate 44
D "early" mafic pods within the Eggjane Gneisses;
(diameter of lens cap : 5.8cm.)

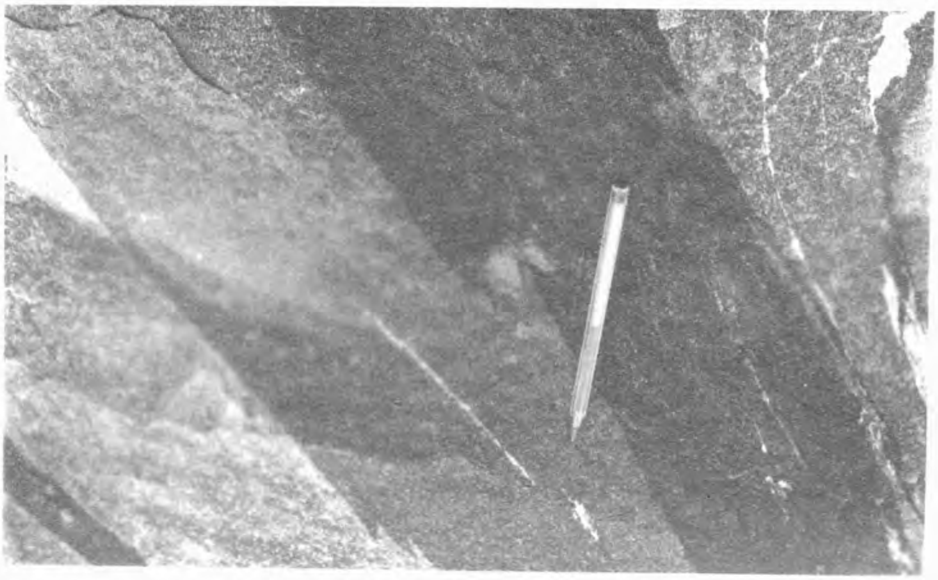


plate 45
D1 amphibolite intrusive into the Eggjane Gneisses;the amphibolite foliation is S1.

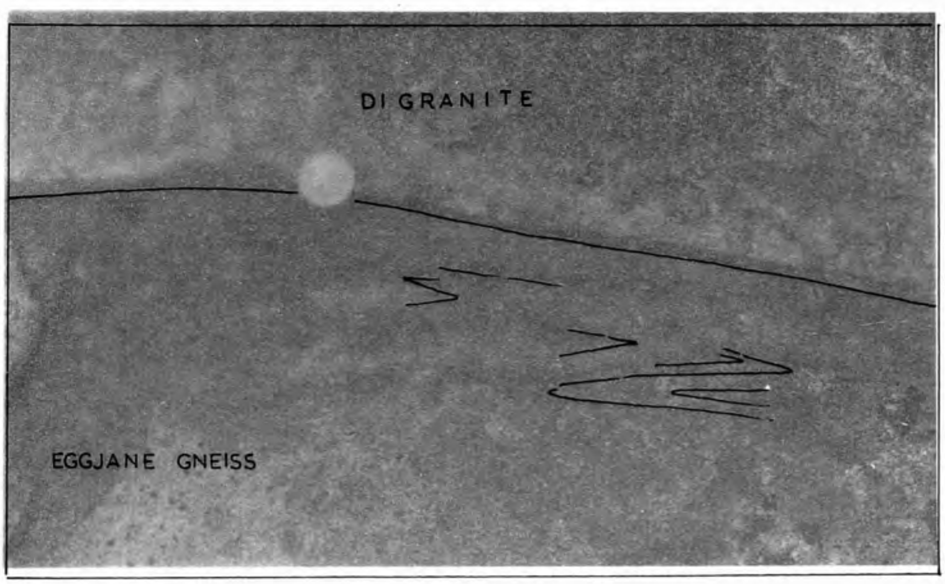


plate 46
a F1 isocline with an axial planar D1 granite in the Eggjane Gneisses.
(diameter of coin: 2.1 cm.)

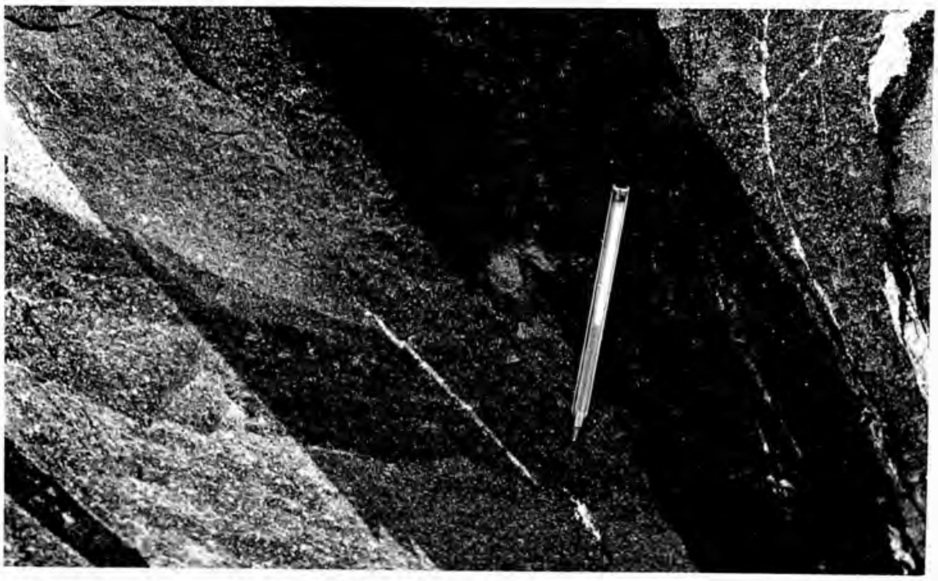


plate 45
D1 amphibolite intrusive into the Eggjane Gneisses;the amphibolite foliation is S1.

plate 46
a F1 isocline with an axial planar D1 granite in the Eggjane Gneisses. (diameter of coin: 2.1 cm.)

plate 47
the flaggy composite foliation (S1/S2) of the Eggjane Gneisses.

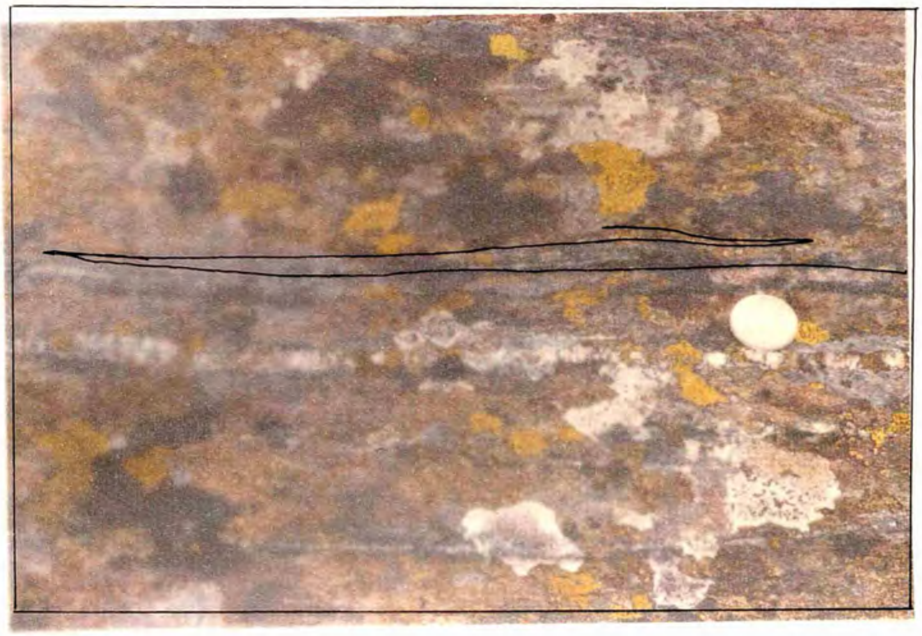


plate 48
F1 isoclinal folding of a calc-silicate band with amphibolite margins in biotite hornblende gneiss (Banded Gneiss), Lower Bergsdalen Nappe.
(diameter of coin : 2.5cms.)

plate 47
the flaggy composite foliation (S1/S2) of the Eggjane Gneisses.

plate 48
F1 isoclinal folding of a calc-silicate band with amphibolite margins;in biotite-hornblende gneiss (Banded Gneiss), Lower Bergsdalen Nappe.
(diameter of coin : 2.5cms.)

plate 49
a calc-silicate band isoclinally folded (F1) within biotite-hornblende gneiss (Banded Gneiss), Lower Bergsdalen Nappe.
(diameter of coin : 2.5 cms.)

plate 50
D2 granite net veining Banded Gneisses, Lower Bergsdalen Nappe.
(height of exposed face : ca. 5m.)

plate 51
F2 folding of biotite gneiss (Banded Gneiss), Lower Bergsdalen Nappe.
(length of hammer shaft : 42 cms.)

plate 52
lineation L1 in the Banded Gneisses, Lower Bergsdalen Nappe.

plate 53
F2 folding of S1 with axial planar quartz veins in the gneissose granite of the Lower Bergsdalen Nappe.

plate 54
a D3 basement thrust within flaggy quartzofeldspathic gneiss; viewed towards the northeast.
(height of face ca. 6m.)

plate 55
the steep limb of a F3 fold in quartzofeldspathic basement gneiss replaced by a D3 thrust, with associated mylonitic foliation.

plate 56
a small scale D3 thrust fault in the hinge of a F3 fold in quartzofeldspathic basement gneiss.

plate 57
photomicrograph of an acidic mylonitic gneiss from a D3 basement thrust zone.
(cross polarised light, x 12.5)

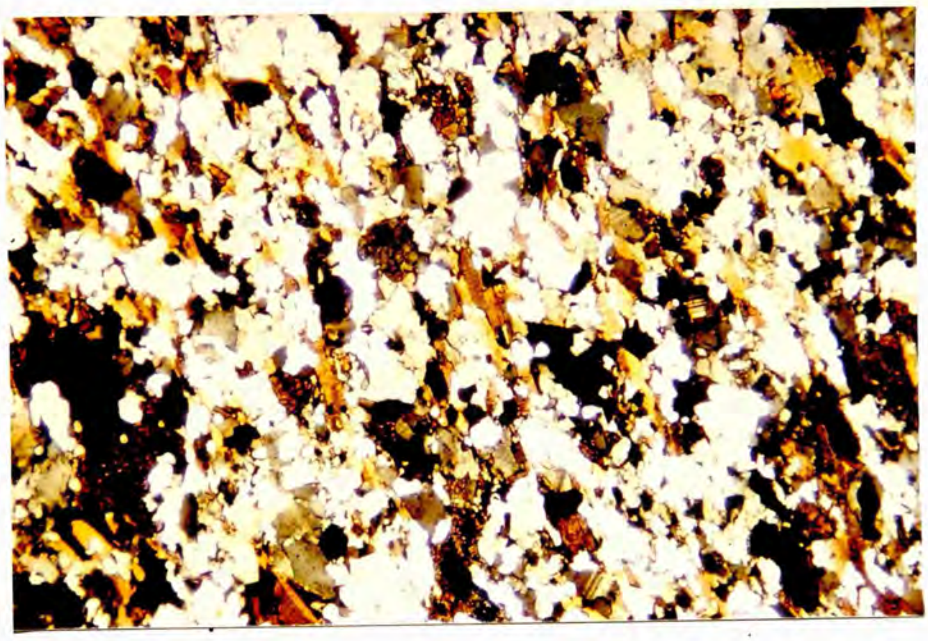


plate 58
photomicrograph of a mafic mylonitic gneiss, from a D3 basement thrust zone.
(cross polarised light, x 12.5)

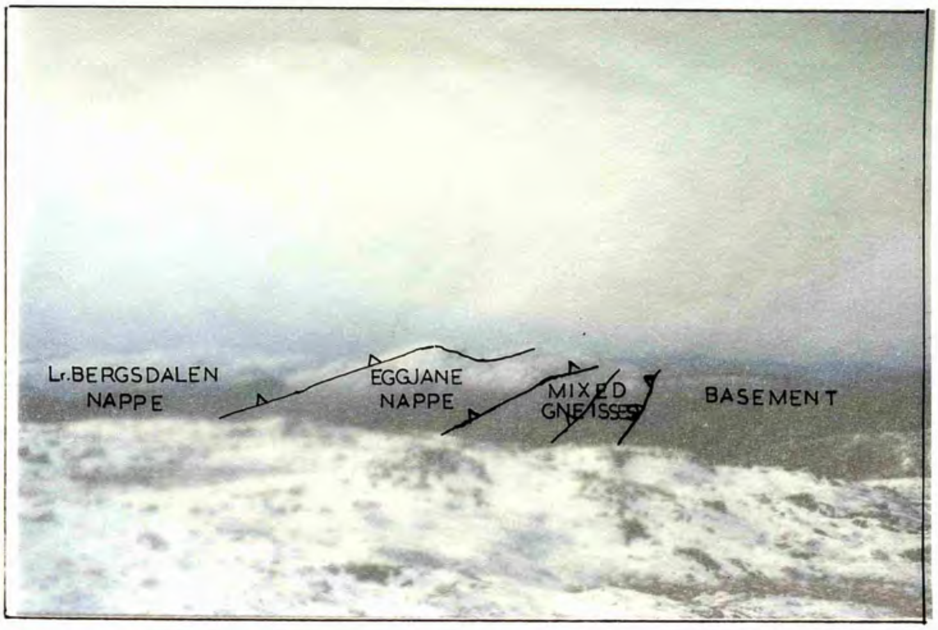


plate 59
view looking to the southwest across the basement/nappe complex. (field of view ca. 4.5 km.)

plate 60
rusty brown weathering tectonic schist (phyllonite) no. 1, overlying the gneisses of the Eggjane Nappe; viewed towards the northeast.

plate 59
view looking to the southwest across the basement/nappe complex.
(field of view ca. 4.5 km.)

plate 60
rusty brown weathering tectonic schist (phyllonite) no. 1, overlying the gneisses of the Eggjane Nappe; viewed towards the northeast.

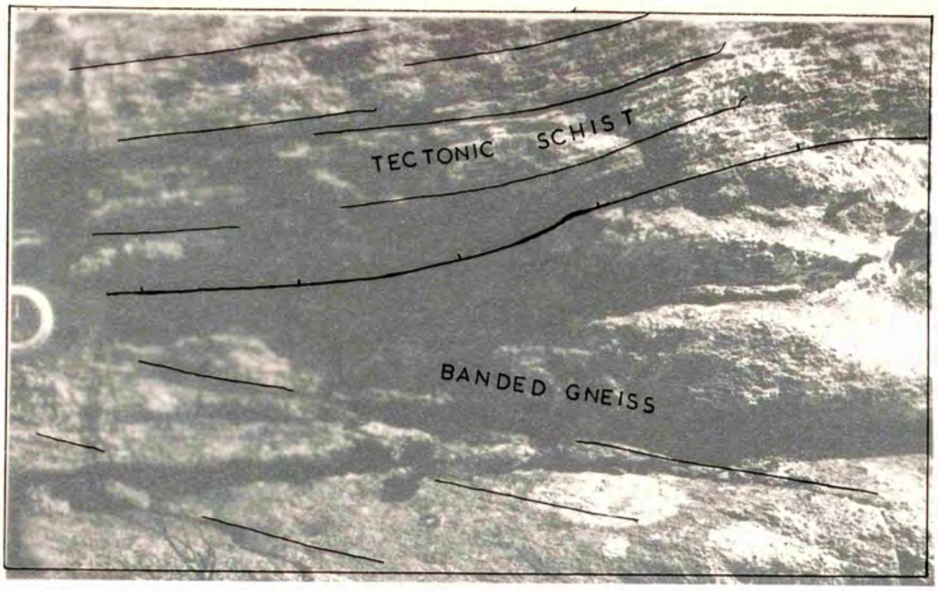


plate 61
a discordant tectonic schist overstepping foliated Banded Gneisses of the Lower Bergsdalen Nappe.

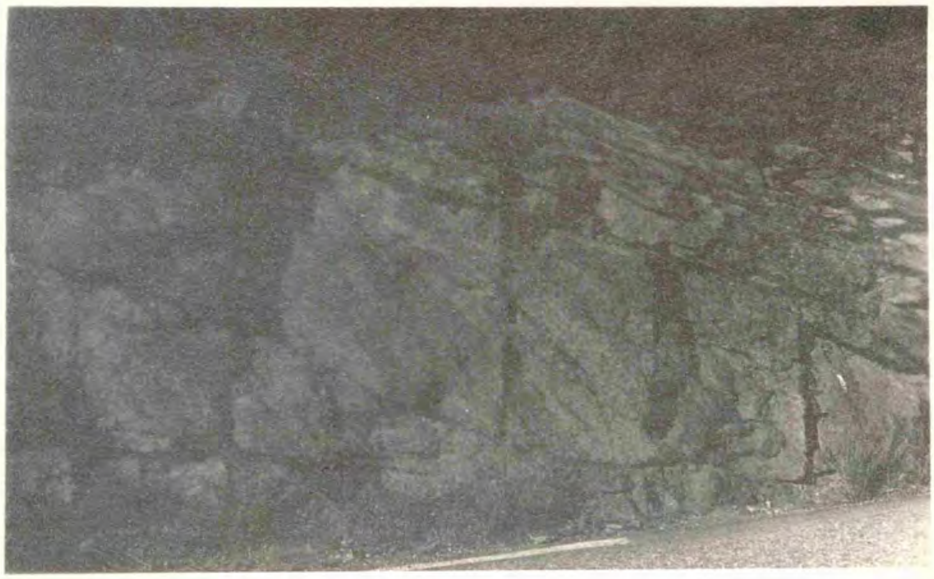


plate 62
a tectonic schist within Banded Gneisses of the Lower Bergsdalen Nappe;note the sharp contact, and the subsequent F3 crenulation cleavage.
(length of hammer shaft : 34 cms.)

plate 61
a discordant tectonic schist overstepping foliated Banded Gneisses of the Lower Bergsdalen Nappe.

plate 62
a tectonic schist within Banded Gneisses of the Lower Bergsdalen Nappe;note the sharp contact, and the subsequent F3 crenulation cleavage.
(length of hammer shaft : 34 cms.)

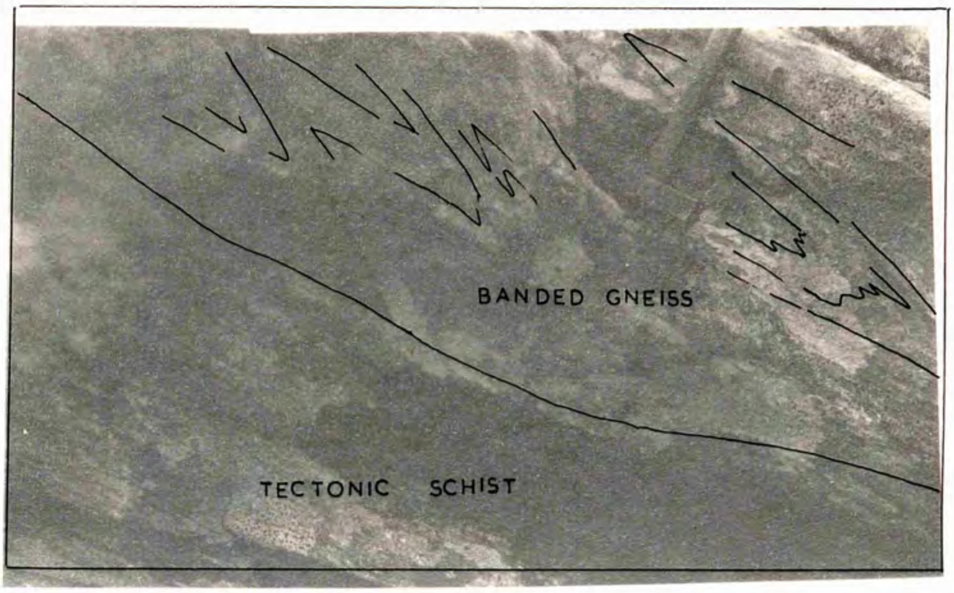


plate 63
F2 folding in Banded Gneisses of the Lower Bergsdalen Nappe, cut by tectonic schist.
(width of hammer head : 16 cms.)

plate 64
a rusty weathering tectonic schist discordant to a F2 fold in the Eggjane Nappe.

plate 63
F2 folding in Banded Gneisses of the Lower Bergsdalen Nappe, cut by tectonic schist.
(width of hammer head : 16 cms.)

plate 64
a rusty weathering tectonic schist discordant to a F2 fold in the Eggjane Nappe.

plate 65
patchy development of muscovite books in a tectonic schist from the Lower Bergsdalen Nappe
(diameter of coin : 2.5cms.)

plate 66
lens of biotite gneiss (Banded Gneiss) within a tectonic schist from the Lower Bergsdalen thrust zone.
(diameter of coin : 2.2cms.)

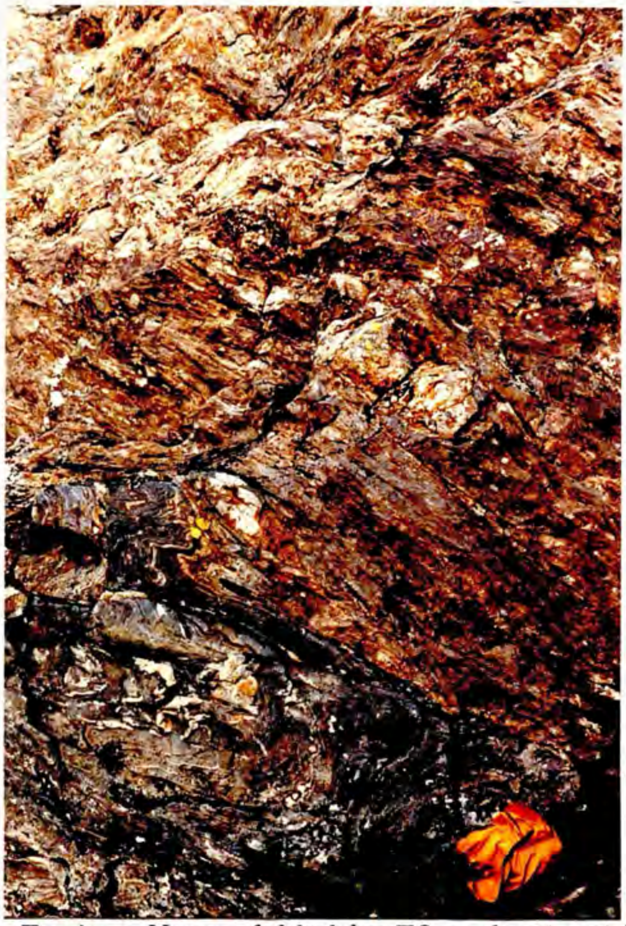


plate 67

gneisses of the Eggjane Nappe folded by F2, and cut out by the rusty weathering tectonic schist;viewed towards the northeast.

plate 68

F2 isoclines deforming the Banded Gneisses of the Lower Bergsdalen Nappe;the hinge zones are disrupted by thin bands of tectonic schist.

(length of hammer shaft : 34 cms.)

plate 69
isoclinally folded pegmatite vein within a tectonic schist of the Lower Bergsdalen thrust zone.
(diameter of lens cap : 5.5 cms.)

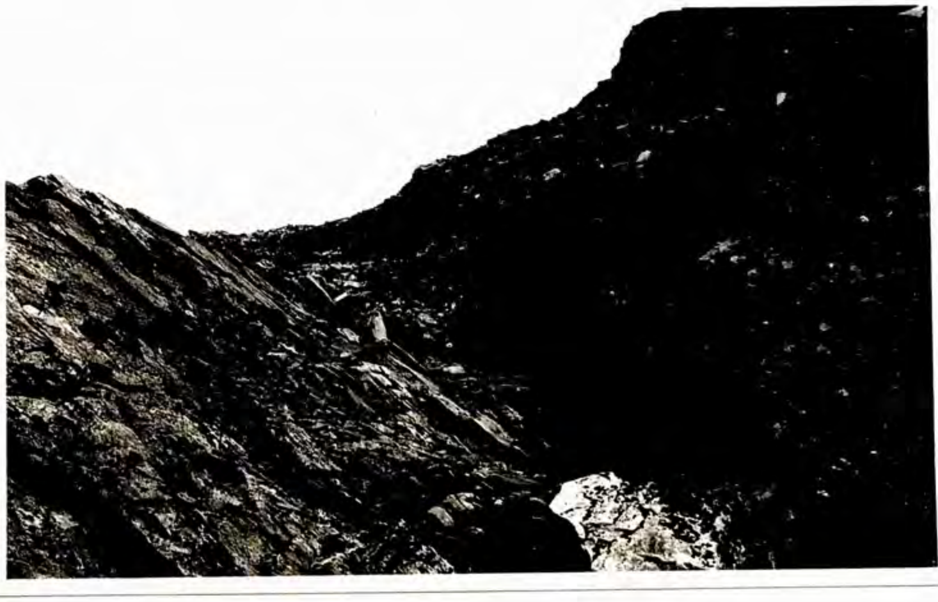


plate 70
platey parting developed in mylonitic Banded Gneisses along thrust no. IV of the Lower Bergsdalen thrust zone.
(height of scarp : ca. 4m)

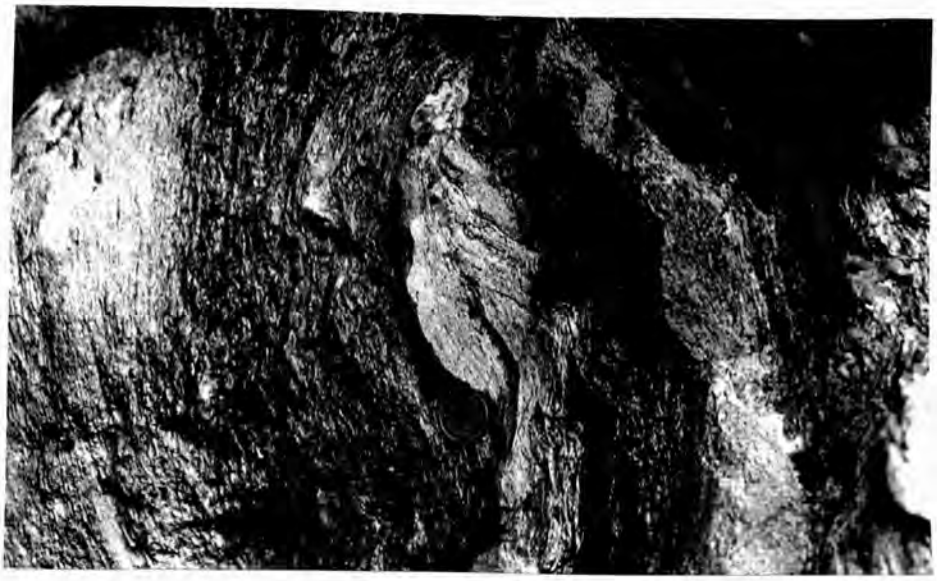


plate 71
lenses of gneissose granite within the granitic tectonic schist of the Lower Bergsdalen Nappe;note the diffuse margins of the lenses. (diameter of coin :2.2 cms.)

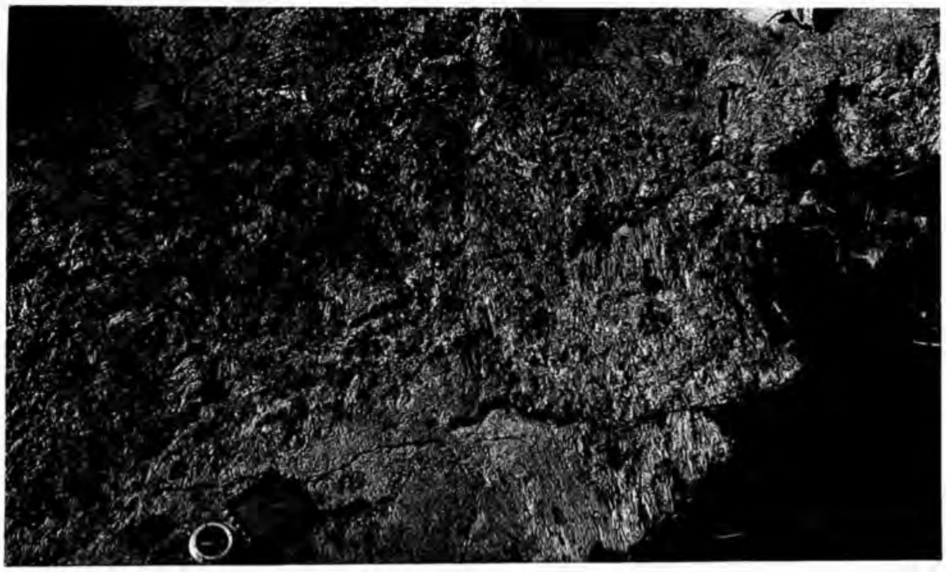


plate 72
tectonic schist developed within gneissose granite;note the F3 schistosity.

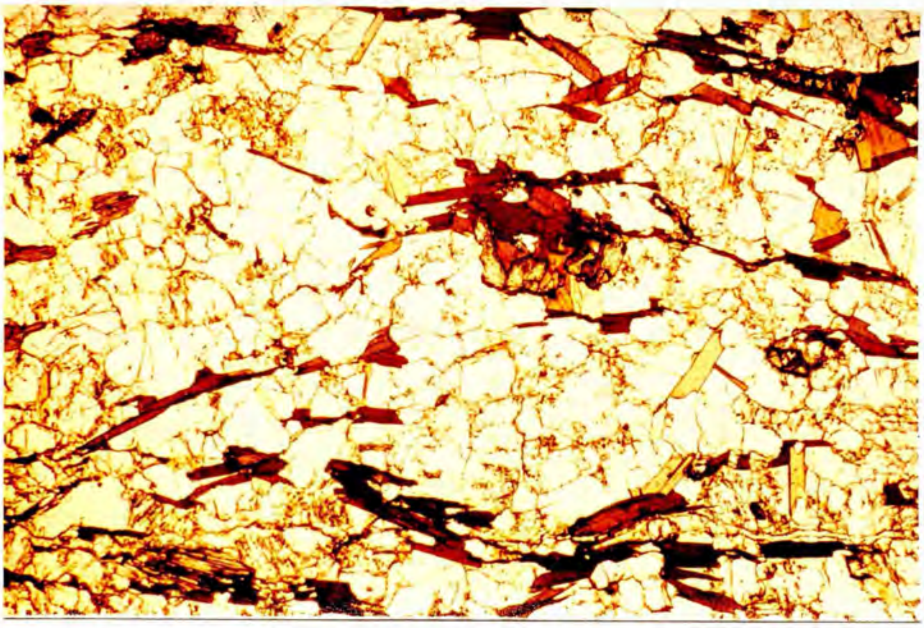


plate 73
photomicrograph of garnet being pseudomorphed by biotite in a biotite gneiss (Banded Gneiss) marginal to a tectonic schist; note the development of muscovite.
(plane polarised light, x 32)

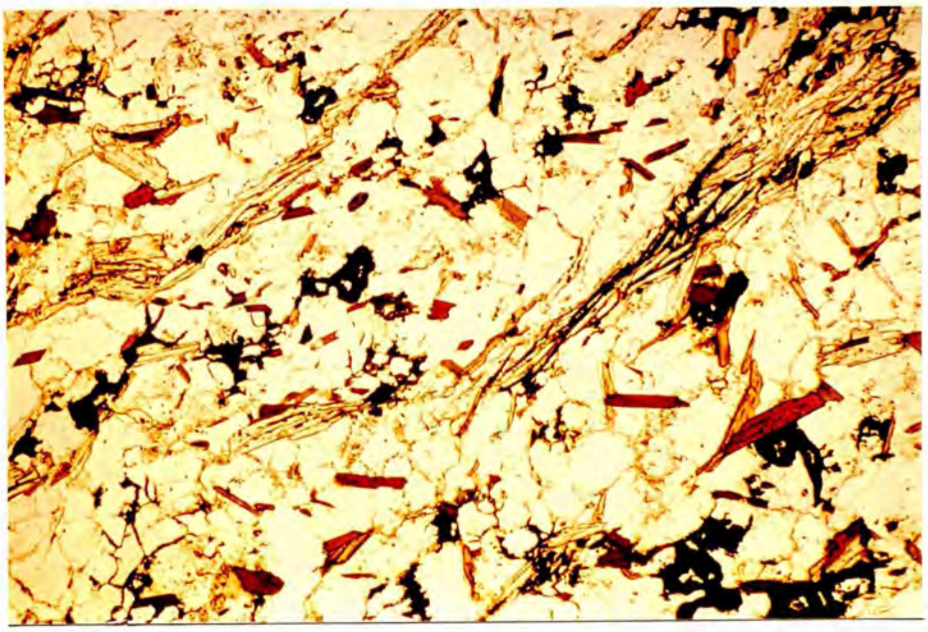


plate 74
photomicrograph of muscovite strings discordant to the S1 biotite fabric, in a weakly developed tectonic schist, Lower Bergsdalen thrust zone.
(plane polarised light, x 32)

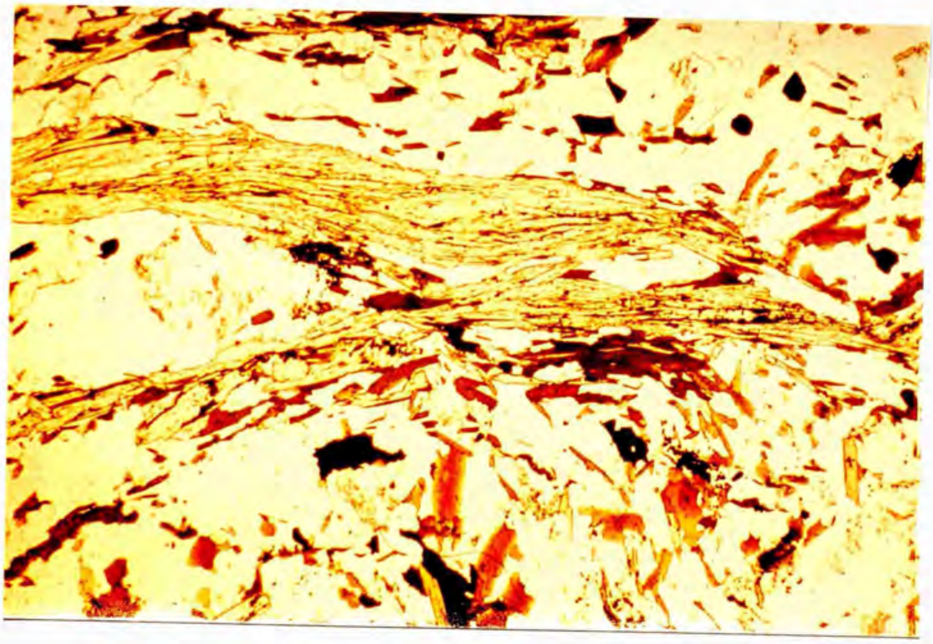


plate 75
photomicrograph of the muscovite fabric discordant to the S1 biotite fabric in a tectonic schist of the Lower Bergsdalen thrust zone.
(plane polarised light, x 32)

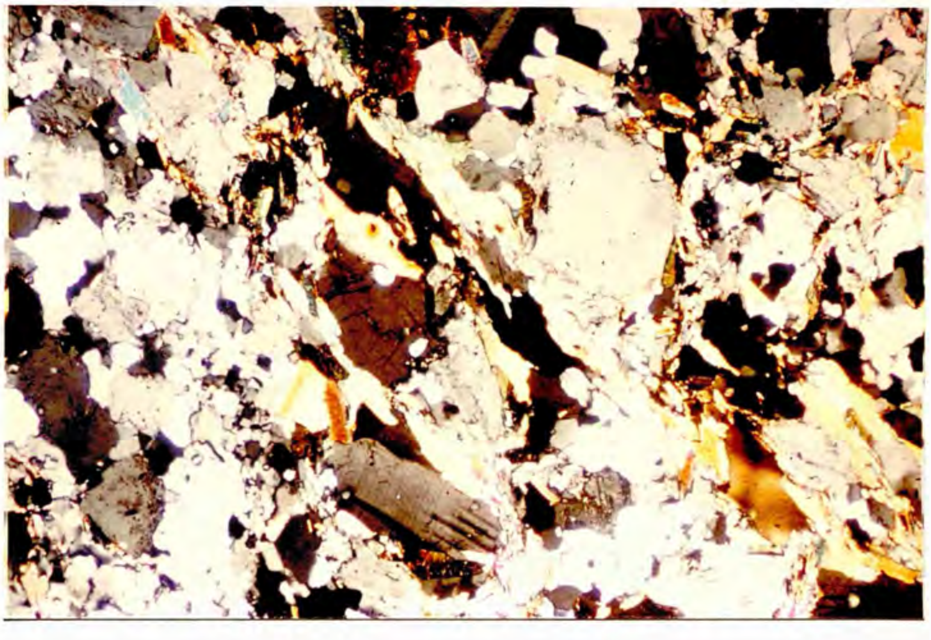


plate 76
photomicrograph of muscovite cross cutting and replacing plagioclas grains in a tectonic schist of the Lower Bergsdalen Nappe.
(cross polarised light, x 12.5)

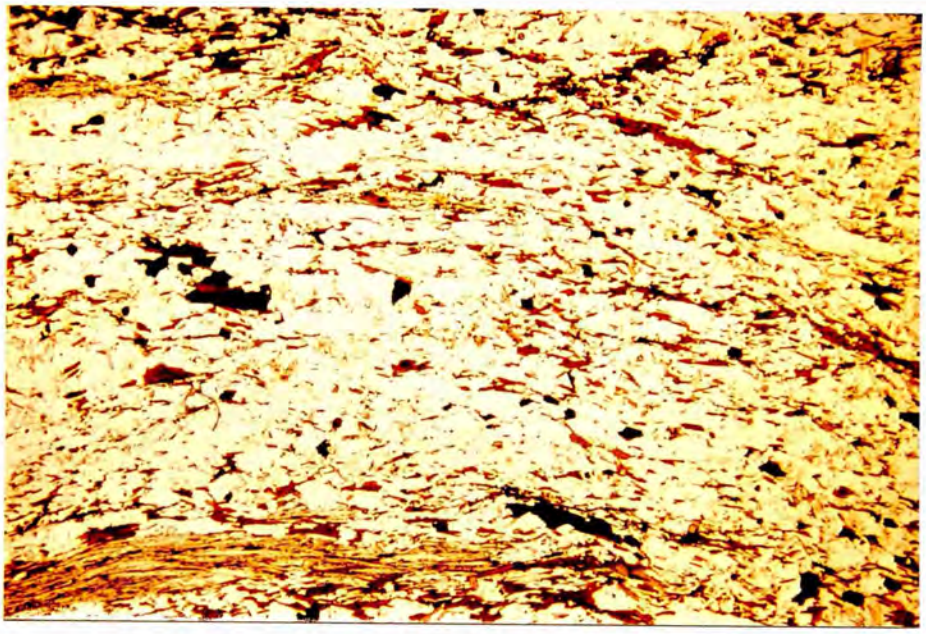


plate 77
photomicrograph of a marginal tectonic schist from the Lower Bergsdalen thrust zone;this is a biotite gneiss with aggregates of muscovite (bottom left hand corner)
(plane polarised light, x12.5)

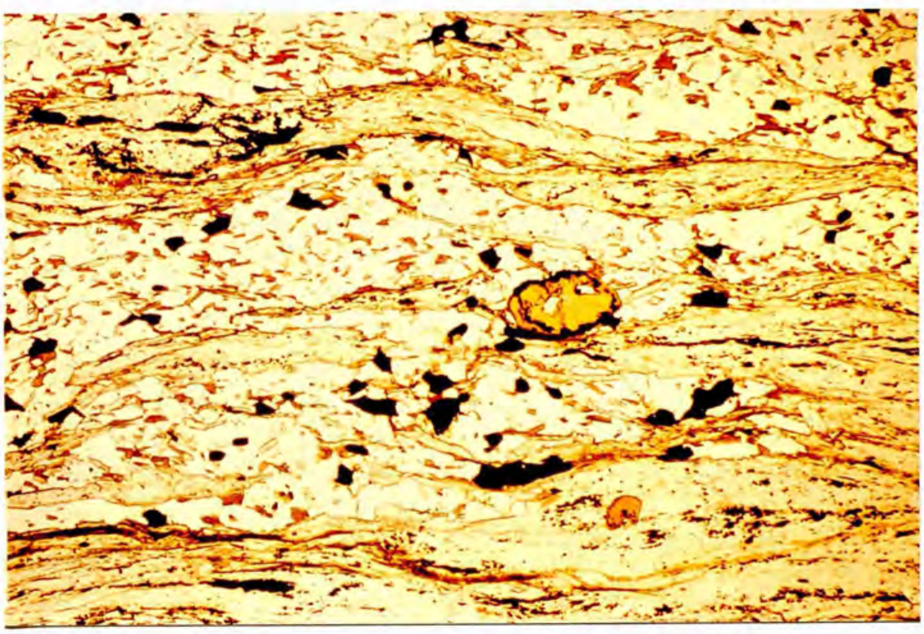


plate 78
photomicrograph of a tectonic schist overgrown by tourmaline, Lower bergsdalen thrust zone.
(plane polarised light, x32)

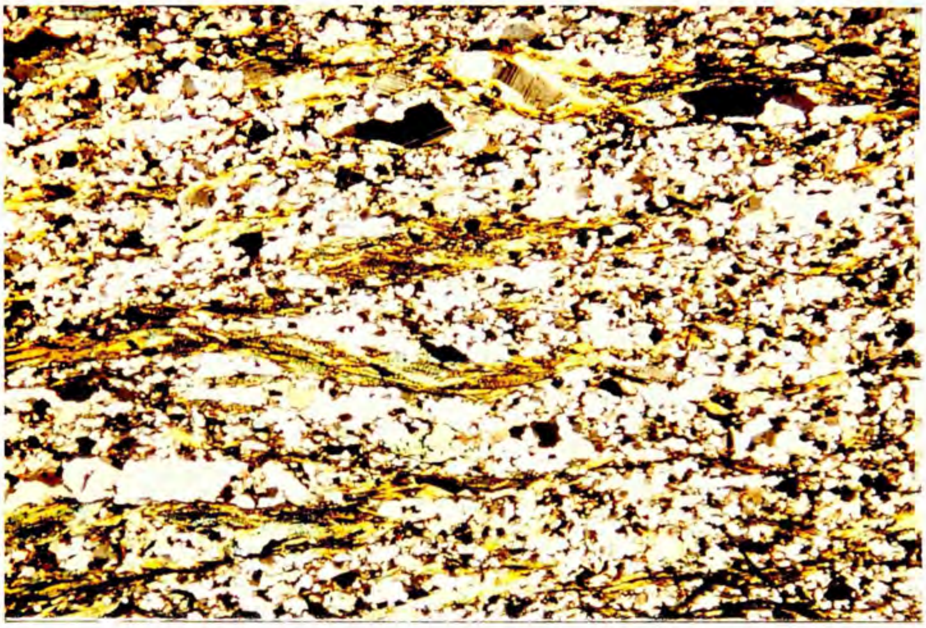


plate 79
photomicrograph of a tectonic schist, Lower Bergsdalen thrust zone;note the mylonitic nature of the augened quartzofeldspathic matrix.
(cross polarised light, x 12.5)

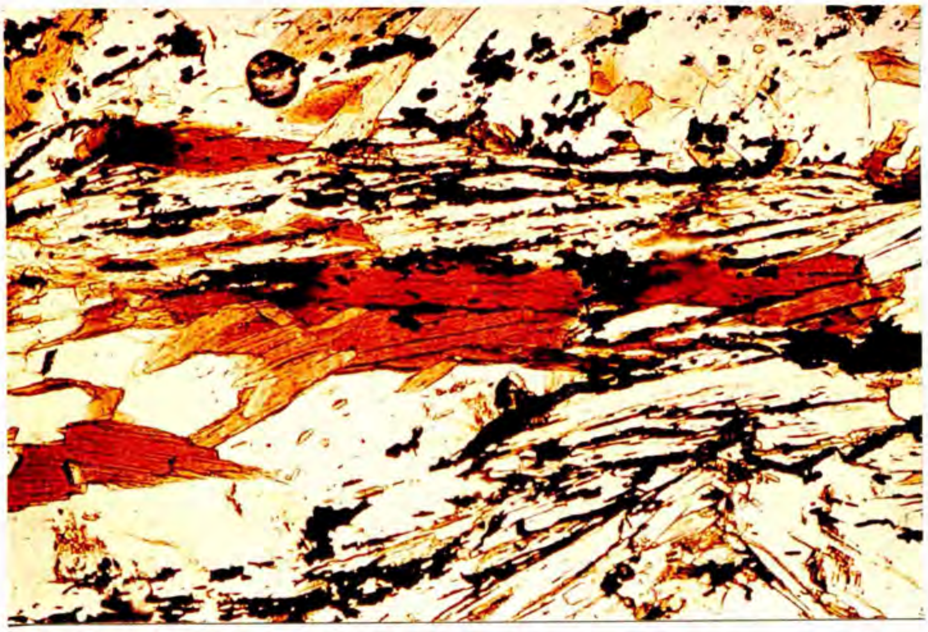


plate 80
photomicrograph of biotite being altered to muscovite and iron oxide, in a tectonic schist of the Lower Bergsdalen Nappe.
(plane polarised light, x 125)

plate 81

large scale F3 folding of Banded Gneisses and tectonic schists at Brekka, Lower Bergsdalen Nappe; viewed towards the northeast.

plate 82

the D3 Bukkafjell thrust within the Lower Bergsdalen Nappe;it carries D1 granites and quartzites over Banded Gneisses. Viewed towards the northeast.

plate 83
F3 schistosity in quartzite of the Lower Bergsdalen Nappe.
(diameter of lens cap : 5.8cms.)

plate 84
F3 folding of mixed amphibolites and granite, Lower Bergsdalen Nappe.

(outcrop height ca. 5m.)

plate 85
non-cylindrical F3 folding of Banded Gneisses within the Lower Bergsdalen Nappe; note the L1 lineation folded around the hinge.
(length of shaft : 42 cms.)

plate 86
a complex outcrop pattern due to the superimposition of non-cylindrical F4 folding on F2 ;in Banded Gneisses of the Lower Bergsdalen Nappe.
(length of hammer shaft : 34 cms.)

plate 87
lineation L1, folded by F4 in Banded Gneisses of the Lower Bergsdalen Nappe.
(length of hammer shaft :34 cms.)

plate 88
F3 folding of Banded Mylonites deformed by F4 folds in the Lower Bergsdalen Nappe

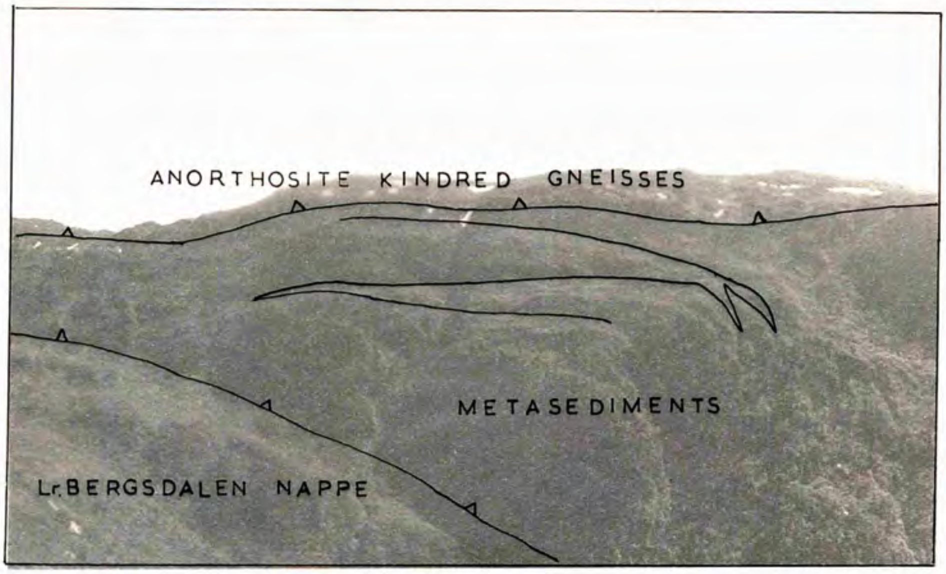


plate 89
F3 folding within the D3 thrust bound block of metasediments at the margin of the Bergen Arcs; viewed towards the southwest.

plate 90
Banded Mylonite gneisses within the Lower Bergsdalen Nappe

plate 89
F3 folding within the D3 thrust bound block of metasediments at the margin of the Bergen Arcs; viewed towards the southwest.

plate 90
Banded Mylonite gneisses within the Lower Bergsdalen Nappe

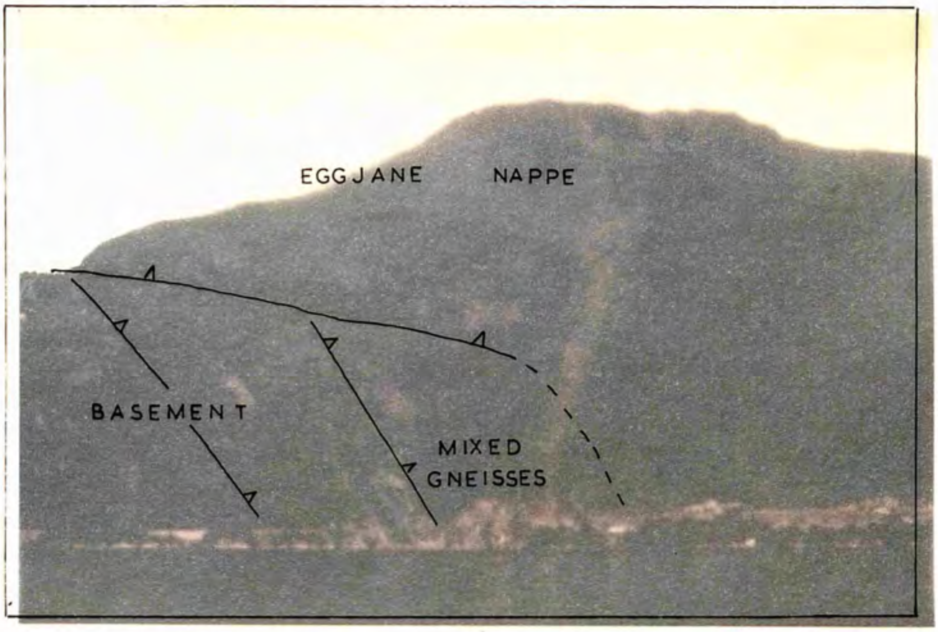


plate 91
the relationship between the basement and Eggjane thrusts, seen on the side (750m. high) of Veafjord; viewed towards the northeast.

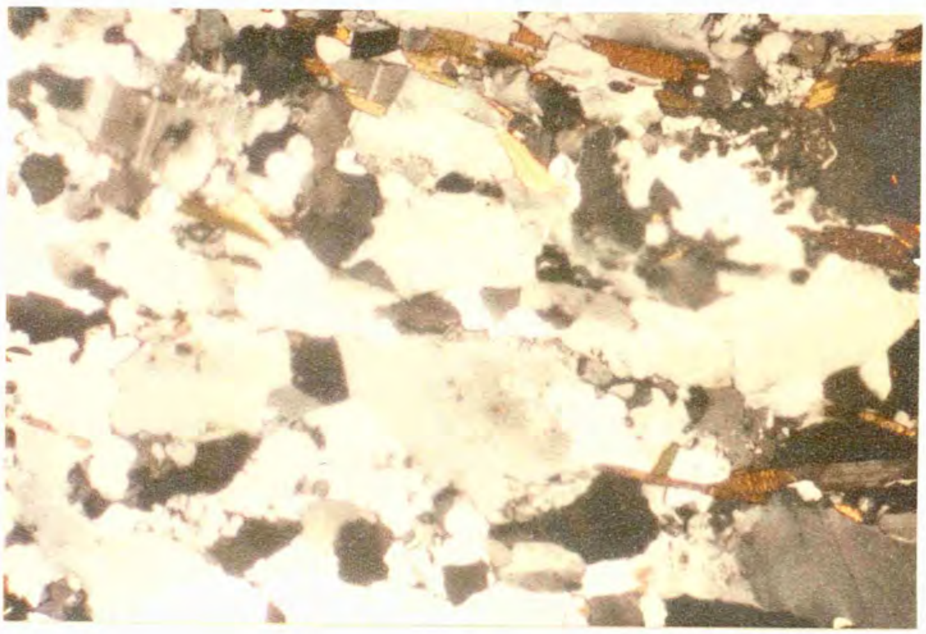


plate 92
photomicrograph of a M1 quartz ribbon passing through a M1 plagioclase, in quartzofeldspathic gneiss of the basement.
(cross polarised light, x 32)

plate 91
the relationship between the basement and Eggjane thrusts, seen on the side (750m. high) of Veafjord;viewed towards the northeast.

plate 92
photomicrograph of a M1 quartz ribbon passing through a M1 plagioclase, in quartzofeldspathic gneiss of the basement.
(cross polarised light, x 32)

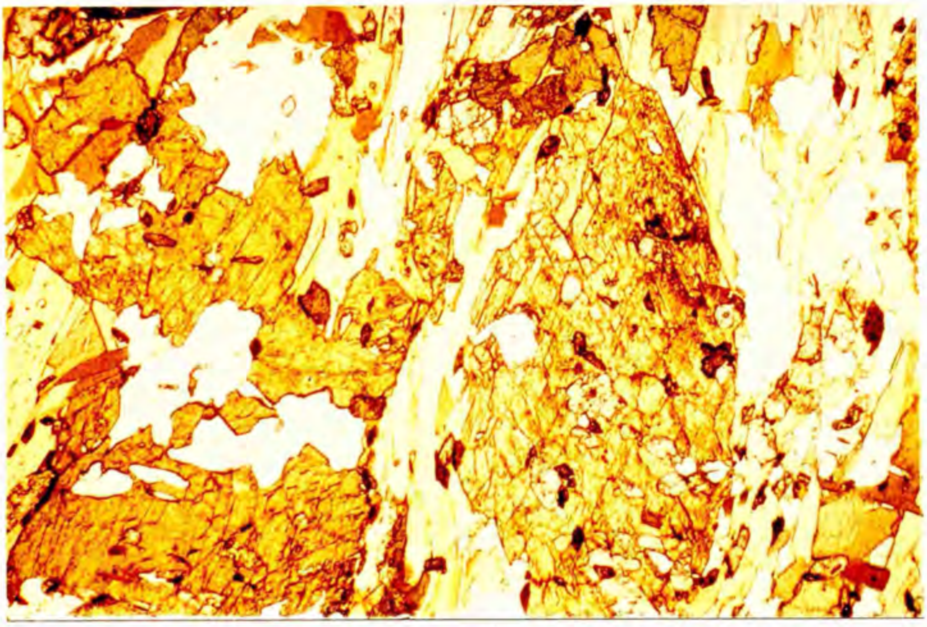


plate 93
photomicrograph of M1 hornblende replaced by M2 biotite (defining S2) in an amphibolite band within the Mixed Gneisses.
(plane polarised light, x32)

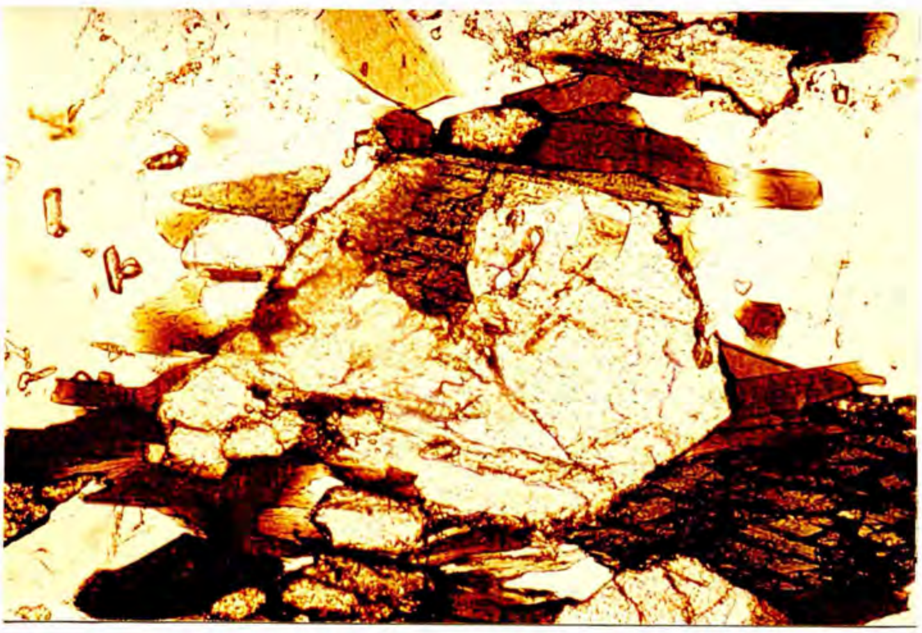


plate 94
photomicrograph of the replacement of M1 hornblende by M2 epidote in the Eggjane Gneisses.
(plane polarised light, x 125)

plate 95
photomicrograph of M1 clinopyroxene, parallel to S1, in biotite-hornblende gneiss (Banded Gneiss), Lower Bergsdalen Nappe.
(cross polarised light, x32)

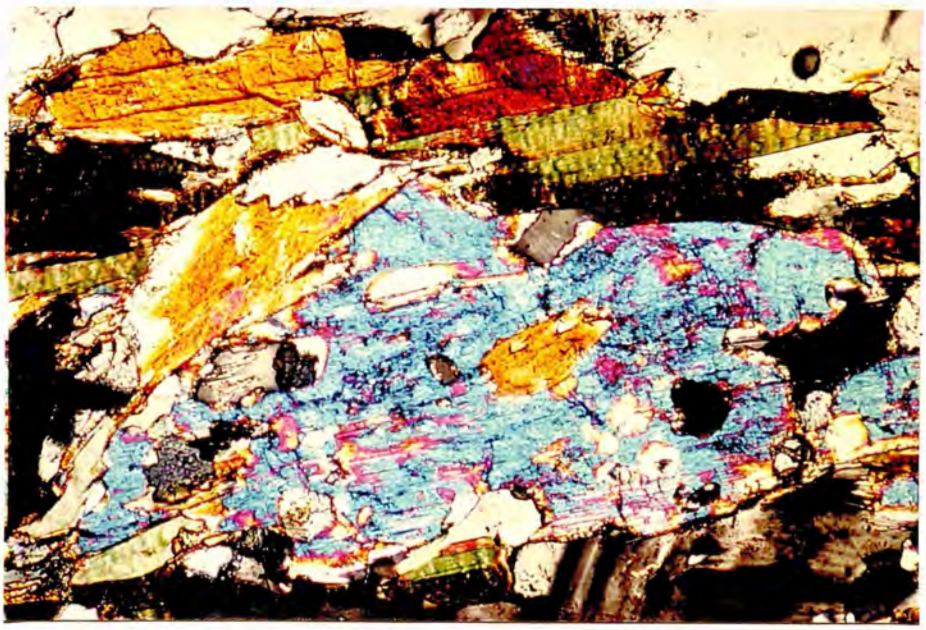


plate 96
photomicrograph of a M1 clinopyroxene marginally replaced by M3 actinolite in a biotite-hornblende gneiss (Banded Gneiss), Lower Bergsdalen Nappe.
(cross polarised light, x 32)

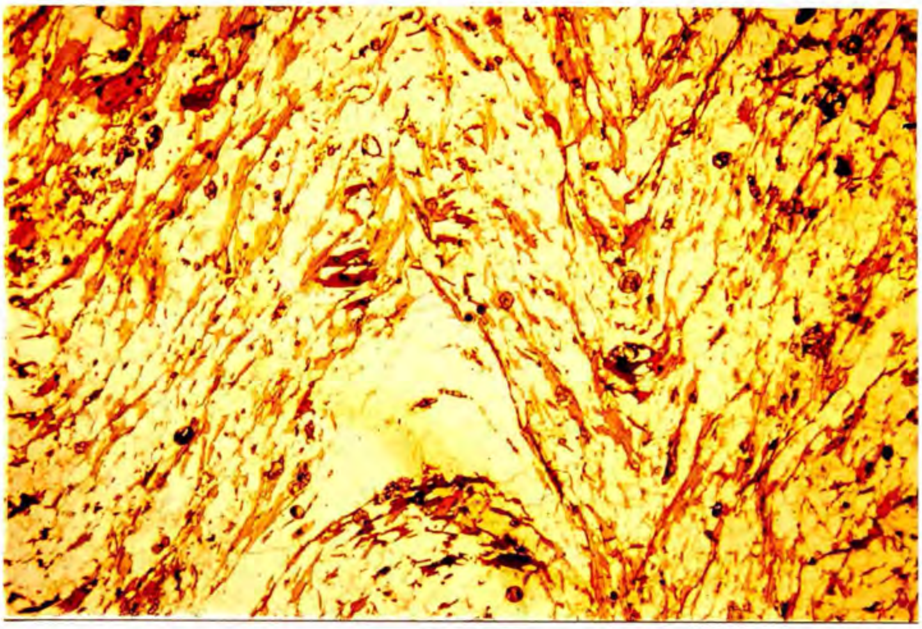


plate 97
photomicrograph of F3 crenulations in a biotite schist, Lower Bergsdalen Nappe.
(plane polarised light, x 12.5)

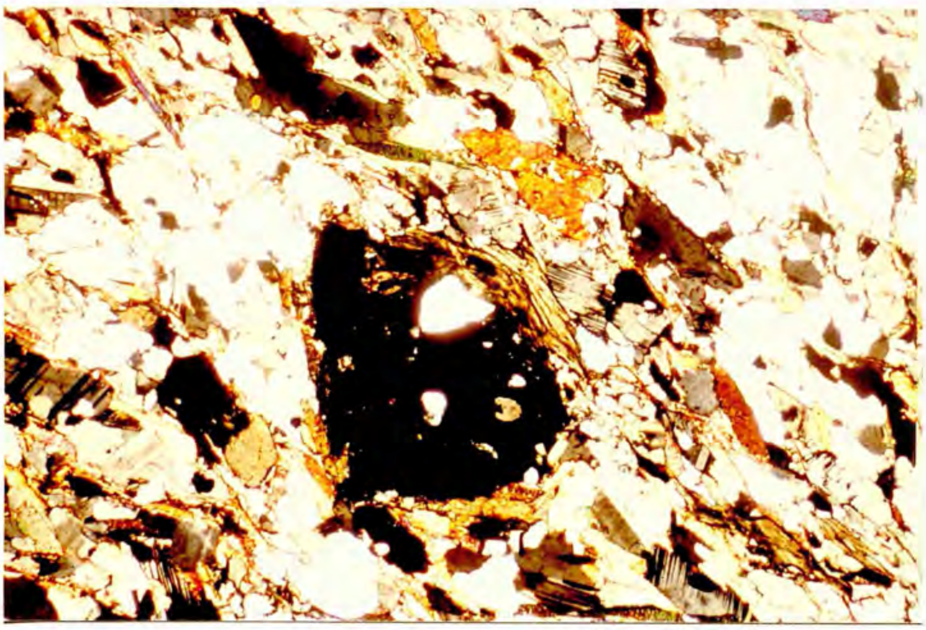


plate 98
photomicrograph of garnet marginally replaced by M5 chlorite in biotite-hornblende gneiss, Lower Bergsdalen Nappe.
(cross polarised light, x 32)

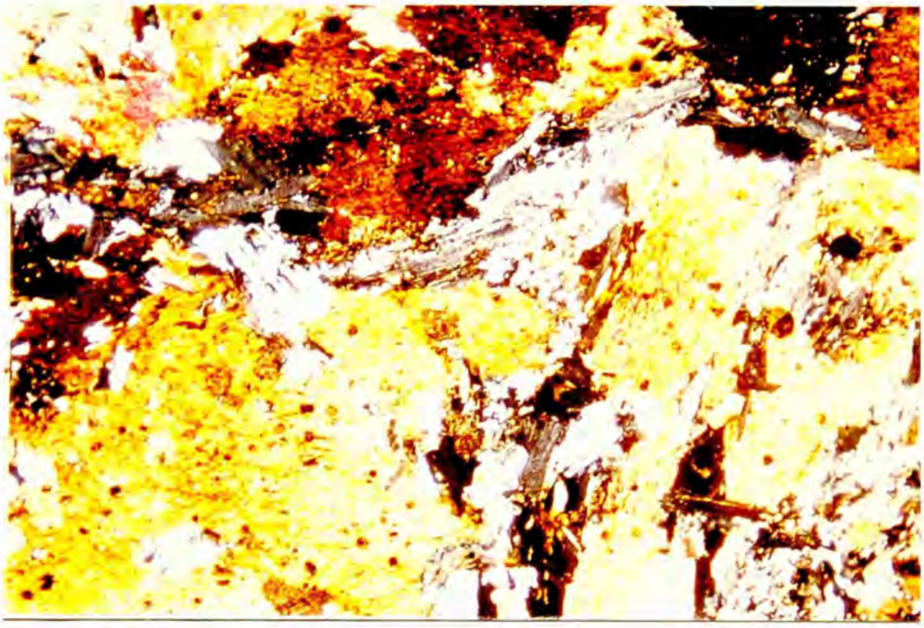


plate 99
photomicrograph of hornblende replaced marginally by M5 chlorite in a metagabbro of the Lower Bergsdalen Nappe.
(cross polarised light, x 12.5)

plate 100
a calc-silicate vein with an amphibolite margin, within Banded Gneisses of the Lower Bergsdalen Nappe
(diameter of lens cap : 5.8 cms.)

plate 101

zoned calc-silicate/amphibolite bands cross cut by a D1 granite vein, in Banded Gneisses of the Lower Bergsdalen Nappe.
(length of hammer shaft : 34 cms.)

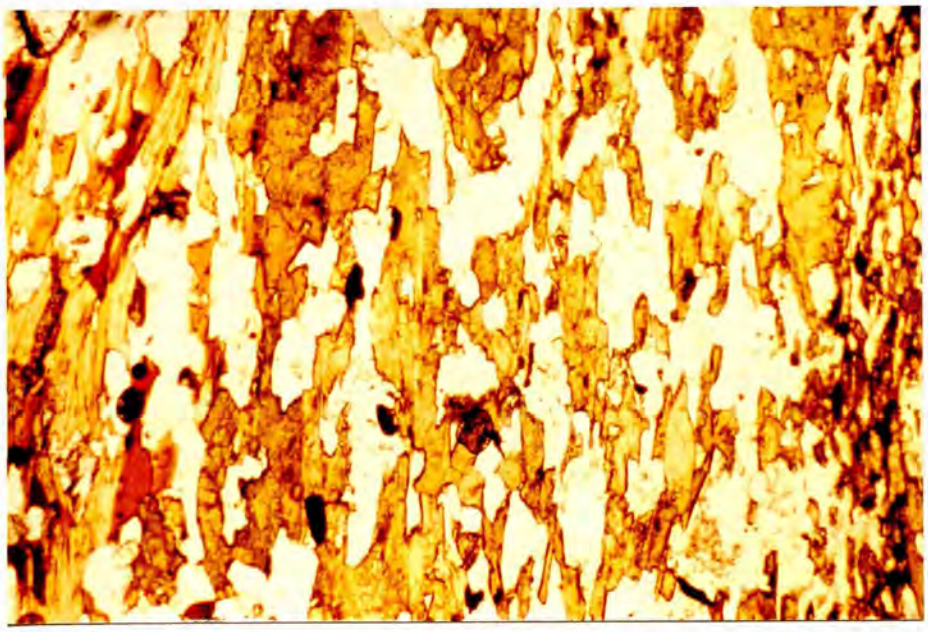


plate 102

photomicrograph of a section across the amphibolite margin to a zoned calc-silicate band from the Lower Bergsdalen Nappe.
(plane polarised light, x 32)

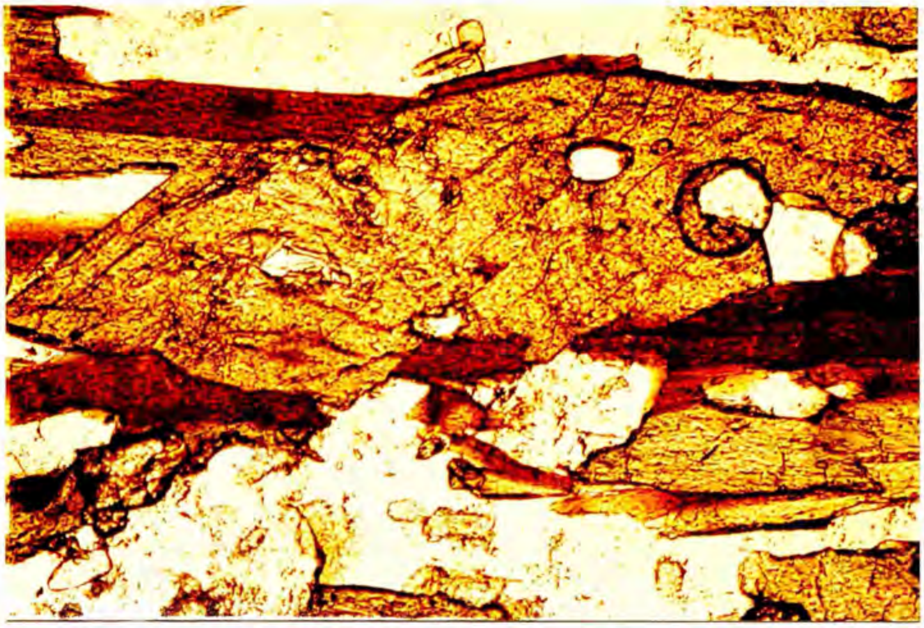


plate 103
photomicrograph of rare biotite within the amphibolite margin of a zoned calc-silicate band;note that biotite appears to be overgrown by hornblende.
(plane polarised light, x 125)

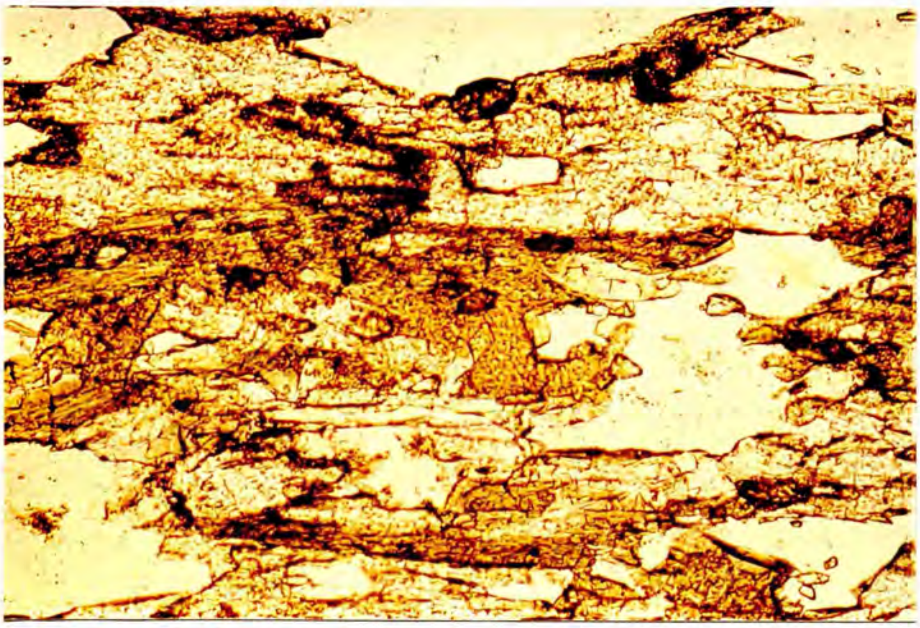


plate 104
photomicrograph of hornblende being replaced by clinozoisite in the central zone of a zoned calc-silicate band, Lower Bergsdalen Nappe.
(plane polarised light, x 125)

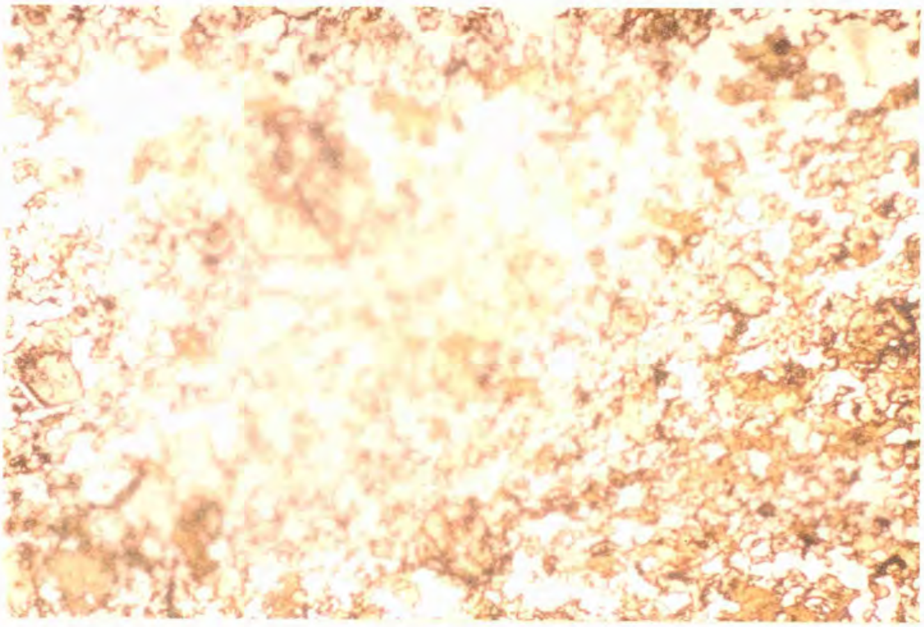


plate 105
photomicrograph of the central zone to a calc-silicate band, with overgrowing garnet, Lower Bergsdalen Nappe.
(plane polarised light, x 32)

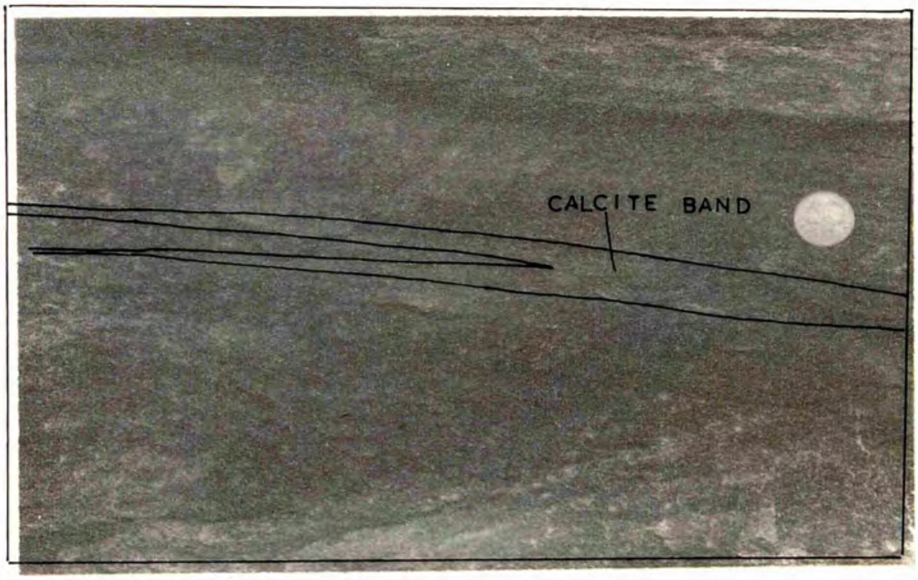


plate 106
isoclinally folded calcite band in the biotite gneiss (Banded Gneiss) Lower Bergsdalen Nappe.
(diameter of coin : 2.1 cms.)

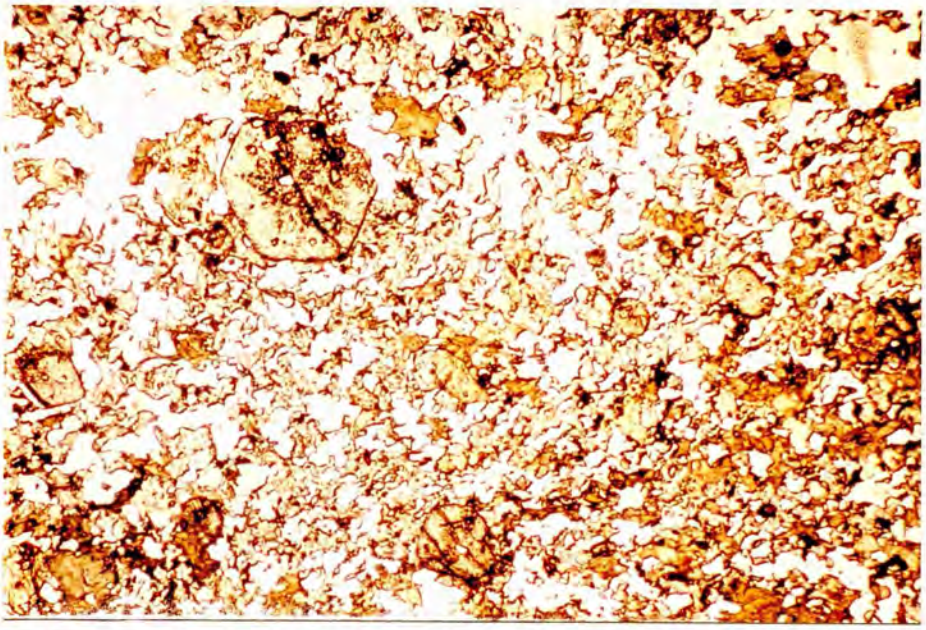


plate 105
photomicrograph of the central zone to a calc-silicate band, with overgrowing garnet, Lower Bergsdalen Nappe.
(plane polarised light, x 32)

plate 106
isoclinally folded calcite band in the biotite gneiss (Banded Gneiss) Lower Bergsdalen Nappe.
(diameter of coin : 2.1 cms.)

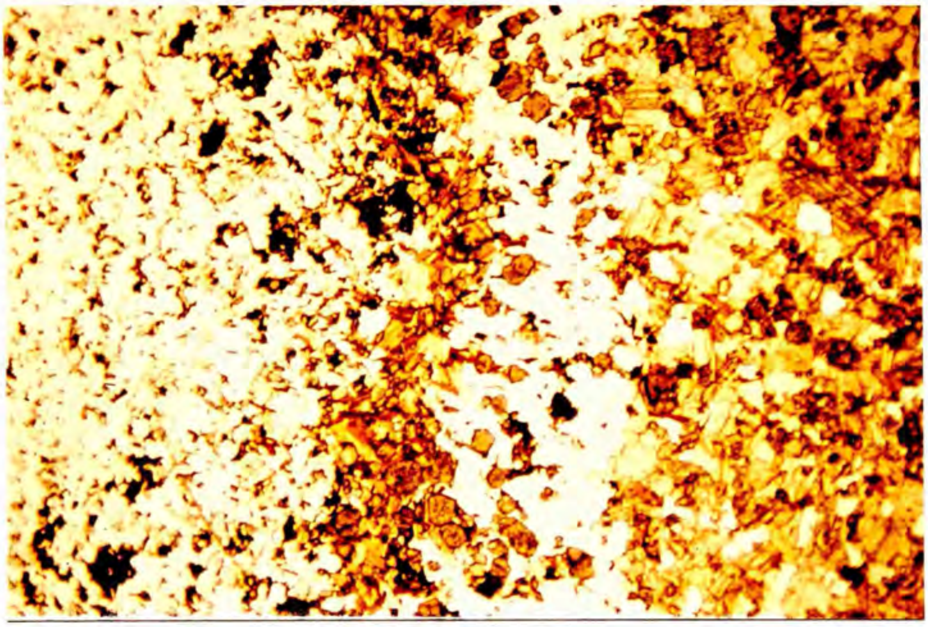


plate 107
photomicrograph of zones 1, 2, 3, 4 in a calcite band, Lower Bergsdalen Nappe.
(plane polarised light, x 12.5)

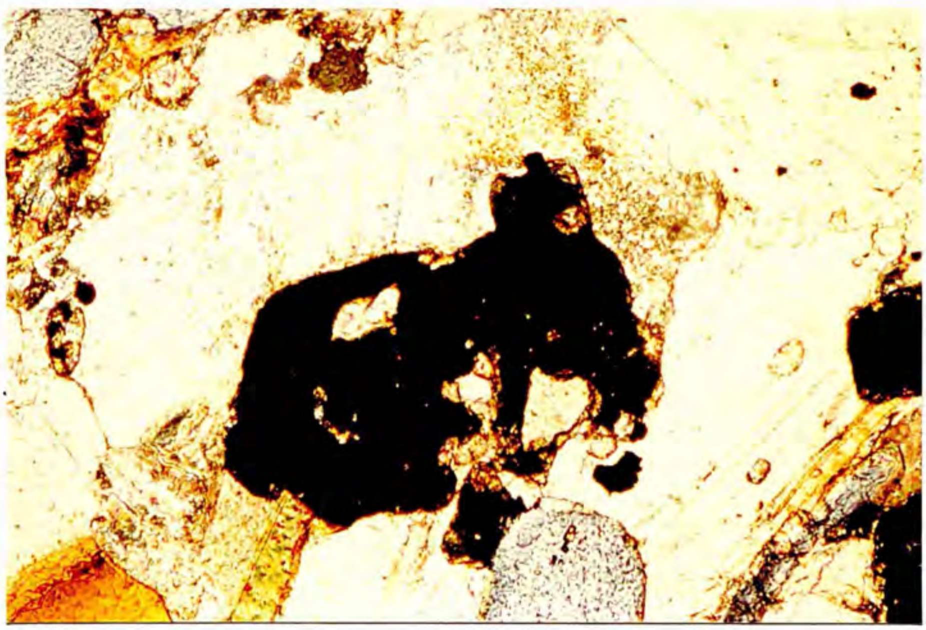


plate 108
photomicrograph of calcite included within a garnet (zone 4) in the zoned calcite bands of the Lower Bergsdalen Nappe.
(cross polarised light, x 125)

plate 109

margin of the net veined complex, showing the progression from Banded Gneisses, through intrusive granite, to green calc-silicate xenoliths, Lower Bergsdalen Nappe.

(diameter of lens cap : 5.8cms.)

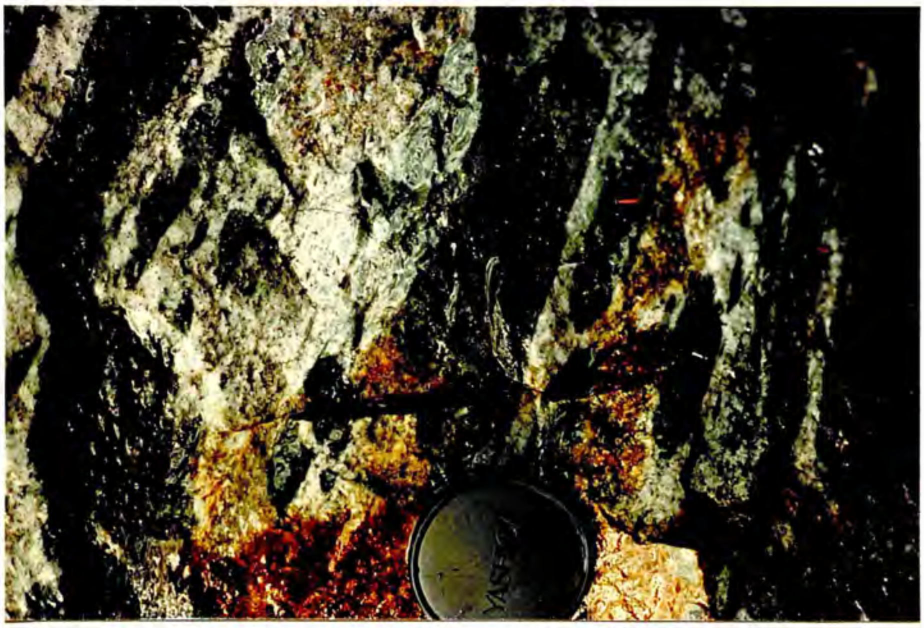


plate 110

calc-silicate xenoliths within the D1 granite of the Lower Bergsdalen Nappe; note the variable biotite content of the xenoliths.

(diameter of lens cap : 5.8 cms.)

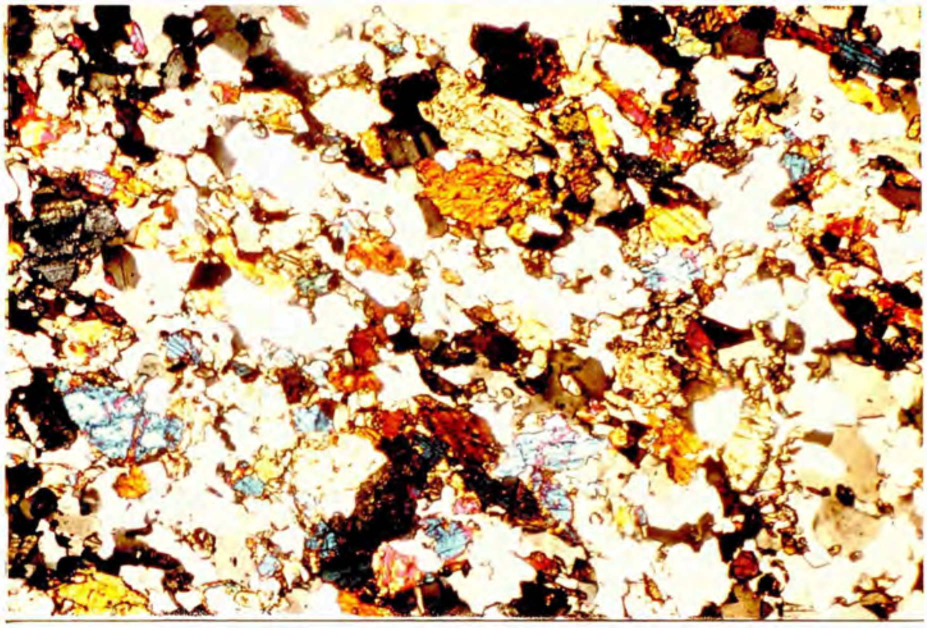


plate 111

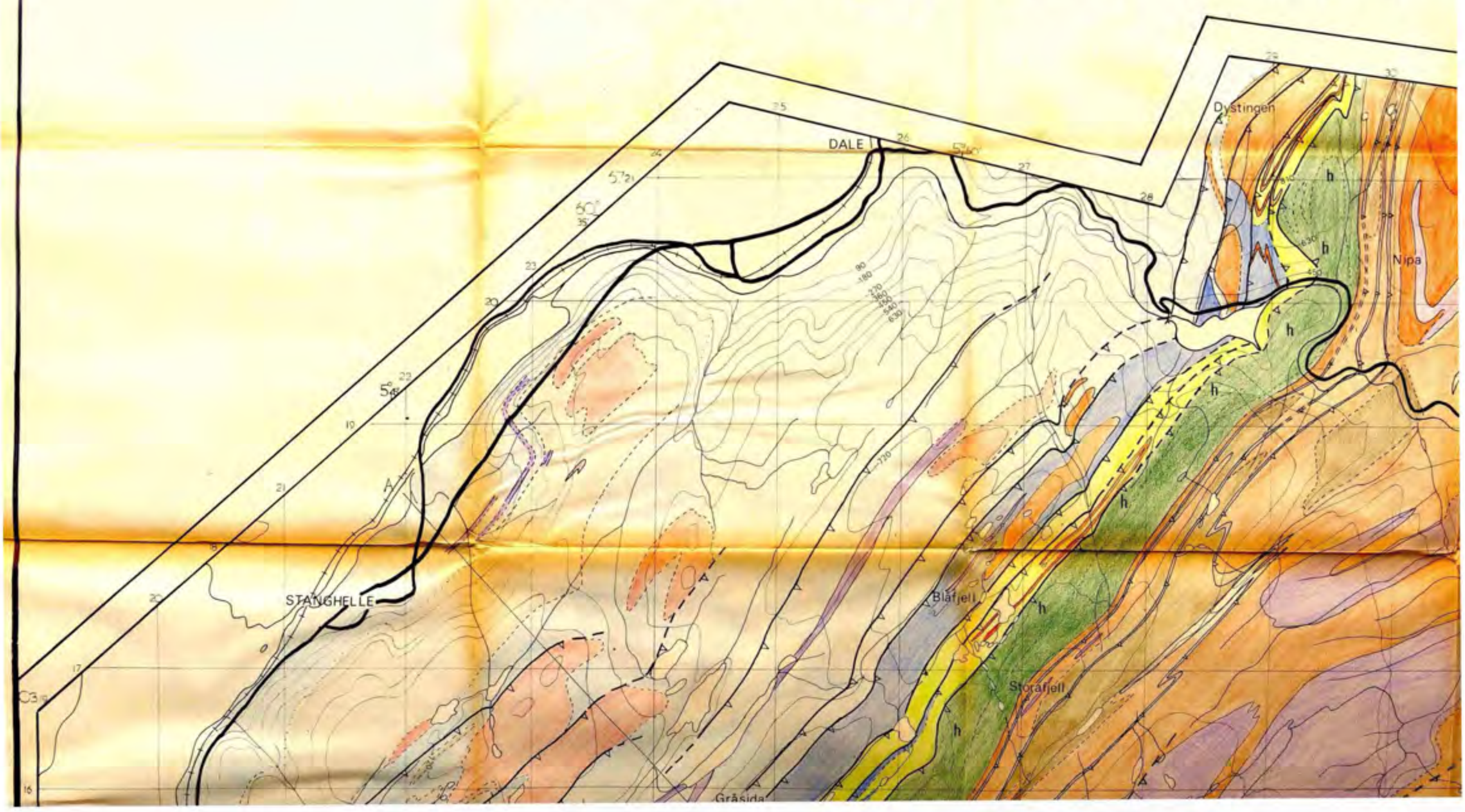
photomicrograph of a calc-silicate xenolith, with a high percentage of diopside; Lower Bergsdalen Nappe.
(cross polarised light, x 32)

plate 112

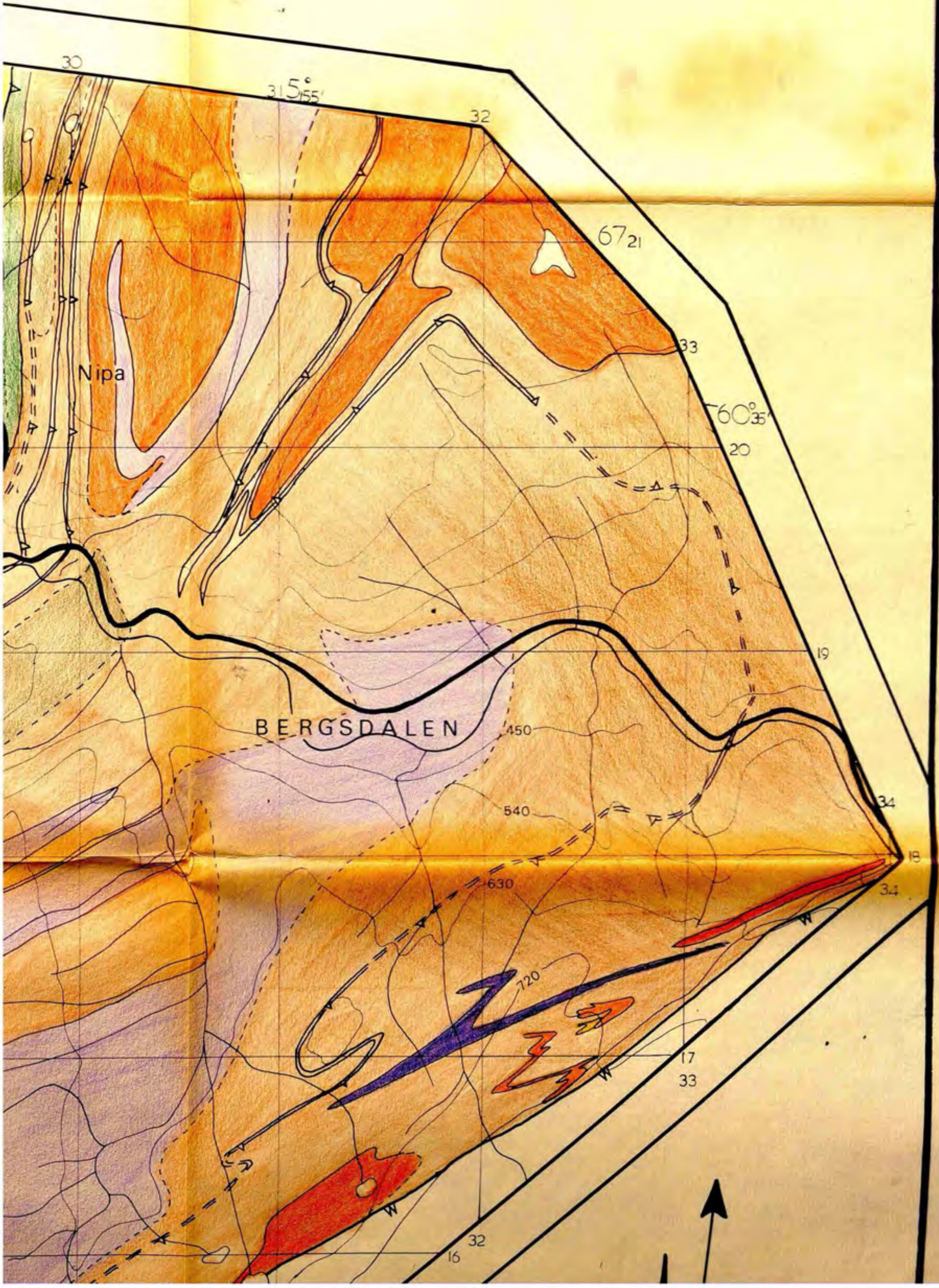
photomicrograph of green diopside within a calc-silicate xenolith, partially altered to pale green actinolite.
(plane polarised light, x 32)

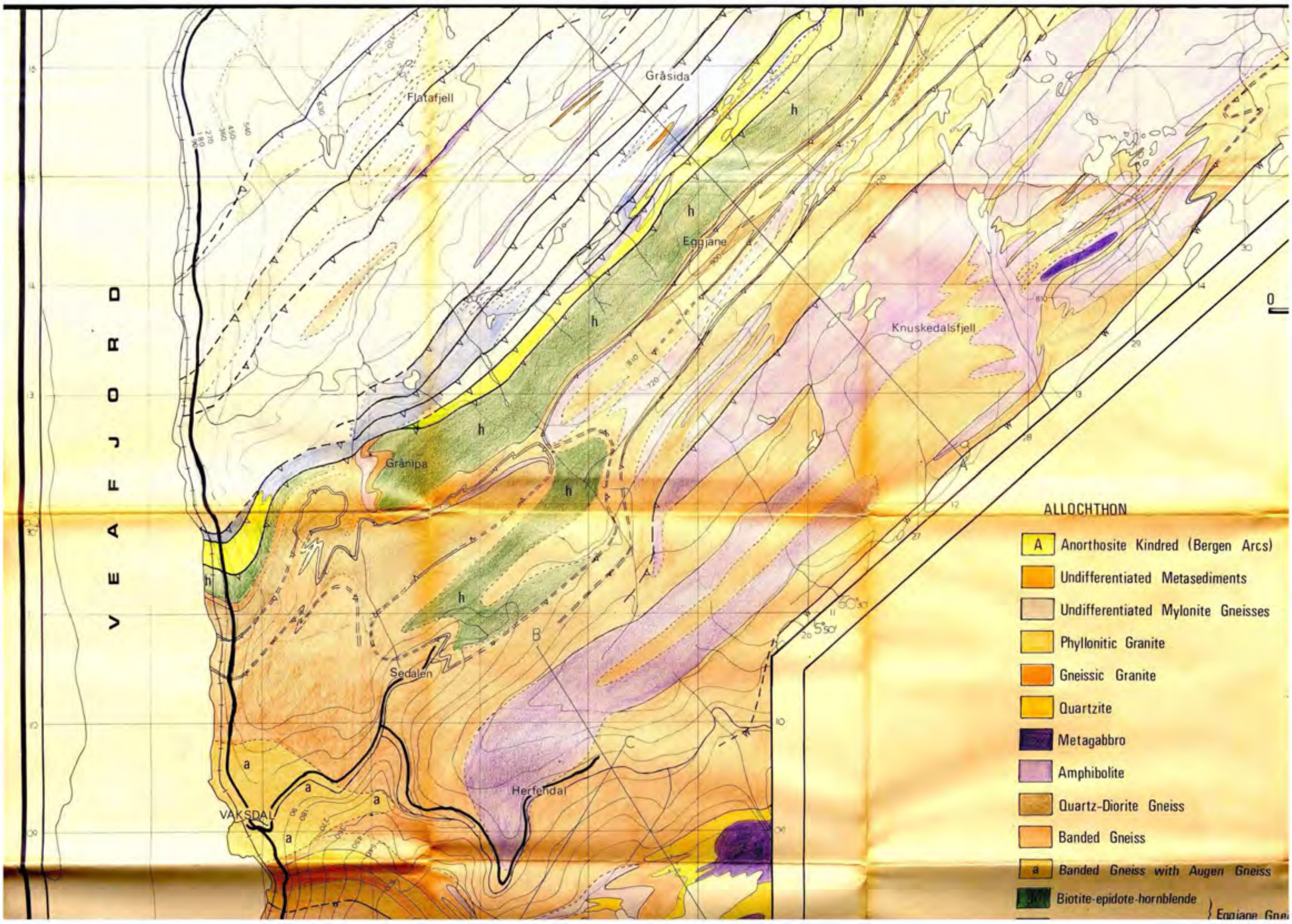
MAP 1

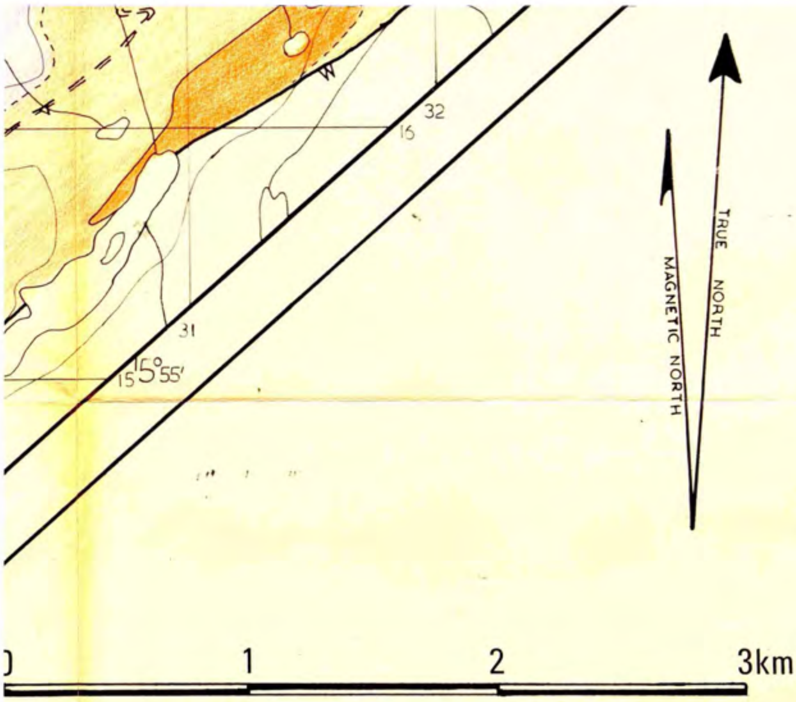
THE GEOLOGY OF THE BERGSDALEN A
CENTRAL SOUTH WEST NORWAY



N AREA
AY


30
31
5°55'
32
67
21
33
60°35'
20
Nipa
19
BERGSDALEN
450
540
630
720
34
18
34
17
33
32
16


VEAFJORD
Flatafjell
Gråsida
Eggjane
Knuskedalsfjell
Granipa
Sedalen
Herfendal
VAKSDAL
ALLOCHTHON
A Anorthosite Kindred (Bergen Arcs)
Undifferentiated Metasediments
Undifferentiated Mylonite Gneisses
Phyllonitic Granite
Gneissic Granite
Quartzite
Metagabbro
Amphibolite
Quartz-Diorite Gneiss
Banded Gneiss
a Banded Gneiss with Augen Gneiss
Biotite-epidote-hornblende

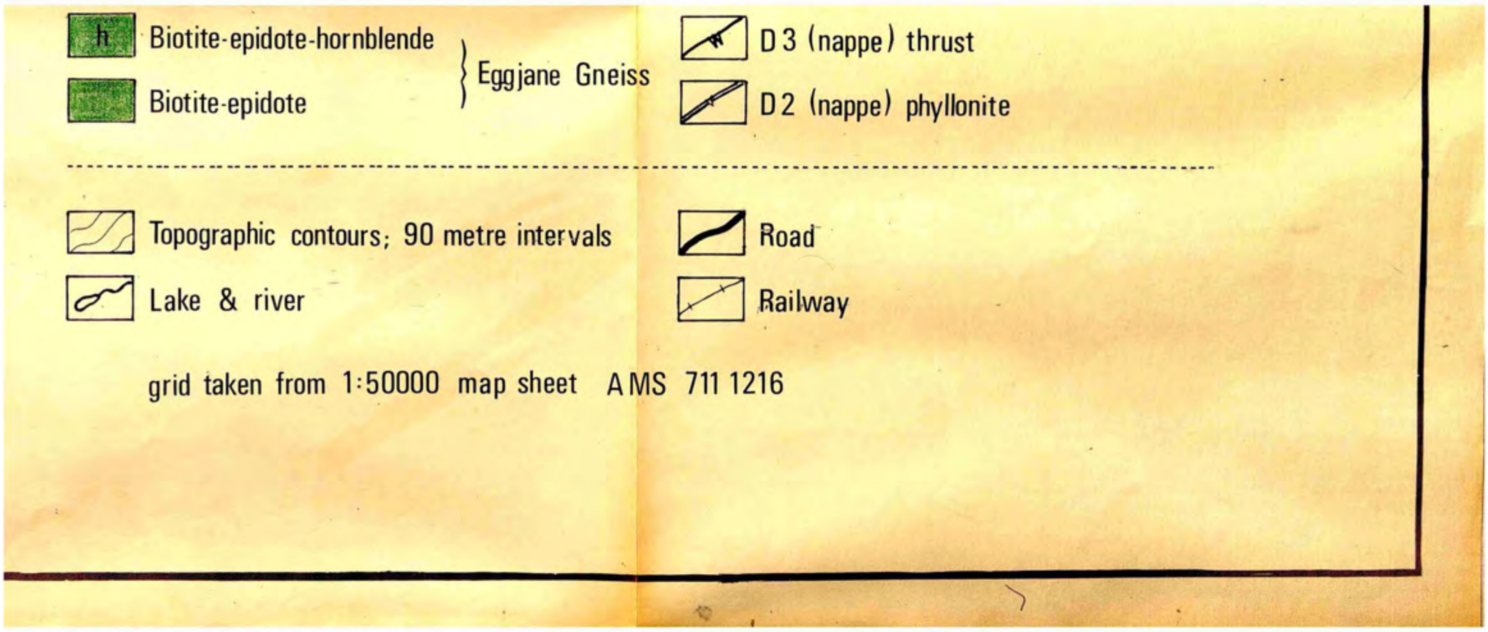


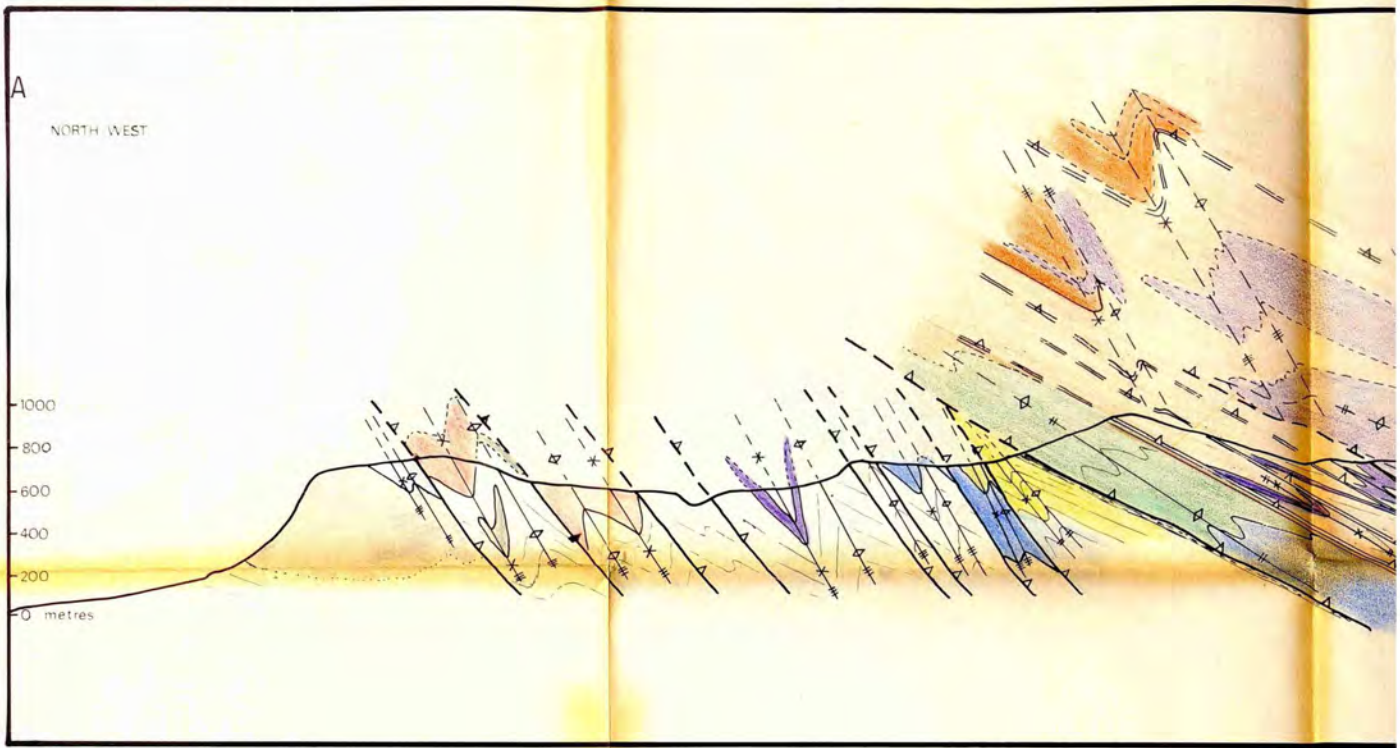
AUTOCHTHON & PARAUTOCHTHON

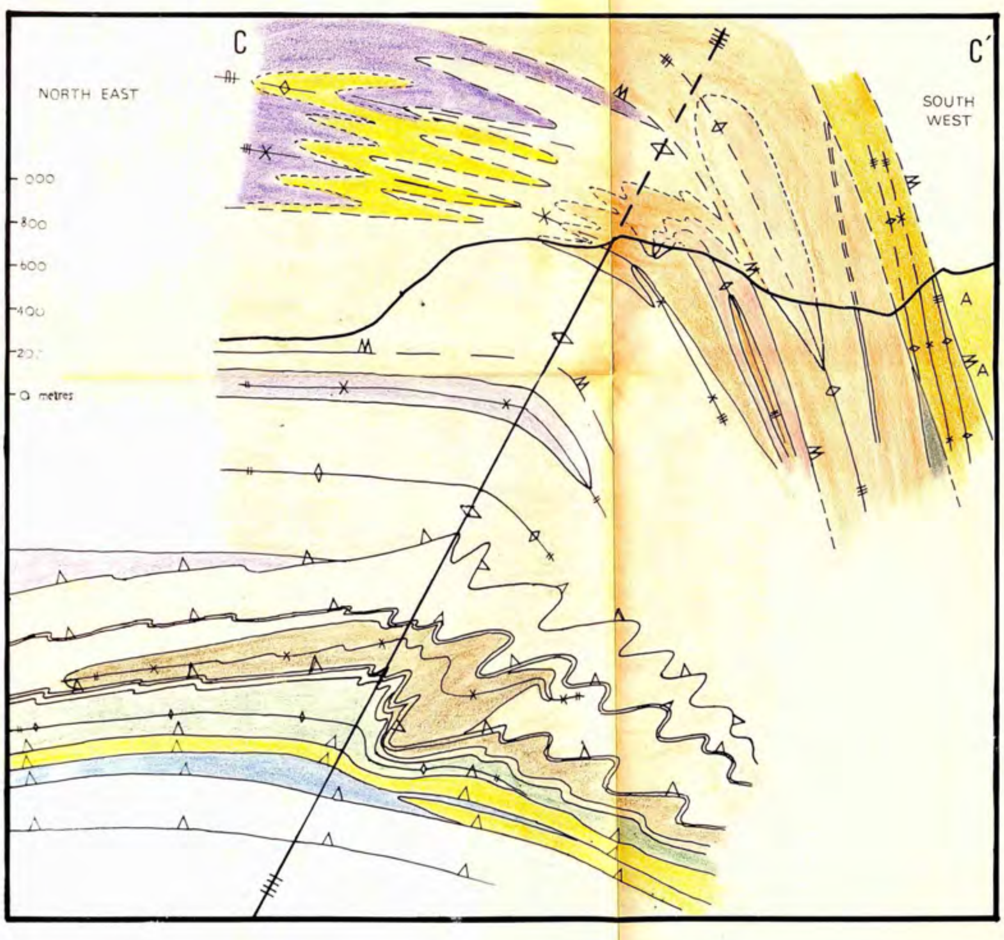
- Mixed Gneisses
- Flattened Quartzofeldspathic & Epidote Gneisses
- D2 Gneissic Granite
- D1 Gneissic Granite
- Amphibolite
- Hornblende-quartzofeldspathic Gneiss
- Quartzofeldspathic Gneiss

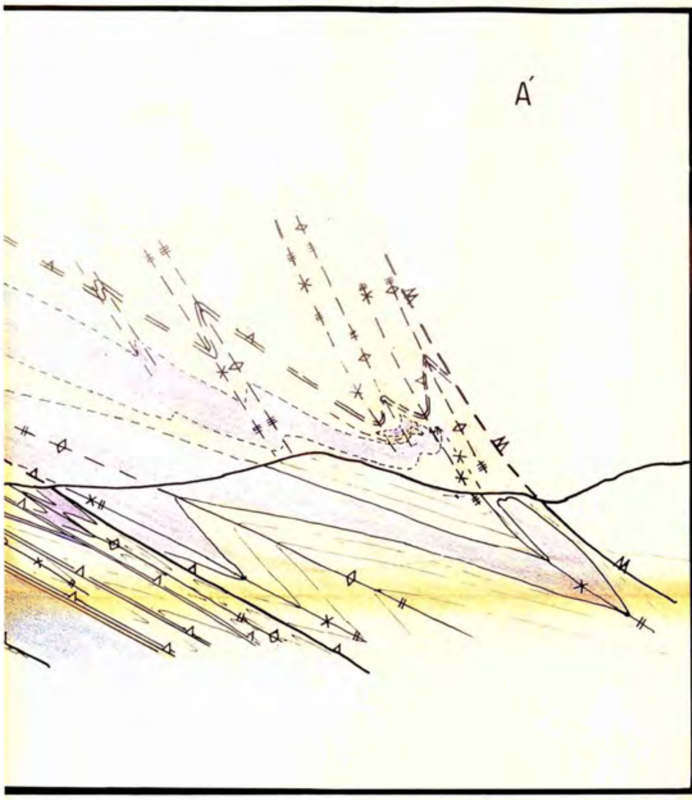
- Lithological boundary
- Lithological boundary, location uncertain
- D3 (basement) thrust
- D3 (nappe) thrust

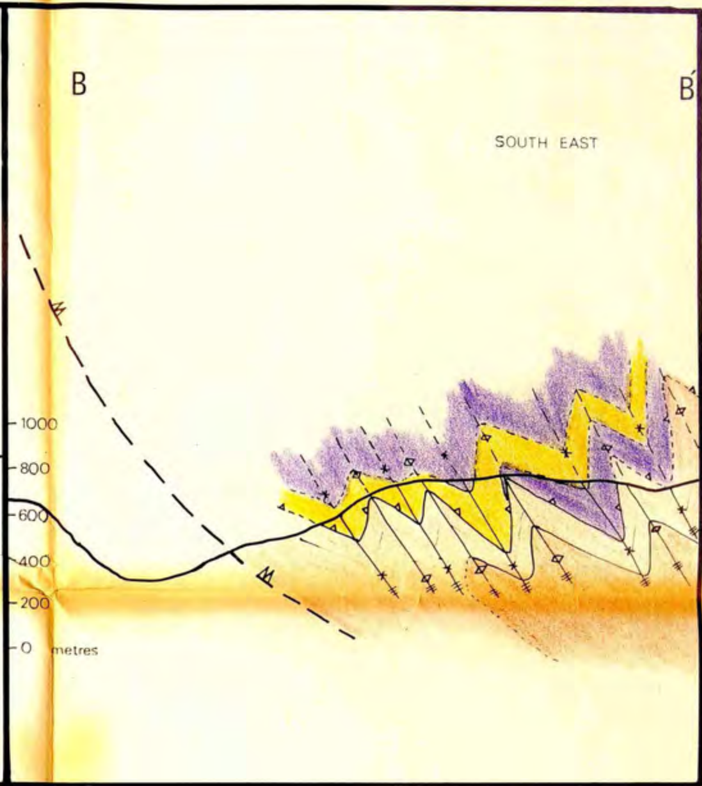

Blåfjell
B'
C'
A
A
A
5°45'
Biotite-epidote-hornblende
Biotite-epidote
Eggjane Gnei
Topographic contours; 90 metre intervals
Lake & river
grid taken from 1:50000 map sheet A


h
Biotite-epidote-hornblende
Biotite-epidote
Eggjane Gneiss
D 3 (nappe) thrust
D 2 (nappe) phyllonite
Topographic contours; 90 metre intervals
Lake & river
Road
Railway
grid taken from 1:50000 map sheet AMS 711 1216


A
NORTH WEST
1000
800
600
400
200
0 metres


C
C′
NORTH EAST
SOUTH
WEST
800
600
400
0 metres
A





GEOLOGICAL CROSS SECTIONS

NO VERTICAL EXAGGERATION

LEGEND AS FOR MAPS 1 AND 2

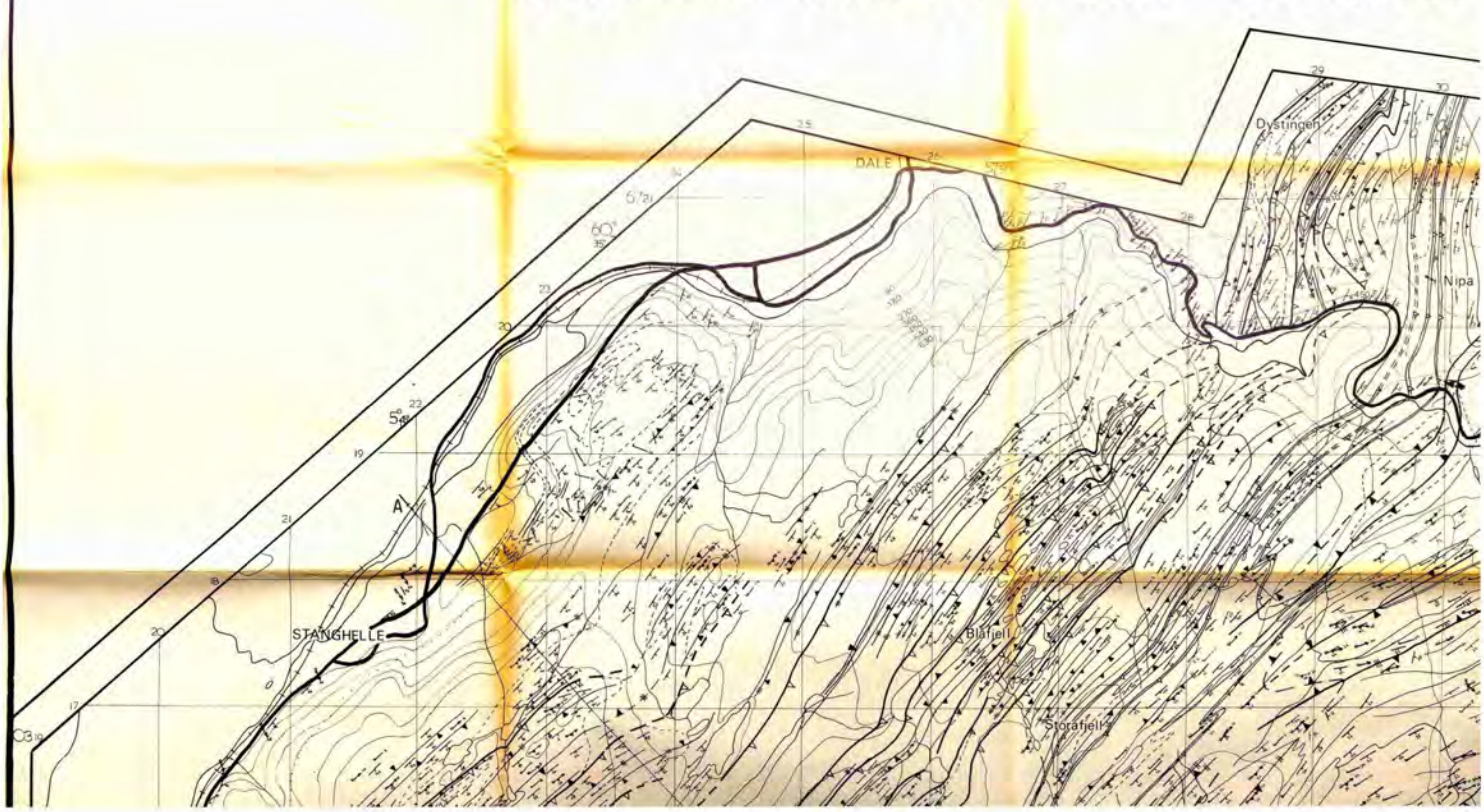
LINES OF SECTIONS ON MAP 2

SCALE – 1:20000

0 1 2km

MAP 2

THE GEOLOGY OF THE BERGSDALEN
CENTRAL SOUTH WEST NORWAY

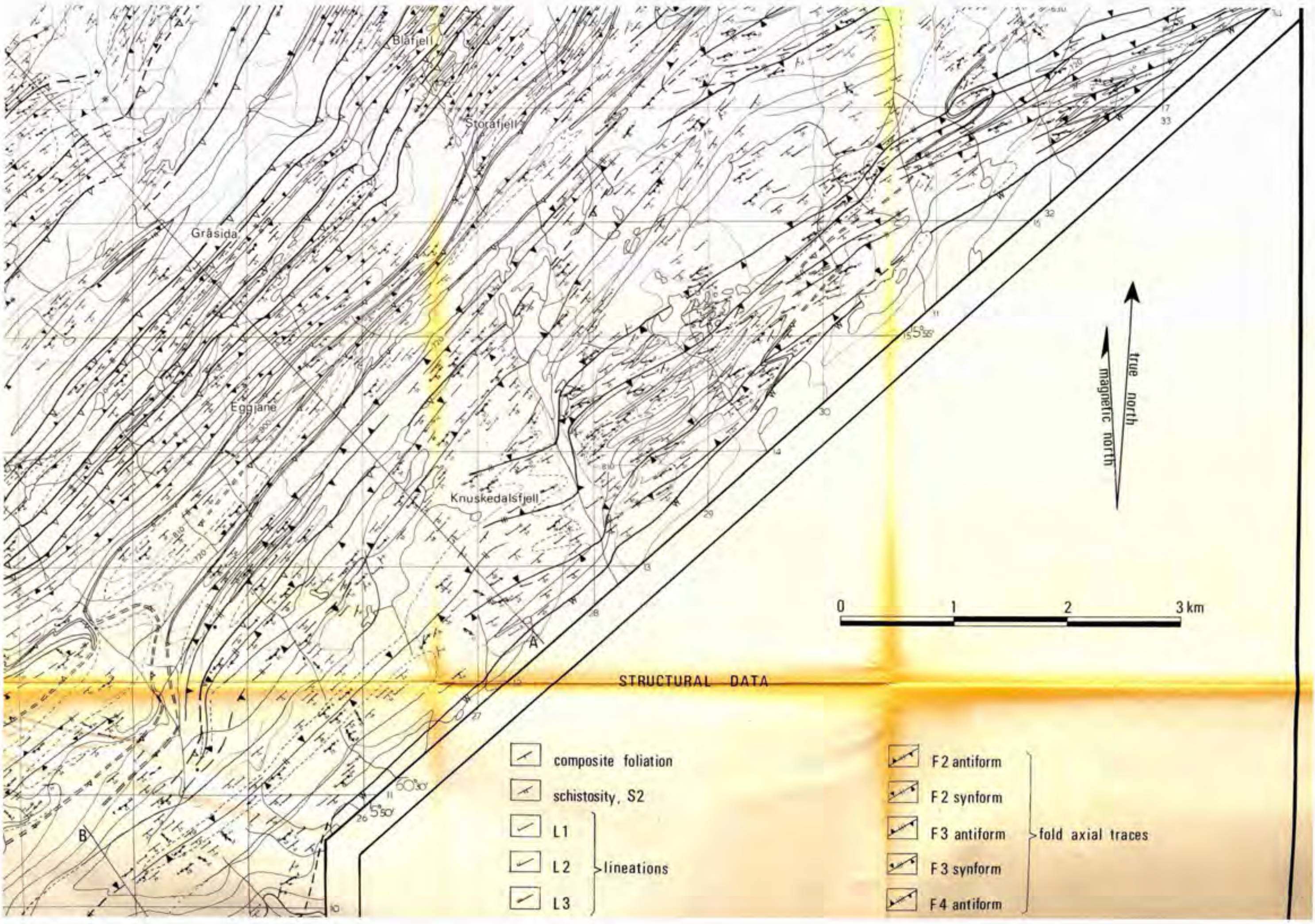


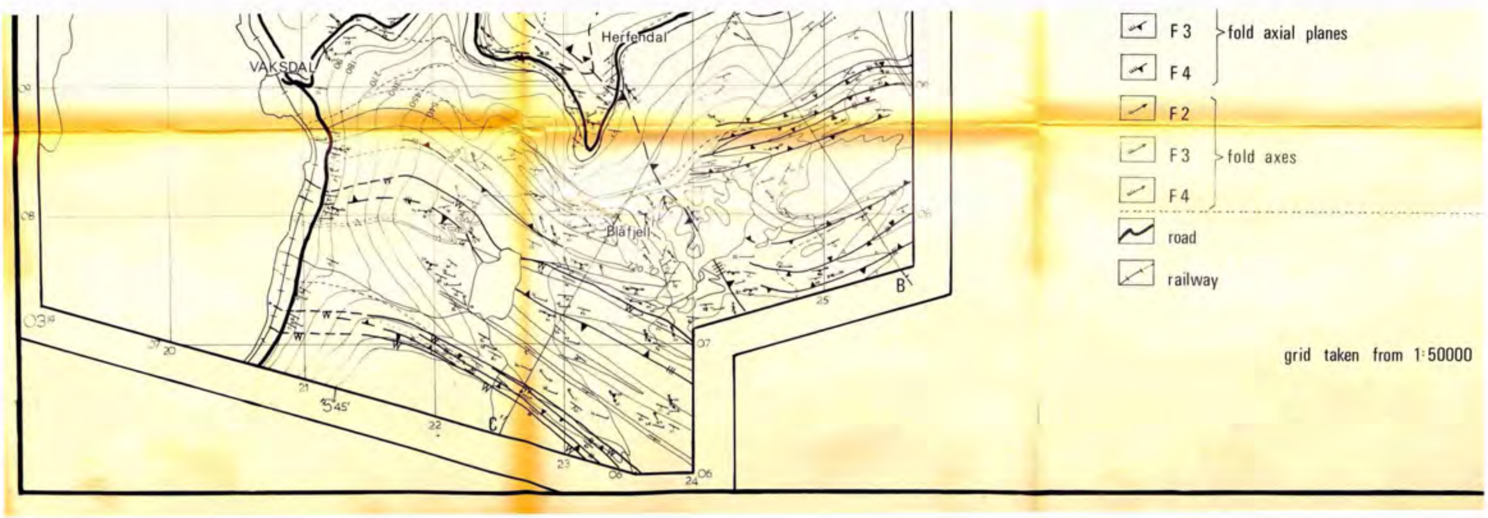
AREA

Y

31
5°
155'
32
67
21
33
60°
35'
20
Nipa
19
BERGSDALEN
450
540
630
720
34
18
34
17
33

VEAFJORD
Storåfjell
Gråsida
Flatafjell
Eggjane
Knuskedalsfjell
Grånipa
Sedalen
Herfendal
STRUCTURAL DATA
composite foliation
schistosity, S2
L1
L2
L3
lineations
F2
F3
fold axial planes


Blåfjell
Storafjell
Gråsida
Eggjane
Knuskedalsfjell
A
B
60°50'
5°50'
5°55'
true north
magnetic north
0
1
2
3 km
STRUCTURAL DATA
composite foliation
schistosity, S2
L1
L2
L3
lineations
F2 antiform
F2 synform
F3 antiform
F3 synform
F4 antiform
fold axial traces


VAKSDAL
Herfendal
Blåfjell
B
C
5°45'
F 3
F 4
fold axial planes
F 2
F 3
F 4
fold axes
road
railway
grid taken from 1:50000

F 3 } fold axial planes
F 4

F 2
F 3 } fold axes
F 4

D2 phyllonite (nappe)

D3 thrust (nappe)

lithological boundary

lithological boundary, location uncertain

line of section

road

railway

topographic contours at 90 metre intervals

river & lake

grid taken from 1:50000 map sheet AMS 711 1216