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THE BASAL GNEISSES AND BASEMENT CONTACT OF THE HESTBREPIGGAN AREA, NORTH JOTUNHEIMEN, NORWAY

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CONTENTS

Abstract.

Petrographic, modal, chemical, X-ray and structural studies have been made on rocks from a mapped area of Basal Gneisses and Basement contact in a glaciated region in the North Jotunheim mountains.

Precambrian Basal Gneisses were deposited, intruded by basic bodies, folded about E—W axes, metamorphosed in the almandine-amphibolite facies, pegmatised, intruded by foliated granite, elevated and eroded before the deposition of Eocambrian (and younger) sediments.

Subsequently, these sediments were thrust (gravity glided?) from the W-WNW, folded and lineated and metamorphosed in the greenschist facies (Caledonian events). Retrograde metamorphism of the underlying Basal Gneisses occurred at this time. Latterly, the area has been dislocated by tear faults, especially the 40°-trending, sinistral, Briedalen tear fault, with which are associated sheared, retrograded, schistose gneisses, quartzite bodies, joints and a quartz-epidote-clinochlore vein mineral assemblage.

Introduction.

Location and topography.

The Hestbrepiggan area (maps 1, 2 and 3) forms part of the northern Jotunheim mountains of southern Norway, and occupies portions of sheets 1518/I, II, III, and IV of the AMS M711 series 1 : 50,000 topographical maps of Norway (from which all grid references quoted are taken).

The topographic backbone of the area is the Hestbrepiggan ridge; this, ideally, is a sharp arête striking E to ENE with peaks of the «Matterhorn type» up to and over 2100 metres above sea-level. The eastern and western ends of this ridge drop down to broad, high plateaux (e. g. Storberka at approximately 1950 metres) and convex peaks (e. g. Merrahøe at 1727 metres). The shape of the ridge has been largely controlled by the development of both north and south flowing flanking glaciers, which may loosely be divided into three types. First, large cirque glaciers (e.g. Høybreen) secondly, small, valley glaciers (e.g. Gjeitaabreen), and, thirdly, small, plateaux ice-caps (e.g. Hestbreen). The side and back-walls of these glaciers may be up to several hundreds of metres high and often form excellent sections through the geology of the area. All glaciers and snowfields have recently retreated considerably and the topographic maps of the area thus have quite large «errors».

To the north and south of the Hestbrepiggan ridge occur low plateaux (1200—1500 metres); these are characterised by numerous lakes and meandering, meltwater streams which finally plunge to the lowest levels in the area (1000 metres and below) in the deep and steep sided U-shaped valleys of Høydalen, Lundadalen and Nørstedalen. It is of interest that the Hestbrepiggan area forms part of the watershed between two very large drainage systems. That of Sogndal to the south-west drains to the North Sea, and that of Ottadalen—Gudbrandsdalen to the Oslofjord.

The area is naturally bounded to the north by the E to ENE-trending glaciated, 2000 metres-plus peaked ridge, Hålåtinden, and the valley Lundadalen, and to the south occurs the NE trending valley of Høydalen.

The NE grain of the southern part of the area is controlled by the strike of the various metasedimentary rocks. Topographic development in the Basal Gneisses to the north has also been controlled by lithology and structure, but perhaps to a less obvious extent. For example, the peaks of the Hestbrepiggan ridge are mainly developed in foliated granite which has an approximately E-W strike. The control of Briedalen and Svartdalen, among other valleys, by tear faults is clear (map 3).

Where not covered by ice, snow or water the rocks of the area are usually well exposed. At higher altitudes much frost shattering has produced large block-fields, and both the high and low plateaux are partly covered with glacial debris in which are developed active permafrost features (polygons, steps, stripes, etc.) In other parts, however, rock pavements have been swept clean, and in these and circum-glacial sections the exposure is commonly complete.

Geological Setting.

The Hestbrepiggan area lies on the southern margin of the NW Basal Gneiss area of southern Norway (see Strand, 1949, Kolderup, 1952, and Gjelsvik, 1953, for general descriptions and reviews of the literature of the area). To the south occurs the NE-trending Jotunheimen «fosse of folding» which contains a great thickness of Precambrian and Lower Palaeozoic (meta) igneous and metamorphic rocks (Goldschmidt, 1912, Smithson, 1963). These, the Bergen-Jotun Kindred, occur in the fartravelled Jotun Nappe whose nearest outcrop is several kilometres to the south of the Hestbrepiggan basement.

Under this nappe occurs an Eocambrian-Lower Palaeozoic «mio-geosynclinal» (Strand, 1961) succession, the lower part of which forms the southern boundary of the Hestbrepiggan basement. Strand (1951) has presented evidence for the existence of another, «Otta» Nappe below the Jotun Nappe in the eastern part of the Jotunheim area. This nappe contains a succession of Lower Palaeozoic metasediments and metavolcanic rocks which may correlate with at least part of a similar succession to the south of the Hestbrepiggan area as here defined (Banham and Elliott, 1965).

Existing conclusions regarding the Hestbrepiggan and immediately surrounding areas, are based largely on the work of Rekstad (1914), who mapped a large area on a small scale, and on more recent work by Landmark (1949) in Lusterdalen and upper Bøverdalen, including a small portion of the presently defined Hestbrepiggan area. Possibly the most important single conclusion of Landmark was that the metasediments rest with discordance upon a «plinth» of basement.

Nearby Basal Gneiss areas have been described by Strand (1949) and Skjerli (1957). In addition to the preliminary account of the Hestbrepiggan area (Banham and Elliott, 1965), a detailed study has been made of vein mineralisation in relation to a basement fault (Banham, 1966(a)), and the application of a rapid version of Barth's felspar geothermometer method has been described (Banham, 1966 (b)). Of the metasediments higher in the succession, the Holleindalen Greenstone Group has been studied in detail by Elliott and Cowan (1966). The work of other Nottingham geologists in the area remains in thesis form (Sotaseter area, Shouls, 1958; Nettoseter area, Cowan, 1966; material from both these areas is to published shortly).

The writer was introduced to the area as an undergraduate in 1957 and 1958 by Dr. R. B. Elliott. Work on the Hestbrepiggan area proper began in 1959 and continues (1967). The altitude of the area restricts the field season to a maximum of 10 summer weeks only, and mapping was carried out from a number of camps sited at various localities throughout the area. This method of work would not have been possible in glaciated, mountainous country without the assistance of several one-time under-and post-graduates of the University of Nottingham.

In this paper attention will be confined principally to the Basal Gneisses. The lower, more northerly, parts of the metasedimentary succession will be briefly treated in order that a discussion of the basement contact may be included. A full account of the metasediments will shortly appear. A map of the area is presented, together with the results of various laboratory studies. (Mapping was carried out on a scale of 1 : 18,500, on maps photographically enlarged from the 1 : 50,000 edition; air photographs were used in an ancillary fashion.)

Field relations and petrography.

I — Basal gneisses. Introduction.

The Basal Gneisses in the Hestbrepiggan area are predominantly granitic in composition, although considerable variations in mineral proportions and textures have been observed. Nine main lithologies have been recognised and described: —

biotite gneiss	foliated granite (and granite agmatite)
augen gneiss	schistose, muscovite gneiss
amphibolite	schistose, chlorite gneiss
pegmatite	flaggy, muscovite gneiss
	quartzite.

Biotite Gneiss

This is the fundamental lithology of the Hestbrepiggan area; other Basal Gneiss lithologies are either intruded into or formed by the shearing of biotite gneisses. The wide outcrop of these gneisses is divided naturally into northern and southern areas by the outcrop of the Hestbrepiggan granite which forms the highest ridge of the area.

The essential minerals are felspars, quartz and biotite and although granitic gneisses predominate, granodioritic types also occur. Epidote and muscovite are of some importance, whereas magnetite, garnet, sphene, orthite and apatite occur in only small amounts. The normal appearance of biotite gneisses is granular to sub-schistose with biotite foliae occurring throughout the rock. More massive gneisses with quartz and felspar enriched bands are less common. Felspar and quartz are commonly somewhat platey in the biotite foliation. Grain size varies from fine to coarse (0. 1—6 mm) although markedly porphyroblastic rocks are not common, and minerals rarely show good crystal form. (See photos. Nos 1 and 2).

The largest grains are those of K-felspar (microcline) and these commonly show perthitic intergrowth with lamellae of albite. Smaller grains show mainly patch and partial rim perthites. K-felspar is absent from a small proportion of granodioritic biotite gneisses usually found in the immediate vicinity of amphibolite bodies.

Two types of plagioclase are developed in all biotite gneisses. Quite well formed, prismatic grains up to 1.5 mm in length and twinned on the Albite, and to a lesser extent, the Pericline Laws, are normally extensively replaced by fine-grained epidote and other «saussurite» minerals (calcite, sericite, ?). A composition of An 5 % has been determined optically for this primary plagioclase. Secondary plagioclase occurs mainly as untwinned, perthitic intergrowths with K-felspar.

Myrmekitic intergrowth between quartz and albite is common, particularly at the margins of K-felspar grains. It has been noted (cf Chayes 1952b) that the number and size of perthitic lamellae increase towards shear zones, where, moreover, the lamellae are often deformed.

The finer grained groundmass of the biotite gneisses is composed mainly of quartz grains (0.1—0.5 mm) which showing sometimes extreme, undulose extinction. (K-felspar also commonly shows this evidence of straining). Some, much larger (1—2 mm) grains of quartz appear virtually unstrained, however.

Photo No. 1. Typical, banded, biotite gneiss.

The relatively high biotite mode (5—28 %, fig. 1) of these rocks distinguishes them from the other acid gneisses of the area. Optical properties indicate a moderately iron rich biotite (X medium brown, Y, Z dark brown to opaque; perfectly uniaxial; chemical analyses p. 71). Biotite is commonly partly enclosed by K-felspar and incipient chloritisation is widespread.

Spec.no.	Quartz	K-felspar	Plagioclase	Biotite	Epidote	Muscovite
14	40	20	10	25	5	—
15	42	23	21	5	6	3
48	41	9	15	12	10	12
50	45	10	17	12	5	11
2	43	17	12	2	26	tr
3	41	19	12	17	9	1
4	36	—	20	31	13	—
81	47	17	10	17	8	2
33	43	25	15	13	4	—
23	28	35	9	24	3	—
27 *	17	29	7	28	19	—

Fig. 1. Modal analyses of biotite gneisses (— augen gneiss). Specimen localities: See map 1.* (All modal analyses conducted after manner of Chayes, 1956; Standard deviation2 % ,or less).

Epidote (3—26 %) is most important in the granodioritic gneisses, where, as elsewhere, it occurs as small, prismatic grains (under 0.2 mm) usually replacing primary plagioclase. Faint pleochroism from colourless to greyish-green, inclined extinction in transverse section and up to third order red birefringence colours indicate a moderately iron rich, monoclinic epidote.

Muscovite (0—12 %) is absent from some few, entirely unsheared, biotite gneisses. Towards any of the numerous shear zones, however, muscovite becomes progressively more abundant along planes which cut and disrupt other minerals. Felspares, in particular, are replaced by muscovite.

Of the remaining accessory minerals magnetite, sphene and orthite (usually with a metamict core and an epidote rim) are present in small quantities, often in association with biotite, whereas apatite and garnet (almandine?) occur in very small quantities, mainly in the granodioritic gneisses.

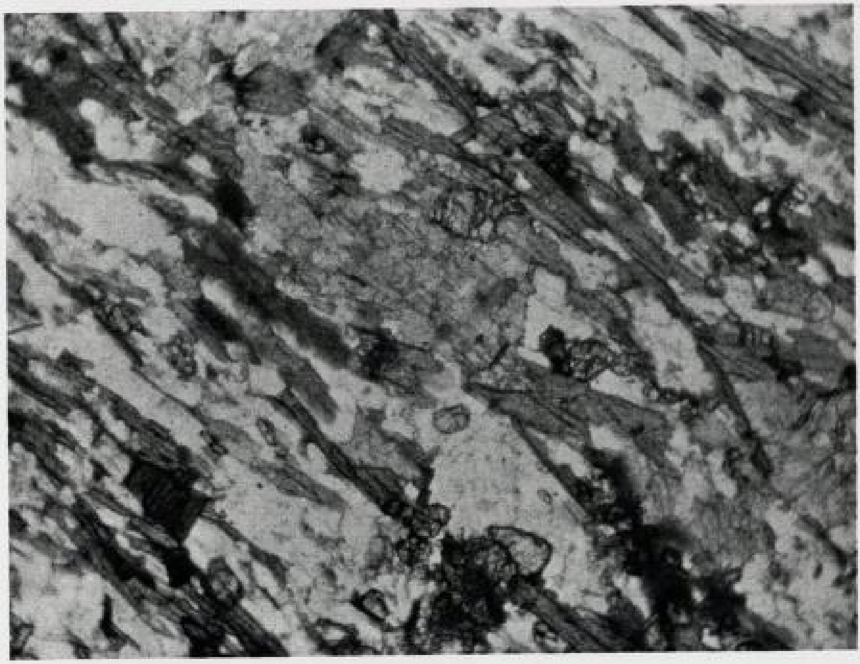


Photo No. 2. Thin section of biotite gneiss ; biotite, quartò, K-felspar, plagioclase, epidote. (x35, plane polarised light).

It seems clear that all minerals and textures did not develop simultaneously. The main event appears to have been the development of the foliation and the syn- or post-(tectonic?) crystallisation of the readily recognised primary minerals-quartz, K-felspar, primary plagioclase, and biotite (with, probably, garnet, orthite, sphene and apatite).

Four, possibly penecontemporaneous re-crystallisations have subsequently occurred. First, a syn- or post-(late) tectonic crystallisation of muscovite along shear planes, together with straining, disruption and replacement of primary minerals. Secondly, replacement of primary minerals by epidote, chlorite (etc?), possibly associated with, thirdly, a degree of recrystallisation of the alkali-felspar. Fourthly, and apparently after all tectonic events, occurred the recrystallisation of unstrained quartz.

All these secondary recrystallisations could have occurred during and/or after a single period of essentially brittle deformation and retrograde metamorphism, although a more complicated history is, of course, possible.

Augen Gneiss

Irregular, lensoid outcrops of augen gneiss occur throughout the biotite gneiss areas. The contacts between the two types of gneiss are everywhere gradational and the foliation of the one passes undeformed into the other. Toward the augen gneiss, biotite gneiss becomes more biotitic, less generally felspathic, and eventually develops small, lensoid or pipelike, principally K-felspar augen which increase in size into the augen gneiss proper. The largest augen measure up to 5 × 2.5 × 15 cms., and grains within the augen commonly exceed 10 mm. In the groundmass, although biotite grains are often of similar, large size, the quartz, felspar, epidote, etc., are usually much finer (0.1—3 mm). (See photo. No. 4).

Mineralogically (modal analysis fig. 1) the augen gneisses are rather similar to the biotite gneisses. Here, however, K-felspar is best developed in the wide, core regions of the augen, where several large grains not in optic continuity may occur. Microcline twinning and albite lamellae are ubiquitous. Cracks, and sometimes pronounced undulose extinction are commonly seen. The narrower, outer rim of each augen consists mainly of strained quartz, and similar grains are an important part of the surrounding groundmass, although lenses of unstrained quartz also occur.

Plagioclase, which, as in the biotite gneisses, occurs as both primary and secondary grains, is relatively unimportant in the augen, except as perthite lamellae. Similarly, biotite is virtually confined to the groundmass, controlling its rather schistose nature.

Epidote replaces primary plagioclase in small prisms, and muscovite, sphene, magnetite, orthite and apatite also occur.

The history of crystallisation of the augen gneisses must be rather similar to that of the biotite gneisses, with a main, primary crystallisation of felspars, quartz, biotite (etc), followed by secondary recrystallisations of epidote, chlorite, muscovite, alkali felspar (slight) and unstrained quartz. The segregation and crystallisation of the augen would appear to be a primary feature.

Amphibolite.

Bodies of amphibolite within the larger outcrop of the biotite gneisses occur particularly in the southern part of the area. The main portion of larger bodies consists of a massive hornblende rock, although a marginal, biotite rich, schistose facies is always present, and, in small bodies, may be the dominant, or only, lithology. The largest example, in lower Steindalen (462392) is broadly stock-like, measures 350 metres in maximum diameter and has a vertical extent of at least 80 metres. A few other bodies exceed 200 meters, but most are smaller than 50 metres in maximum diameter. Contacts between amphibolites and biotite gneisses are invariably sharp, and the foliation of the marginal, biotite schists in any amphibolite is conformable with the contact.

The amphibole which forms the main bulk of the central portion of each body is a prismatic common hornblende (possibly an iron rich hastingsite) with the following optical properties: X pale greenish brown, Y light olive green, Z dark olive green; $Z \wedge c$ $18° \pm 2$; birefringence up to second order yellow (0.031); length slow, 2V-moderate to large. Grains up to and over 2 cms. in length are common. In the marginal facies in particular this hornblende is replaced by often large, biotite grains (10 mm) to form schistose bands within the more massive amphibolite. The biotite is pleochroic from pale straw (X) to medium brown (Y, Z), possibly indicating a higher magnesium content than that in the biotites of the surrounding biotite gneisses. (See photo. No. 3).

Quartz is an important mineral (up to 25 %, fig. 2) in the marginal facies, where it occurs both as fine (under 0.1 mm) strain shadowed grains, and as larger (up to 0.5 mm) unstrained grains. «Spots» of quartz with plagioclase occur in an amphibolite from Høybreen (484442), and plagi-

Spec.no.	Hornblende	Biotite	Epidote	Plagioclase	K-felspar	Quartz
5	22	31	23	3	—	20
6	56	22	8	2	—	12
7	83	11	4	2	—	—
8	73	—	17	tr.	7	2
28	50	11	10	5	—	24
29	41	41	3	tr.	—	15
30	15	28	22	10	—	25
31	46	34	—	9	—	11

Fig. 2. Modal analyses of amphibolites. Specimen localities: See map 1.

oclase also occurs associated with quartz as saussuritised relicts (An 5 %) in the normal marginal facies.

Epidote, which is indistinguishable optically from that in the surrounding biotite gneisses, occurs as small grains and larger patches replacing hornblende, plagioclase (and biotite to a lesser extent, apparently) in both the marginal and central facies.

Of the remaining accessory minerals, K-felspar occurs in small quantities as stringers and amoeboid masses which enclose quartz, plagioclase and epidote in the marginal facies, and also penetrate into the hornblendic,

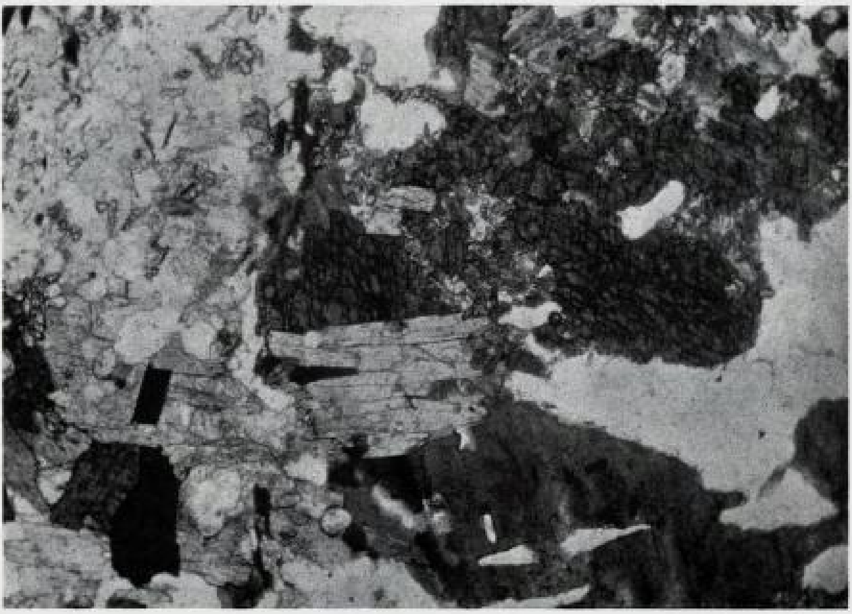


Photo No. 3. Amphibolite; hornblende replaced by biotite, quartz and epidote, which also replaces plagioclase, (x35, plane polarised light).

central portion. Magnetite occurs sporadically, showing particular association with hornblende, biotite and K-felspar. Calcite uncommonly replaces hornblende and may be an important part of the saussurite after plagioclase. Sphene occurs in the Steindalen (462392) and Lake Merrahøe (434387) bodies in particular, in grains up to 0.6 mm in length associated with biotite and epidote. Fine (under 0.1 mm) garnets are found associated with biotite in the Høybreen amphibolites, and chlorite commonly replaces hornblende in these latter, somewhat sheared bodies.

Hornblende appears to be the sole result of primary crystallisation. Subsequently, marginal hornblendes, especially, have been largely replaced by biotite which grew in association with quartz and plagioclase and, possibly, K-felspar. Later, hornblende, biotite and plagioclase have suffered replacement by a suite of other secondary minerals of which epidote is the most important, although chlorite and calcite also ocur. The presence of patches of unstrained quartz is, presumably, evidence for the recrystallisation of that mineral after the last significant deformation of the amphibolite bodies.

Whatever their ultimate origin, the amphibolite bodies appear to have been emplaced after the development of the biotite gneiss foliation, a planar orientation which they do not possess.

Quartzo-felspathic pegmatite

Pegmatite veins and segregations occur within the larger biotite gneiss outcrop, particularly to the south of the Hestbrepiggan granite. Above the granite the biotite gneisses have a more evenly distributed felspar content than elsewhere, and in the side-wall of the glacier Høybreen (around 500451) occurs a magnificent 30—50 metre section from granite at the bottom up through felspathised biotite gneiss to darker biotite gneisses containing up to 50 %, apparently randomly oriented, massive pegmatite veins. Further south this pegmatite to biotite gneiss volume ratio is exceeded and a more realistic description of the rock complex so formed might be «pegmatite-agmatite». Not infrequently, for example around 465397 and 495421, large areas of pegmatite contain only rare, sharply defined, rather biotitic blocks of gneiss. These usually show evidence of at least slight rotation, although in the main, in the less pegmatised areas, the orientation of the foliation of the gneiss blocks is apparently little disturbed. Augen gneisses and amphibolites are veined by the same pegmatite, but usually to a lesser extent. (See photos. Nos. 4, 5, 6 and 7).

Photo No. 4. Pegmatised augen gneiss, (g.r. 500419), intruded by foliated granite (top left).

K-felspars of quite good shape and superindividuals of quartz sometimes exceed 25 cms in length, although 5 cms is a more normal maximum grain size. These two minerals predominate (modal analyses fig. 3) and their frequent sub-platey orientation, together with the approximate alignment of the few, often large and undulose, biotite flakes gives rise to the weak foliation of the rock. Microcline twinning is very common, as are large perthitic lamellae of albite and myrmekite texture. Both quartz and K-felspar show strain extinction, and are frequently cut and disrupted, as is the plagioclase, by muscovite-bearing shear planes. Plagioclase is always present and occurs as both primary, saussuritised grains and as perthite. Orthite with an epidote and metamict core is the only, rare, accessory mineral. In vesicles, such orthites may measure 3 cms, and biotite books up to 10cms.

The minerals of the pegmatite are essentially those of the biotite gneisses,

Spec.no.	Quartz	K-felspar	Plagioclase	Biotite	Epidote	Muscovite
66	24	71	3	tr.	tr.	1
39	27	63	5	1	1	3
45	22	72	4	1	tr.	1

Fig. 3. Modal analyses of quartz-felspar pegmatite. Specimen localities: See map 1.

Photo No. 5. Ramifying pegmatite veins in biotite gneisses, in a steep, backwall section of Høybreen, (g.r. 501455).

and the crystallisation history seems to have been comparable also. A primary crystallisation of quartz, K-felspar, primary plagioclase and biotite (all more or less foliated) has been followed by secondary recrystallisation of muscovite along shear planers, epidote (saussurite) and chlorite partially after primary plagioclase and biotite, respectively, and felspars. That pegmatisation occurred after the development of the biotite gneiss foliation seems clear.

Foliated Granite.

In terms of area of outcrop, foliated granite is the dominant lithology in the Hestbrepiggan area. It occurs mainly as an E-W striking body (the Hestbrepiggan granite) up to 5 kms wide and at least 10 kms long,

Photo. No. 6. Pegmatite emplaced in biotite gneisses (g.r. 469398).

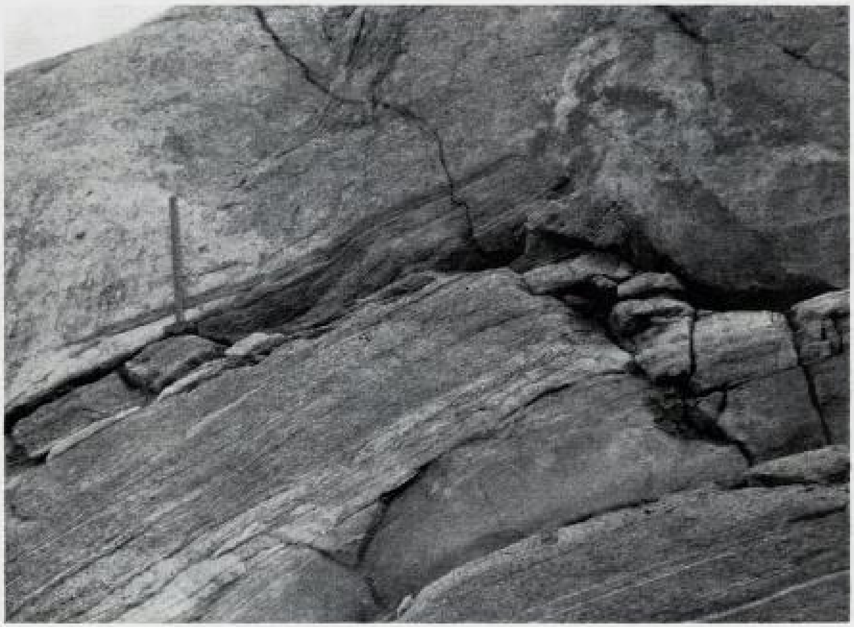


Photo No. 7. A detail of Photo. No. 6.

although numerous, very much smaller bodies occur, especially within the southern biotite gneiss area. The granite mineralogy is quite normal (felspars, quartz and biotite, essentially; modal analyses fig. 4), and all

Spec.no.	Quartz	K-felspar	Plagioclase	Biotite	Epidote	Muscovite	Magnetite
34	30	49	14	7	tr.	tr.	tr.
35	30	46	20	2	2	tr.	tr.
36	34	45	15	3	2	tr.	1
37	31	39	20	5	3	1	tr.
38	38	38	11	7	4	2	tr.
54	36	31	15	6	3	9	tr.
56	39	33	15	4	3	6	tr.
60	32	40	11	8	3	6	tr.
61	29	40	15	8	5	2	1
80	40	32	16	6	2	4	tr.
79	30	35	18	8	4	5	tr.
43	30	41	15	8	4	1	tr.
1 *	40	35	17	4	4	tr.	tr.
9 *	35	42	15	2	6	tr.	tr.
17 *	33	37	11	7	7	5	tr.
67 *	39	23	17	6	4	10	tr.

Fig. 4. Modal analyses of foliated granite (— small granites). Specimen localities: See map 1.*

minerals share in the foliation best defined by biotite. In deep, central parts of the Hestbrepiggan granite (e.g. in Svartdalen at 445406 and around Høybreen at 465429) grain size increases, porphyroblasts of K-felspar up to 2cms in length occur and the foliation becomes rather faint. Here, as elsewhere, however, the foliation remains conformable to the margins of the granite. (See photos. Nos. 9 and 10).

Regionally, the structure of the granites is conformable with that of the biotite gneisses. In detail, however, the contact is everywhere sharp, both mineralogically and texturally, and there is sometimes marked structural discordance (e.g. around 436396). The northern contact of the main granite is rather flat and is overlain by similarly inclined felspathic biotite gneisses. The southern contact by contrast is steep and marked by a zone of agmatite up to 100 metres wide. Large (several metre) blocks of pegmatised biotite gneiss, often containing small, quartz-felspar augen, are surrounded by granite and have evidently been rotated in that matrix.

In the region of the small granite bodies occurs another type of agmatite. Here, numerous, often subrectangular, sharply defined penetrations of foliated, often coarse grained, granite occur within the pegmatite-

Photo No. 8. Granite veins in biotite gneiss xenolith, (Briedalen, g.r. 456431).

biotite gneiss «agmatite» already described. Such «double agmatites», with certain resemblances to crazy paving, are particularly well developed around 481409, for example.

The only xenolith discovered within the main granite occurs in Briedalen and has been in part deformed and recrystallised as the result of movement along the nearby tear fault. As far as can be determined, the xenolith consisted originally of a slab-like mass of biotite gneiss (50 × 800 × at least 100 metres) oriented conformably within the granite foliation. The southern part of the slab is divided into three prolongations which are riddled in parts with granite net-veins. (See photo. No. 8).

The normal range of grain sizes within the granite is 2—10 mm, although individual quartz and other grains may be under 0.1 mm, and porphyroblasts of K-felspar up to 2 cms. Near Merrahøe (434399) occurs a small outcrop of «augen granite»; the augen (2.5 × 5 × 4cms, maximum) consist mainly of several crystals of K-felspar. Mineral grains, in particular, felspars, normally have quite good shapes, although quartz occurs as sutured superindividuals.

The K-felspar is at least largely microcline, and shows frequent twinning on both the Microcline and Carlsbad Laws. Perthitic intergrowths with albite are common, and large grains can occasionally be seen to enclose patches of quartz and biotite. Both K-felspar and quartz show sometimes pronounced undulose extinction. (See photos. Nos. 12, 13 and 14).

Plagioclase occurs, again, as both primary, epidotised (An 5 %), and secondary perthitic grains. Biotite occurs in flakes and aggregates and is pleochroic from light brown (X) to medium to dark brown (Y, Z).

Of the secondary minerals, epidote occurs as a replacement of plagioclase, muscovite is developed along cross-cutting shears and magnetite, orthite, sphene and apatite occur in small quantities throughout the granite. (See Photo. No. 11).

Once again, there seem to have been two main phases of crystallisation (cf biotite gneisses, pegmatite, etc). The primary minerals, as usual, are biotite, quartz, primary plagioclase and K-felspar, possibly in that order of crystallisation. Secondary recrystallisation involved the development of muscovite along shears, the partial replacement of plagioclase and biotite by epidote and chlorite (slight), respectively, and the recrystallisation of the alkali-felspar.

It seems probable from the field evidence that the Hestbrepiggan and smaller granites were intruded as mobile masses either during or after the main folding and after the pegmatisation of the biotite gneisses.

Muscovite and Chlorite gneisses.

Micaceous gneisses occur only within shear zones, and may readily be divided into two textural types. First, schistose, muscovite (and chlorite) gneisses, and, secondly, flaggy, muscovite gneisses, which cocur in association with tear faults and thrusts, respectively. Both types contain high proportions of muscovite and quartz, and relatively low proportions of felspar, biotite, etc (modal analyses fig. 5).

Schistose muscovite gneisses are of sufficient importance to map only along the Briedalen tear fault, where they occur within a zone up to approximately 1000 metres wide. Much smaller zones occur along other high-angled shears throughout the area, however. Incipient stages of shearing and recrystallisation have been described already in many of the fundamental gneiss lithologies of the area. Into the shear zones the number of disruptive planes increases as do the muscovite and quartz modes at the

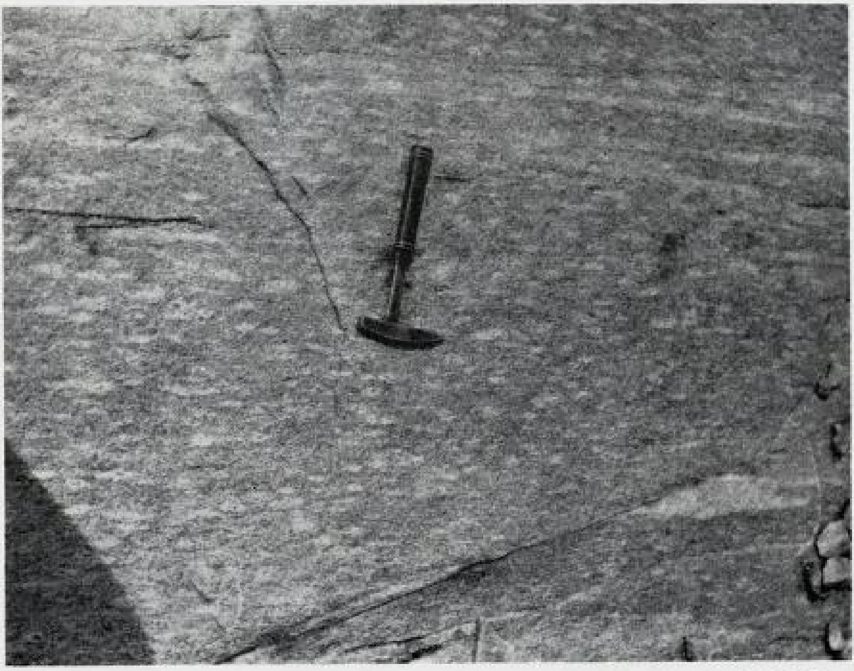


Photo No. 9. Well foliated augen granite from Merrahøe, (g.r. 436398). Photo by R. B. Elliott.

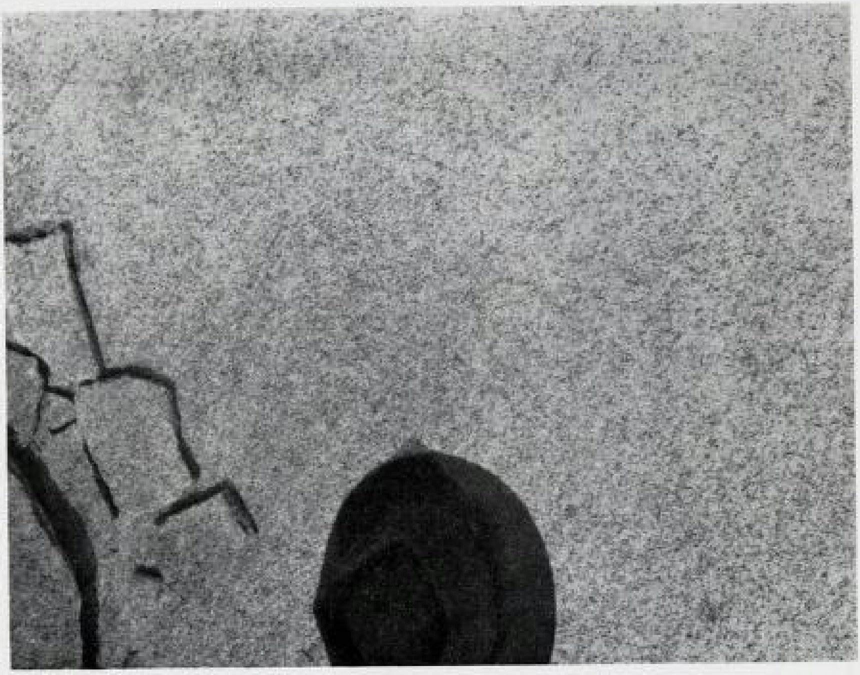


Photo No. 10. Poorly foliated granite from Høybreen (g.r. — 462430). Photo by R. B. Elliott. (Note scale from hat.)

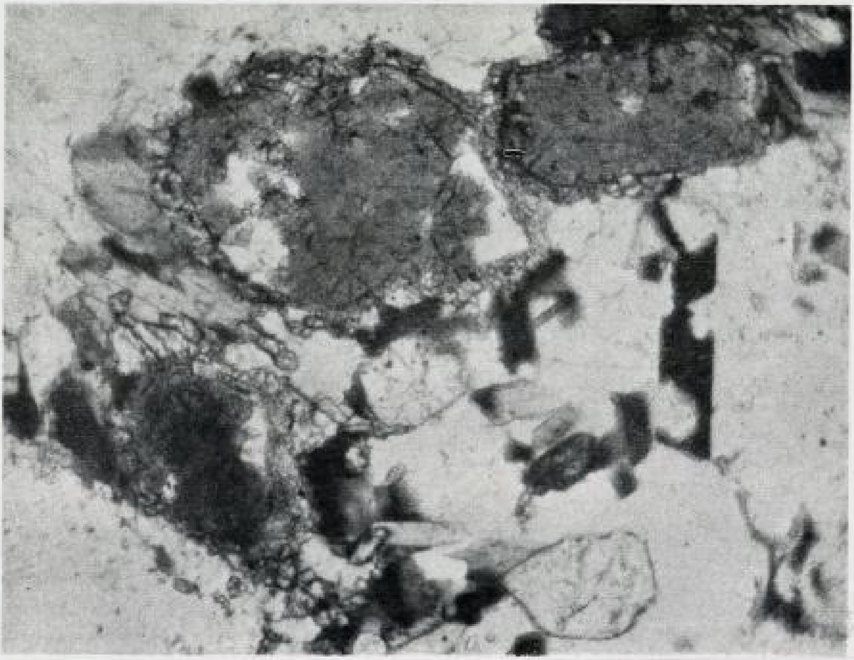


Photo No. 11. Orthite with epidote rims in foliated granite, (.70, plane polarised light).

Photo No. 12. Undulose extinction in K-felspar in sheared, foliated granite (x35, crossed polars).

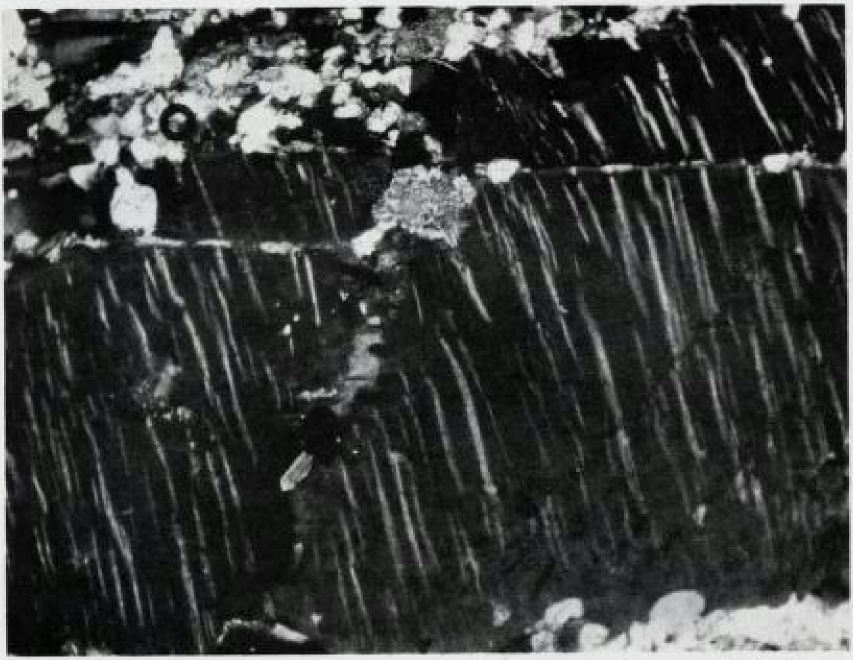


Photo No. 13. Deformed K-felspar in sheared, foliated granite (.35, crossed polars).

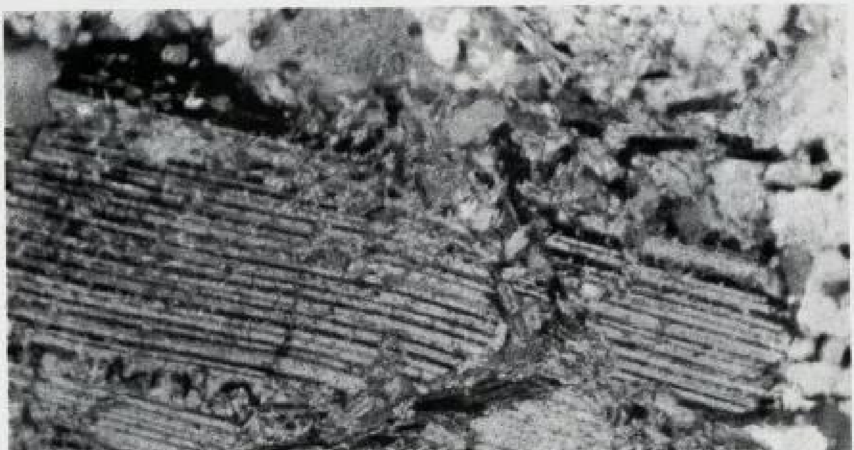


Photo No. 14. Plagioclase with muscovite on planes of dislocation in sheared, foliated granite. (x35, crossed polars).

Spec.no.	Quartz	K-felspar	Plagioclase	Biotite*	Epidote	Muscovite	Magnetite
19	47	15	10	9	—	18	tr.
20	56	17	17	5	1	4	tr.
21	47	15	3	3	—	32	—
22	46	26	17	2	—	9	tr.
91	22	19	7	6	3	42	1
77	39	18	25	3	2	12	1
64	46	8	4	19	3	20	—
13	40	39	7	7	1	6	tr.
26	37	41	8	3	tr.	10	tr.
95	55	31	tr.	—	1	9	4
68	39	22	9	15	2	13	—
74	26	31	8	10	3	22	—
75	31	38	11	7	1	11	—

Fig. 5. Modal analyses of sheared gneisses (biotite may be heavily chloritised). Specimens 19—22, plus 91 and 77 — schistose muscovite gneisses; 64, 13, 26, 95, 68, 74 and 75 — flaggy muscovite gneisses. Specimen localities: See map 1.*

expense of the felspars, mainly, although biotite and epidote also progressively disappear. In the central portion of the shear occur quartzitic, muscovite schists containing quartzo-felspathic augen up to several cms in length. These augen become progressively smaller and ultimately disappear in the zone of presumed most intense shear. (See photo. No. 15).

Felspar grains in the clastic augen are cut and displaced by shears, and plagioclase in particular shows evidence of facile replacement by muscovite. The K-felspar is strain-shadowed microcline which shows abundant perthitic albite, many lamellae being displaced and folded. Muscovite grains in the schistose groundmass are often large (several mms) and undulose, wrapping around and through the clastic augen. Quartz grains are everywhere strainshadowed, and although relict porphyroclasts may be larger, grain sizes in the groundmass are uniformly fine (under 0.1 mm).

Chloritic schistose gneisses (chlorite, muscovite, quartz epidote and magnetite) have a small outcrop in Briedalen (458435 for example) within the shear zone. No evidence of primary mineralogy remains in these rocks, although in somewhat sheared amphibolites at Høybreen (around 486443) chlorite, quartz and epidote may be seen to replace hornblende. Small clastic, quartzo-felspathic augen are common. (See photo. No. 16).

Mineralogically, the flaggy muscovite gneisses are similar to the schistose gneisses. (fig. 5). Under the Basal thrust, where this lithology has its main outcrop, the textural differences are clear, however. Although muscovite

Photo No. 15. Muscovite bearing planes disrupting K-felspar in schistose, muscovite gneiss, (x35 plane polarised light).

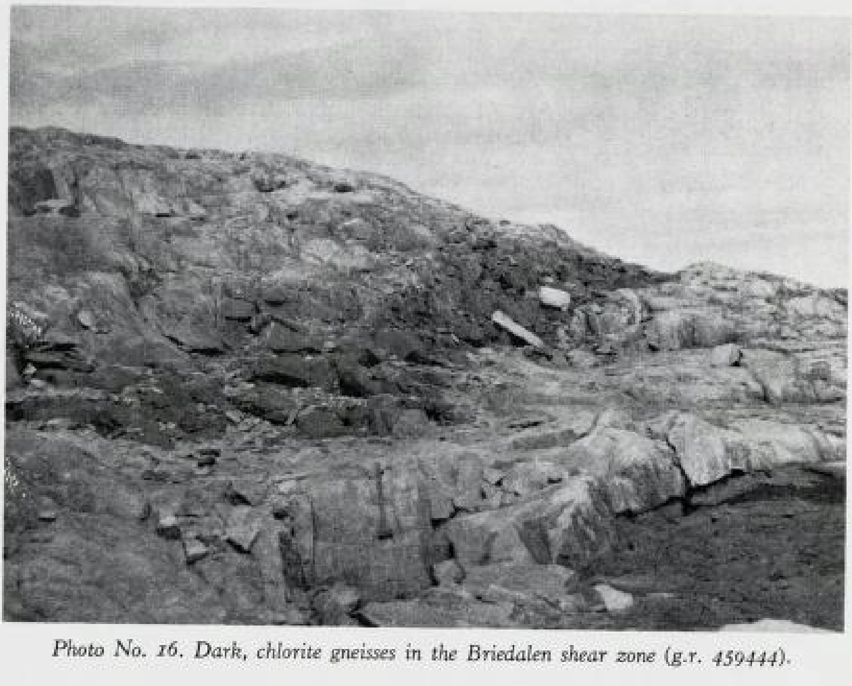


Photo No. 16. Dark, chlorite gneisses in the Briedalen shear zone (g.r. 459444).

Photo No. 17. Flaggy, muscovite gneisses associated with a low-angled shear cross-cutting pegmatite near the Basal thrust.

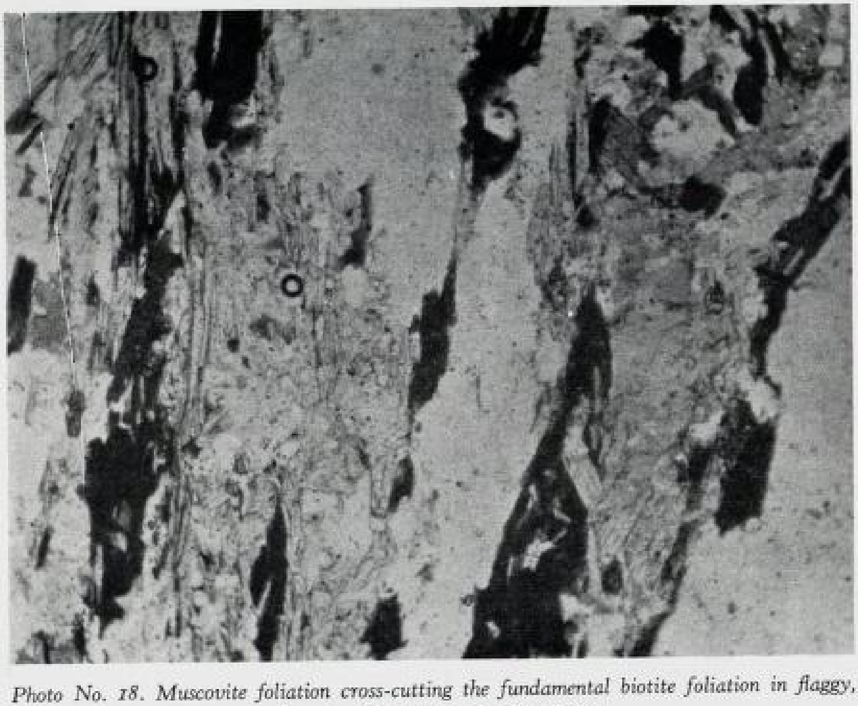


Photo No. 18. Muscovite foliation cross-cutting the fundamental biotite foliation in flaggy, muscovite gneiss, (.35, plane polarised light).

bearing, disruptive planes occur, they tend to be concentrated in planar subzones which give the rock its flaggy character. In between the muscovitic layers occur bands of often relatively unaltered acid gneiss. Primary minerals are replaced in much the same way as described for the schistose muscovite gneisses, although clastic augen are small and uncommon. (See photo. Nos. 17 and 18).

There can be little doubt that these micaceous gneisses result from the shear-induced recrystallisation of fundamental gneisses in the region of tear faults and thrusts. These secondary gneisses are probably not the only product of such shear-induced processes. Large quartzite bodies and numerous veins bearing an assemblage of quartz, epidote and clinochlore etc. (Banham, 1966 a) also occur in association with the tear faults.

Quartzite.

Lenses of quartzite up to 300 metres long and 50 metres wide occur in the shear zones of tear faults in association with the schistose, muscovite gneisses. In broader terms, they invariably occur where such a shear zone cuts an acid gneiss (or granite).

In hand specimen, quartzites are greyish-blue or black and normally show a poor foliation parallel to the long axis of the body and the plane of the tear fault. Quartz is virtually the only mineral present; it is extremely fine-grained (commonly less than 0.05 mm and rarely over 0.2 mm), shows pronounced undulose extinction and individual grains are commonly platey within the foliation. The only other identifiable mineral, present in very small quantities, is muscovite, which occurs as single flakes under 0.3 mm in length oriented within the foliation. Another, unidentifiable mineral occurs in streaks of fine specks (under 0.001 mm) along planes where the straining of the quarts is most pronounced (possibly chlorite or magnetite?)

Whatever the ultimate origin of these quartzite bodies there can be little doubt that they have been involved in the shearing associated with tear faults. In view of the further association with acid gneisses it is thought probable that they result from the shear induced breakdown of felspars, etc, to muscovite (schists) and quartzite. (Banham, 1966 a). If this is so, there can be little validity in the joining up of these quartzite bodies (plus metasedimentary quartzites) into one «stratum» of «flagstone» over a very large area of basement (cf Gjelsvik, 1953, p76 and fig. 2).

II — Metasediments. Introduction.

A preliminary account of the succession, lithogy and structure of the metasediments has been published (Banham and Elliott, 1965; see also Elliott and Cowan 1966 for a detailed account of the Holleindalen Greenstone Group) and as a full study is in preparation at the moment no comprehensive survey is undertaken here. However, the lowest stratigraphic and structural unit, the Psammite Group, requires description for it lies immediately above the Basal Gneisses. Three main lithologies occur within this Group: —

quartzite (and micaceous quartzite)
felspathic quartzite (sparagmite)
mica schists.

Quartzite (and micaceous quartzite)

Blue and bluish-grey quartzites occur in massive, regionally lensoid outcrops of beds up to 60 metres thick interbedded with mica schists into which they may grade both laterally and vertically. A simple foliation or schistosity is always present and sensibly parallel to the lithological contacts. The predominant mineral is quartz, which occurs as fine (under 0.5 mm) sutured grains showing often pronounced undulose extinction. The only other mineral of importance is muscovite (modal analyses, fig. 6)

Spec.no.	Quartz	K-felspar	Plagioclase	Biotite	Epidote	Muscovite	Magnetite
10 +	32	—	3	10 *	—	41	6
11	47	—	2	1 *	—	50	tr.
12	58	—	1	—	—	40	1
24	14	—	tr.	21 *	—	53	12
25	49	1	4	29 *	17	—	tr.
78	62	19	5	—	8	6	tr.
94	61	6	2	8	tr.	23	—

*Fig. 6. Modal analyses of Psammite Group lithologies (+ — contains 7 % garnet; *-biotite chloritised) Specimen localities: See map 1. 10—12 schists; 24 and 25, schists; 78, felspathic quartzite; 94, micaceous quartzite.*

which occurs as small (under 2 mm) flakes and flat aggregates oriented within the foliation. Large numbers of very fine grains of magnetite are rather evenly scattered throughout. K-felspar may occur in exceedingly fine grains (under 0.005 mm) associated with (and replacing?) muscovite. A few flakes of biotite may occur, usually interfoliated with muscovite; X light brown, Y, Z dark brown. A very few patches of cloudy, saussurite-like material may represent relict, small grains of plagioclase.

The present metamorphic mineralogy would seem to suggest that the original sediments ranged from rather pure to rather dirty and slightly felspathic quartz sandstones. Only one period of metamorphic crystallisation is evidenced by the largely stable mineral assemblages. Quartz straining presumably indicates some degree of post-crystallisation deformation.

Felspathic quartzite (Sparagmite)

Massive, banded, sometimes flaggy, white to pinkish felspathic quartzites are largely restricted to the eastern part of the area. Here they may exceed 600 metres in thickness and appear to be the rapidly-developed lateral equivalents of the blue-quartzite and mica schist succession further west. Only few, thin, schist bands occur within the felspathic quartzites.

Granular, sutured, strain-shadowed quartz grains, which form the bulk of this rock (fig. 6) are rather fine (under 0.2 mm), although K-felspar grains may be much larger (over 1 mm). These larger grains often show quite good crystal form and Microcline twinning, and contain albite perthites. Other K-felspars are equigranular with the quartz and appear to have thin prolongations which enclose grains of that mineral.

Muscovite, normally an important mineral, occurs in both a schistose and flaggy manner. The presence of plagioclase relicts is perhaps indicated by small (0.05 mm) patches of saussurite material. Biotite is absent or unimportant; X light brown, Y, Z medium to dark brown. Magnetite occurs as very fine (0.002 mm) disseminated grains. Epidote may occur as small (under 0.1 mm) scattered prisms, apparently associated with the micas.

The banding, schistosity and flagginess of these rocks are conformable and presumably represent original bedding, possibly much deformed. The original sediments were probably slightly dirty arkoses and felspathic sandstones, such as constitute the Eocambrian Sparagmites of southern Norway.

The present mineralogy and texture suggest that only one major phase of crystallisation has occurred. Later, slight regrowth of K-felspar seems to have taken place, however. The sometimes very pronounced strain shadows of quartz grains may perhaps be correlated with the thrusting, as may the occasional cross-cutting orientation of the muscovite.

Mica schist.

Mica schists occur mainly in the western part of the Psammite Group outcrop, interbedded with blue and micaceous quartzites. Muscovite commonly forms up to 50 % and biotite (often heavily chloritised) may make up to another 30 % (fig. 6) Quartz, in fine, sutured, strain shadowed grains (under 0.2 mm) is the only other mineral of any inportance. Felspars are generally not present; the, perhaps surprising, lack of albite has been confirmed by chemical analysis (p. 55). Porphyroblasts of garnet up to 7 mm in diameter; are common; their pinkish-red colour and complete isotropy may indicate an almandine garnet (X-ray study, p. 74). Epidote is important in only one sample so far examined.

The pronounced schistosity, formed by the common orientation of the micas and quartz lenses, is minorfolded, although no minerals have been observed in axial planar orientations. Close to the Basal thrust a rather widely spaced cross-cutting, non-mineral bearing, cleavage is commonly seen.

Presumably, these schists represent metamorphosed, more or less sandy, and, less frequently, limey, shales. Only one major period of crystallisation seems to have occurred, and that this was syntectonic is possibly indicated by the «S's» of the mainly quartz inclusions within many of the garnet porphyroblasts. Chloritisation of biotite seems to be most pronounced in the vicinity of the Basal thrust (and the secondary cleavage).

Post script. In places at or near the base of the Psammite Group occurs a strongly deformed «phacoidal quartzite». This may represent a conglomerate, and the problem is receiving attention from Dr. D. R. Cowan (See photo. No. 19).

Metamorphic history.

Conclusions. Basal Gneisses

Petrographic study seems to consistently indicate the existence of both primary and secondary metamorphic mineral assemblages in the Basal Gneisses.

Primary mineral assemblages: —

1. quartz-plagioclase (An 20 +, see p.70)-K-felspar-biotite-(orthite-magnetite-apatite)

2. quartz-plagioclase (An 20+)-biotite-(accessories)
3. aluminous hornblende(+?)
4. biotite (Mg rich)-quartz-plagioclase (An 20+?)-K-felspar-almandine garnet.

Following Fyfe, Turner and Verhoogen (1958) and Turner and Verhoogen (1960) in general, and Christie (1959, 1962), de Waard (1959) and Rutland (1961) regarding the relation of plagioclase composition to metamorphic facies, these primary assemblages indicate the almandine-amphibolite facies of metamorphism (possibly the staurolite-amphibolite subfacies?)

Secondary minerals in apparently stable assemblages are: —

5. quartz-plagioclase (An5)-biotite-epidote-calcite-(K-felspar)
6. quartz-plagioclase (An5)-biotite-epidote-calcite-muscovite-(-K-felspar)
7. quartz-plagioclase (An5)-epidote-calcite-chlorite-(-K-felspar)
8. quartz-plagioclase (An5)-epidote-calcite-chlorite-muscovite-(K-felspar).

Photo No. 19. Deformed conglomed conglomerate (?) from Hesthøe (g.r. 572498(.

Assemblages 5 and 6 appear to indicate the middle (quartz-albite-epidote-biotite) sub-facies of the greenschist facies. Assemblages 7 and 8, however, indicate the lowest greenschist sub-facies (quartz-albite-muscovite-chlorite). It is therefore particularly interesting to note that these latter assemblages are found especially well-developed in the sheared, schistose and flaggy gneisses associated with the tear faults and thrusts.

Metasediments

Only a small number of samples, all from the Psammite Group, have so far been examined. Apparently stable assemblages are as follows: —

9. quartz-K-felspar-muscovite-biotite-plagioclase (An5)-magnetite
10. quartz-muscovite-biotite-garnet-magnetite
11. quartz-muscovite-magnetite
12. quartz-biotite-epidote-K-felspar-magnetite
13. quartz-muscovite-chlorite.

Assemblages 9—12 may be referred to the two higher sub-facies of the greenschist facies. Assemblage 13 appears to belong to the lowest greenschist sub-facies, however, and is found most commonly in the vicinity of the Basal thrust.

Conclusions

The following metamorphic history is suggested for the Hestbrepiggan area: —

1. Metamorphism of the Basal Gneisses in the almandine-amphibolite facies (pre-Eocambrian).
2. Metamorphism of the metasediments and retrograde metamorphism of the Basal Gneisses in the upper part of the greenschist facies (post Eocambrian).
3. Retrograde metamorphism of parts of both the Basal Gneisses and Metasediments in the region of tear faults (and thrusts-some evidence, not conclusive, of local recrystallisation, possibly consequent on slight, late, removement) (post Caledonian).

Mineralogical and chemical relations between lithologies.

Introduction.

Mineralogical and chemical traverses have been made across many examples of lithological contacts in the Hestbrepiggan basement. Details of petrology and modal analyses have been already given. Chemical analyses of 33 rocks from the area are presented here. Most determinations were made in the Department of Geology at Nottingham University by the writer and by the then silicate analyst (1959—62), Miss Maureen Dowlman. The rapid methods of Shapiro and Brannock (1952, 1956 and 1960) were used throughout with only minor modifications. In addition 95 determinations (mainly CO_2 and H_2O) have been carried out (1966) by Per Reidar Graff by courtesy of Norges Geologiske Undersøkelse.

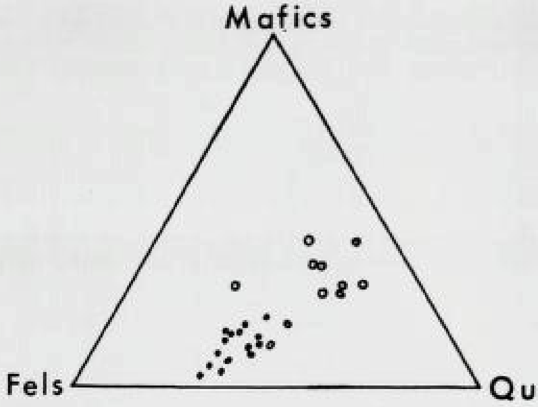


Fig. 7. Quartz/felspar/mafic minerals diagram for foliated granites (closed dots) and biotite gneisses — (open circles).

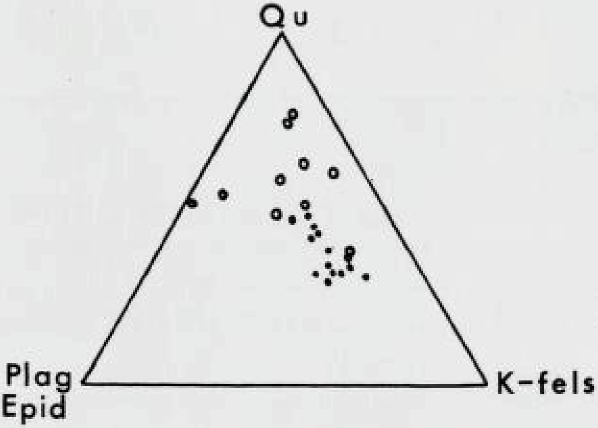


Fig. 8. Quartz/K-felspar/plagioclase (and epidote) diagram for foliated granites (closed dots) and biotite gneisses (open circles).

Basal Gneisses.

1. *Biotite Gneiss/Foliated Granite*

Mineralogical relations. Modal analyses of these lithologies are presented in figs. 1 and 4 respectively, and values for selected minerals are plotted in figs. 7 & 8. These clearly show firstly, that the granite is mineralogically much more homogeneous than the gneisses, and, secondly, that although the quartz: mafics ratios are similar, the felspar proportion is much higher in the granites. Thirdly, it can be seen that the granites plot in a relatively high temperature, quartz-and K-felspar —rich position on the «residual» system diagram (fig. 8).

These diagrams might also suggest that continuous mineralogical gradients occur between biotite gneiss and granite. That this is not so on the ground, however, is shown by traverses (figs. 9, 10, 11 + 19) where certain variations consistently occur across a sharp contact. The quartz and biotite modes are notably higher in the gneisses, whereas felspars are more important in the granite.

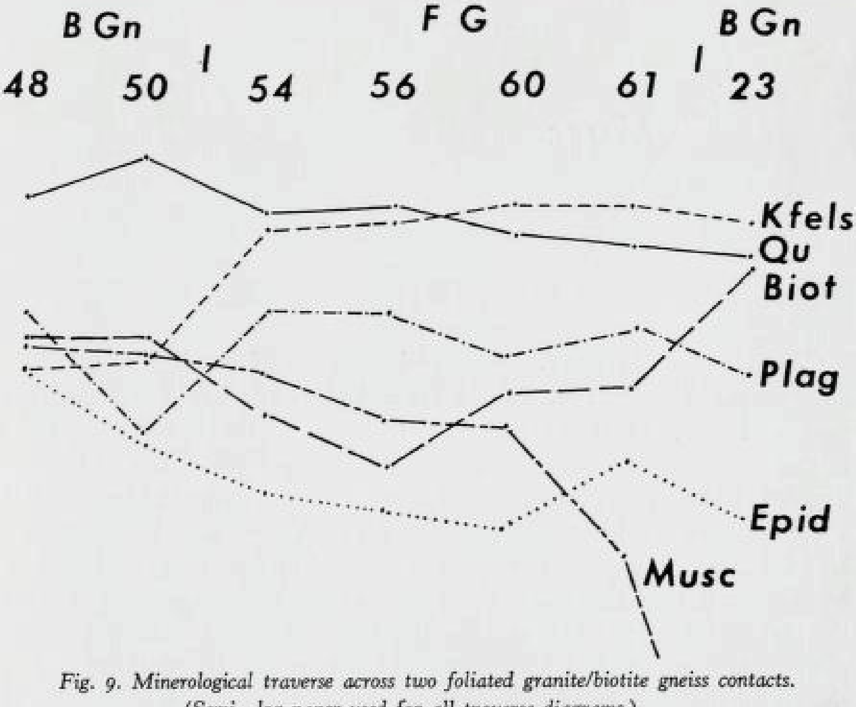


Fig. 9. Minerological traverse across two foliated granite/biotite gneiss contacts. (Semi—log paper used for all traverse diagrams.)

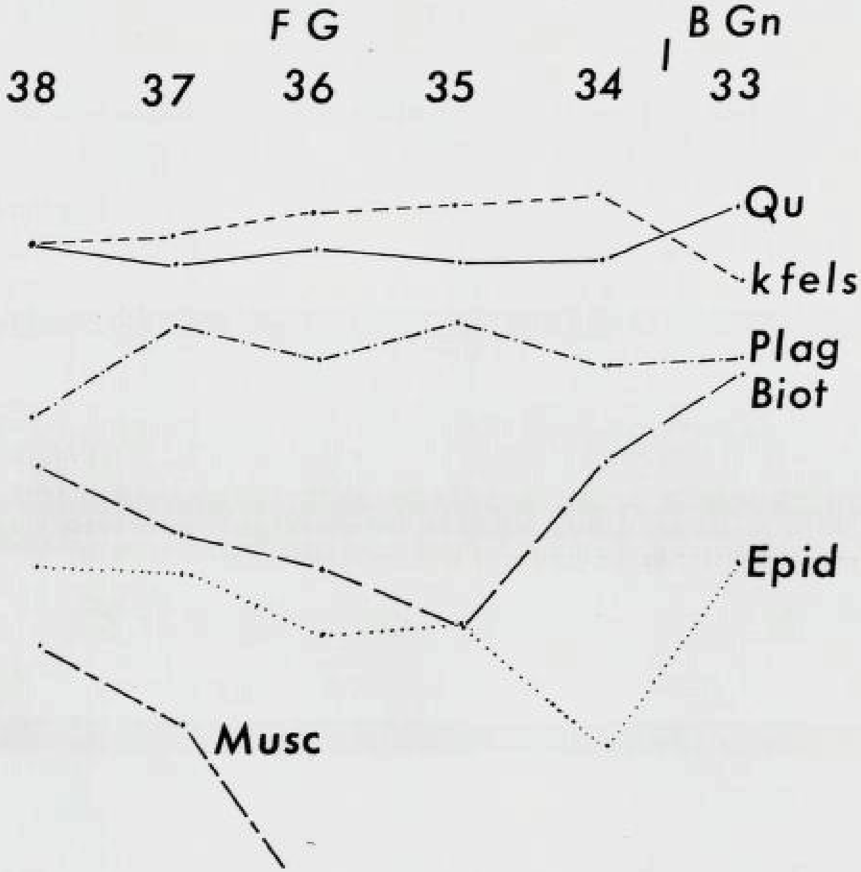


Fig. 10. Mineralogical traverse across a foliated granite/biotite gneiss contact.

Chemical Relations. Chemical analyses of granites and biotite gneisses are given in figs. 12 and 13, and plots of alkalies and CaO are presented in fig. 14. It is apparent, as might be expected, that the granite is the more homogeneous rock. The gneisses, moreover, are to varying degrees richer in CaO and, again, it would seem possible that there is a continuous, granitisational gradient between the more basic gneisses and the granite. When the analyses are related to their geological setting, however, it is clear that the gneisses do not become more granitic towards the granite (figs. 15, 16 + 21), but show a considerable variability across the strike. The chemical homogeneity of the granite, by contrast, is well shown by the flatness of the oxide curves.

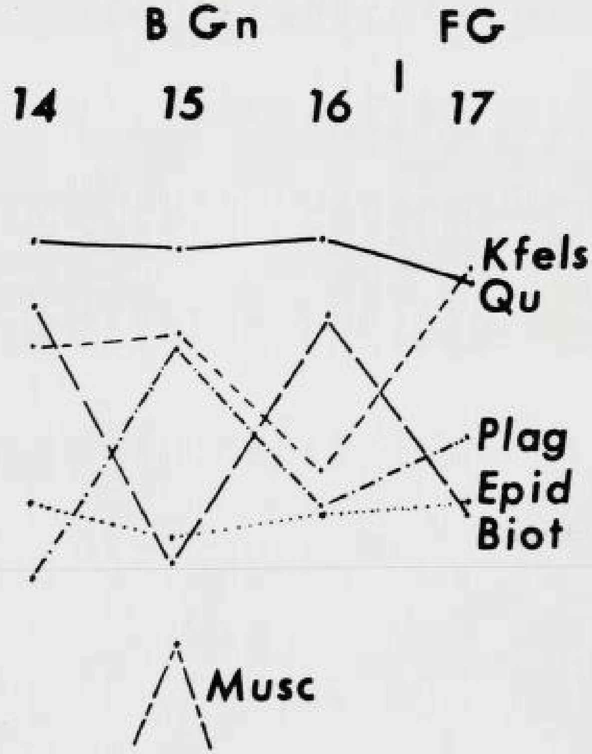


Fig. 11.
Mineralogical traverse across biotite gneiss/foliated granite contact.

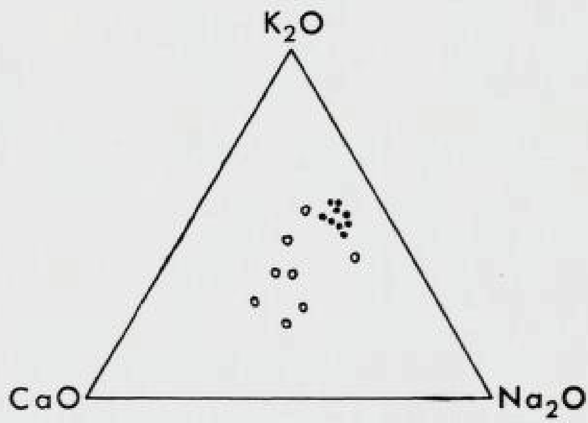


Fig. 14.
$CaO/K_2O/Na_2O$ diagram of foliated granites — (closed dots) and biotite gneisses (open circles).

Spec.no.	2*	3*	4*	14*	15*	16	33	23	27	x	s
SiO_2	69.2	66.4	65.8	58.1	72.2	69.5	65.1	59.64+	61.21+	65.2	4.4
TiO_2	0.42	0.53	0.61	0.93	0.33	0.70	0.64	0.43	0.40	0.58	0.21
Al_2O_3	15.5	17.3	16.5	18.1	14.4	12.9	16.4	17.45+	16.24+	16.0	1.62
Fe_2O_3	n.f.	n.f.	0.85	0.19	n.f.	3.89	2.98	0.77	nf.	0.96	1.84
FeO	2.0	2.4	3.9	6.1	2.3	2.03	0.96	4.4	4.5	3.0	1.91
MnO	0.002	0.001	0.005	0.10	0.05	0.23	0.054	0.01	0.12	0.06	0.10
MgO	1.3	1.1	1.7	1.6	0.49	2.36	1.98	1.44	1.06	1.5	0.51
CaO	2.3	3.7	4.1	4.9	1.5	3.20	3.69	3.64	3.51	3.5	1.10
Na_2O	2.8	3.8	3.8	3.8	4.5	3.4	4.4	3.32	5.56	3.7	0.57
K_2O	6.3	4.3	2.3	5.0	4.1	2.6	2.8	6.29	5.27	4.2	1.57
P_2O_5	0.08	0.18	0.24	0.33	0.07	0.27	0.24	0.95	0,37	0.3	0.37
H_2O	0.80	n.f.	0.32	n.f.	0.6	0.83+	0.57+	0.87+	0.82+	0.53	0.26
CO_2	0.07+	0.05+	0.04+	0.04+	0.06+	0.06+	0.03+	0.04+	0.03+	0.05	0.15
Totals	100.77	99.96	100.17	99.19	100.60	99.97	99.84	99.25	98.99		

Fig. 12. Chemical analyses of biotite gneisses (and augen gneiss- 27) Specimen localities are given on map 1.
*Key: * — analysis by Miss Dowlman (Nottingham University).*
+ — oxide determination by Per Reidar-Graff (NGU).
x — *mean.*
s — standard deviation

Spec.no.	43	35	37	53	79	1*	17*	9*	87	x	s
SiO_2	68.42+	72.0	73.1	69.31+	71.95+	72.8	72.2	75.1	66.8	71.3	2.5
TiO_2	0.24	0.27	0.26	0.21	0.16	0.14	0.32	0.01	0.29	0.21	0.09
Al_2O_3	16.23+	14.4	14.1	15.97+	15.35+	13.6	13.7	13.9	16.6	14.8	1.39
Fe_2O_3	0.85	0.59	n.f.	0,41	0.18	0.04	n.f.	0.15	0.42	0.27	0.33
FeO	1.8	1.28	1.73	2.2	2.2	1.6	2.8	0.6	2.33	1.8	0.66
MnO	n.f.	0.007	n.f.	n.f.	0.01	n.f.	0.04	n.f.	n.f	0.01	0.08
MgO	0.51	n.f.	0.36	0.43	0.34	0.44	0.54	n.f.	0.75	0.45	0.16
CaO	1.54	1.63	1.63	1.4	1.78	1.2	1.2	1.4	1.35	1.5	0.18
Na_2O	4.98	4.2	3.4	3.62	2.72	3.0	3.7	3.7	3.8	3.7	0.62
K_2O	6.79	5.8	5.3	6.20	4.94	6.5	5.0	4.9	6.6	5.8	0.76
P_2O_5	0.19	0.069	0.055	0.10	0.08	0.02	0.10	n.f.	0.14	0.09	0.05
H_2O	0.47+	0.54+	0.55+	0.29+	1.58	0.60	1.1	0.16	0.68+	0.66	0.43
CO_2	0.04+	0.04+	0.03+	0.06+	0.05+	0.06+	0.03+	0.05+	0.08+	0.05	0.02
Totals	102.06	100.43	100.52	100.00	101.34	100.00	100.73	99.97	99.84		

Fig. 13. Chemical analyses of foliated granites; Key as in fig. 12
Spesimen localities: see map 1.

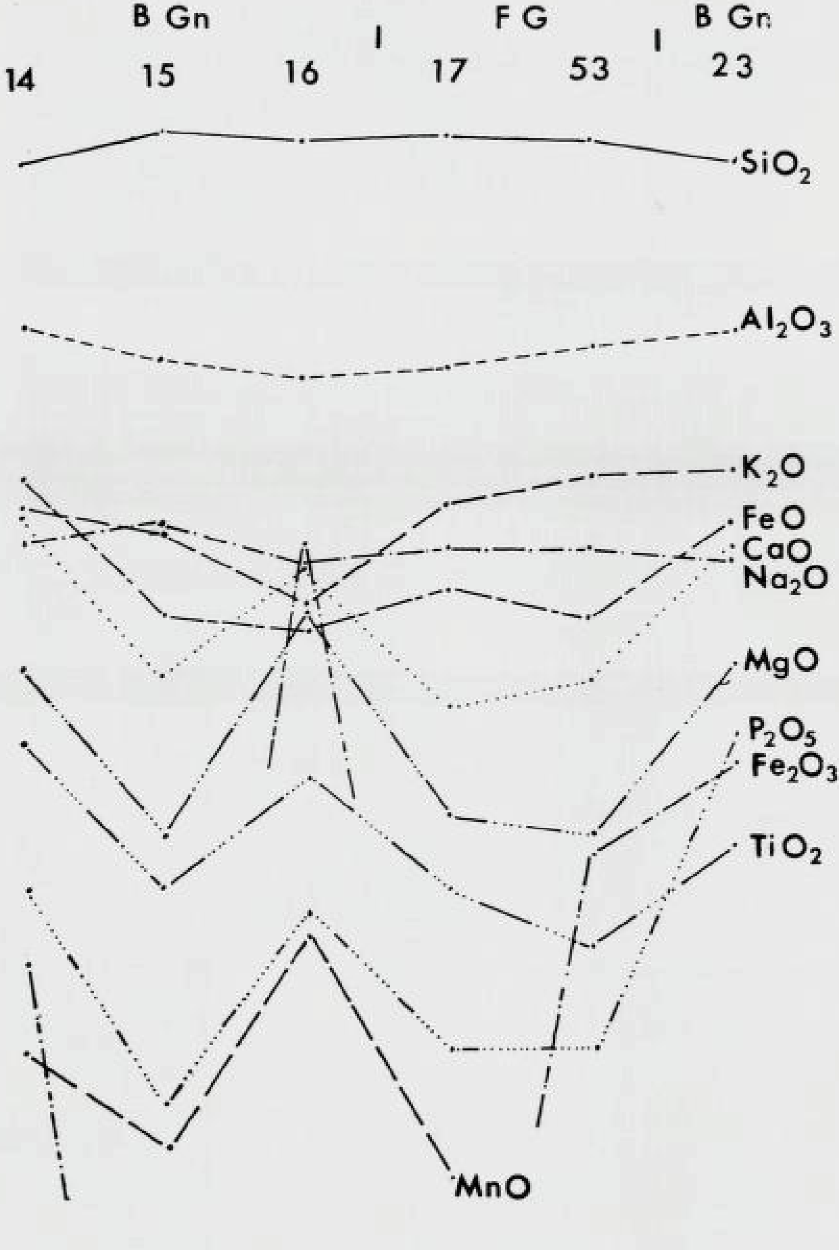


Fig. 15. Chemical traverse across two foliated granite/biotite gneiss contacts.

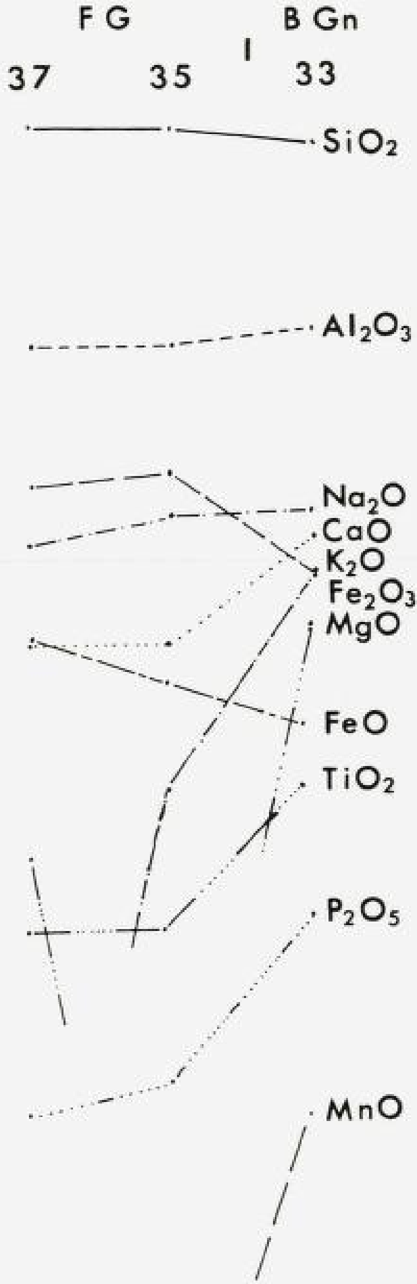


Fig. 16.

Chemical traverse from foliated granite to biotite gneiss.

Apart from this broad distinction into more and less homogeneous provinces, there are consistent differences in oxide values across the sharp contact between the two lithologies. Granites are richer in SiO_2, FeO and K_2O, and the biotite gneisses are richer in Al_2O_3, MgO, MnO, CaO, TiO_2 and P_2O_5.

Within the gneisses the «basic oxides» vary more or less sympathetically, and antipathetically with SiO_2 and K_2O. This basic to acid variability may most probably represent original sedimentary (and volcanic?) parentage, although metamorphic differentiation may have enhanced original differences between beds.

That metasomatism on a regional scale has also occurred is indicated by the extremely interesting Na_2O figures, which are remarkably similar throughout the area and across granite/gneiss contacts. It is possible that this mobile chemical has equalised by local diffusion within the biotite gneisses, although the similarity to the granite level perhaps indicates introduction of Na.

The K_2O curves within the gneisses also show a certain flattening, although the extent of K_2O homogenisation in the area is here minimised by the consideration of biotite gneiss analyses only. It will be recalled that in large parts of the area K-felspar pegmatite, with predictably well homogenised K_2O (see modal analyses, fig. 3) has replaced the biotite gneisses.

It seems possible to conclude generally that while an homogeneous granite formed at depth, the gneisses at a higher level were homogenised only with respect to Na ($_2$O) and, to a lesser extent, K ($_2$O). Subsequent upward intrusion of the granite brought an homogenised rock into contact with the higher, less homogenised biotite gneisses. (cf. Strand, 1949, who,

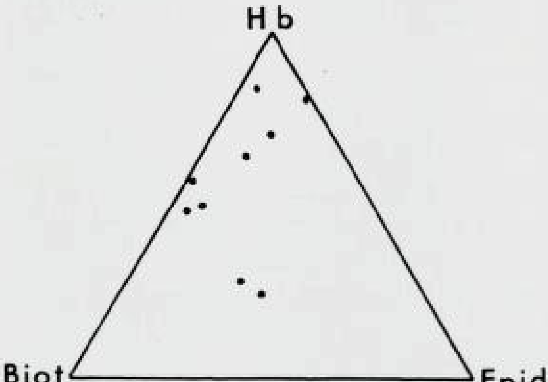


Fig. 17.

Hornblende/biotite/epidote diagram for amphibolites.

in a nearby area concluded that no granite is intrusive). The absence of a thermal metamorphic aureole around the granite, however, must indicate that little or no difference in temperature existed between it and the gneisses at the time of intrusion.

2. *Biotite Gneiss/Amphibolite.*

Mineralogical relations. Modal analyses have already been given (figs. 1 + 2), and the values for selected minerals are plotted here (figs. 17 + 18). A modal traverse (fig. 19) across the margin of the Steindalen

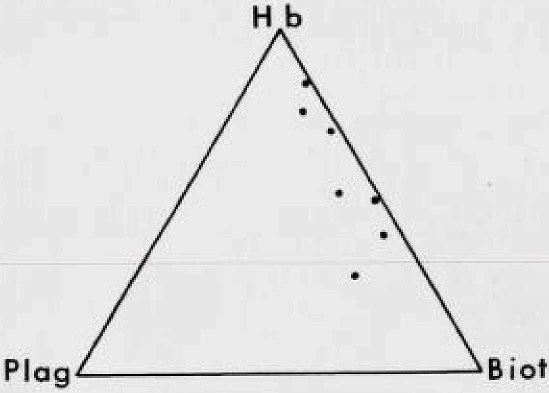


Fig. 18.

Hornblende/plagioclase/biotite diagram for amphibolites.

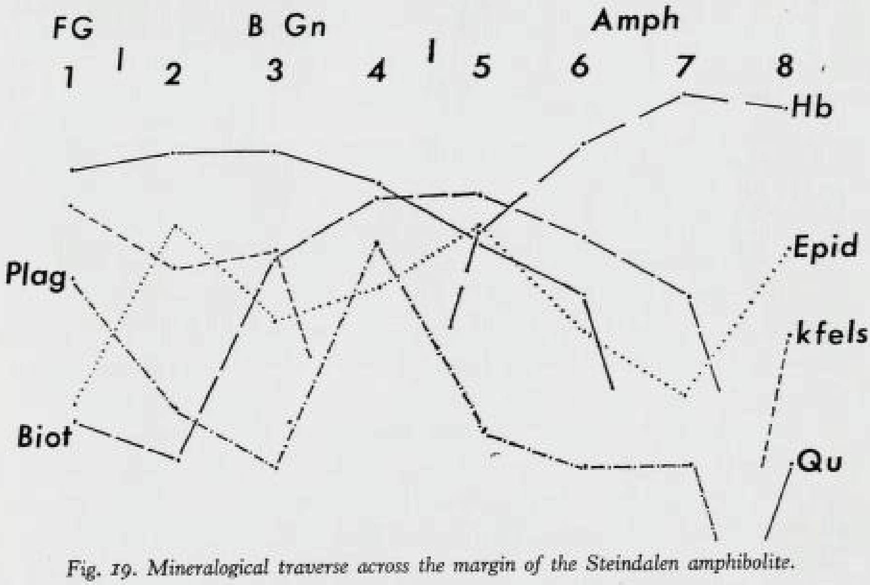


Fig. 19. Mineralogical traverse across the margin of the Steindalen amphibolite.

amphibolite confirms the field observation that the contact with the surrounding biotite gneisses is fundamentally sharp. Here, hornblende is present in even the most marginal amphibolite sample (5), although other mineral variations are neither so extreme nor so obviously related to the precise margin, and there seems to be evidence for a discreet contact zone, shown here by samples 4 and 5. This zone is best characterised by the high biotite mode, which decreases into both the amphibolite and the biotite gneisses, although K-felspar and plagioclase also have an intermediate level. (The epidote mode shows no significant relationship with the contact, confirming the petrograhpic observation that it is a later, replacement mineral.)

Chemical relations. The same samples have been analysed (fig. 20) and a chemical traverse is presented (fig. 21). Chemically, the intermediate

Spec.no.	5*	7*	8*	x	s
SiO_2	53.9	49.8	53.3	52.3	2.3
TiO_2	0.78	0.44	0.49	0.57	0.19
Al_2O_3	16.2	8.4	8.4	11.0	4.8
Fe_2O_3	3.60	2.62	2.71	2.71	0.66
FeO	5.47 +	7.16 +	5.17 +	5.93	1.01
MnO	0.025	0.032	0.22	0.092	0.114
MgO	8.5	17.1	13.3	12.7	4.28
CaO	7.0	11.3	13.0	10.4	3.1
Na_2O	1.2	0.7	1.5	1.1	0.41
K_2O	3.7	1.3	1.25	2.1	1.5
P_2O_5	0.16	0.17	0.11	0.16	0.03
H_2O	0.40	0.44	0.08	0.31	0.20
CO_2	n.f. +	0.03 +	0.02 +	0.02	0.01
Totals	100.94	99.49	99.55	—	—

Fig. 20. Chemical analyses of amphibolites; Key as in fig. 12. Specimen localities on map 1.

zone is perhaps less distinct; Ca, Mg and Fe are relatively high in the amphibolite, whereas Na, K, Al and Si are relatively high in the biotite gneisses. However, Al and K are particularly interesting for the drop in their levels occurs not at the contact between biotite gneiss and amphibolite, but between marginal, biotitic amphibolite, and central, hornblendic amphibolite.

These features are taken to indicate migration of chemicals across a distance of a few metres near the amphibolite contact. As a result, new minerals have grown in a sort of «reaction rim». More particularly, the

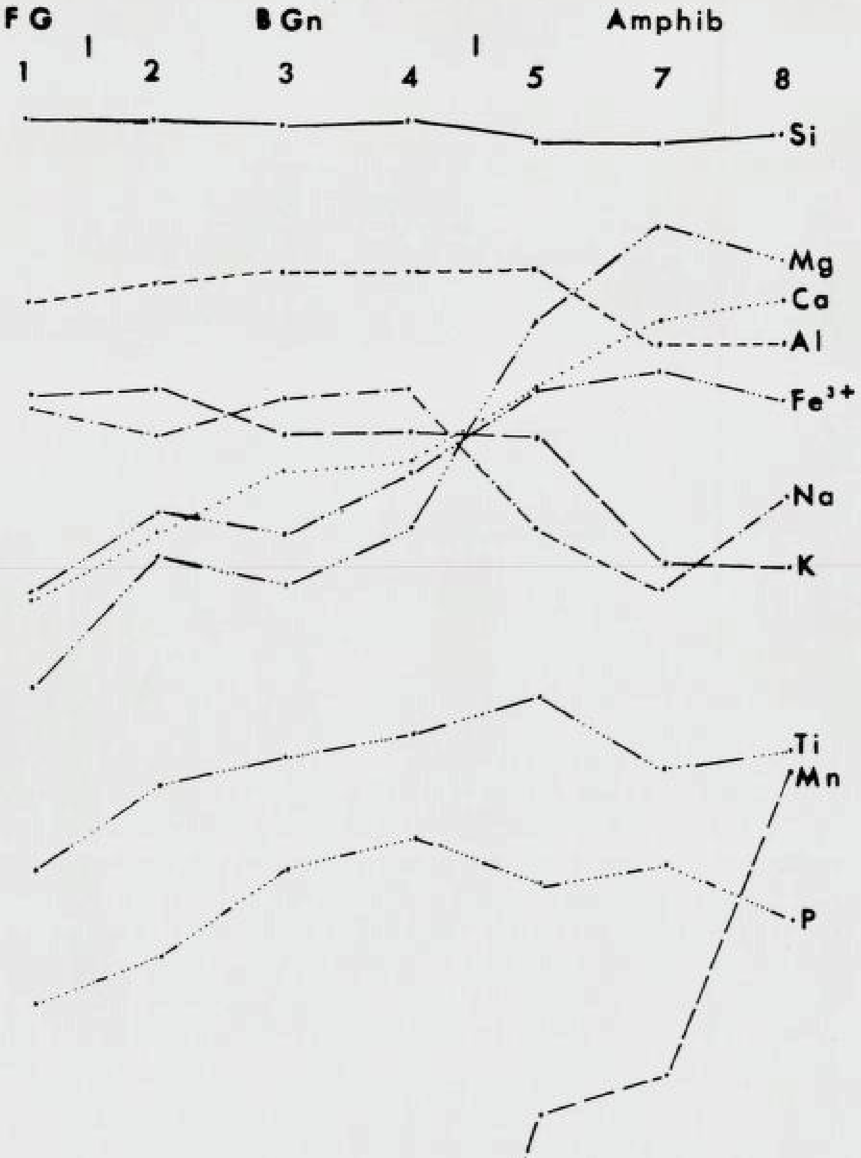


Fig. 21. Chemical traverse across biotite gneiss/ amphibolite contact.

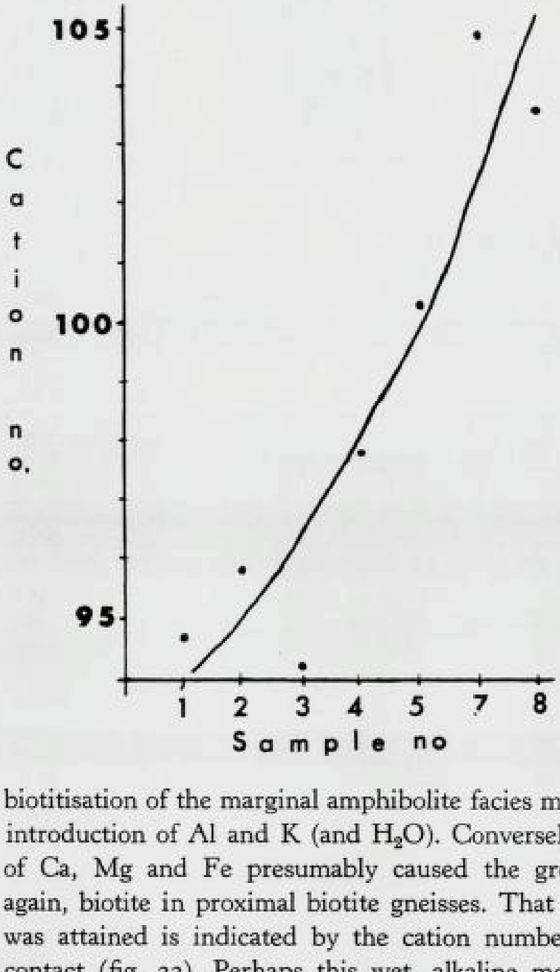


Fig. 22.

Cation numbers per standard (Barth) cell across the Steindalen amphibolite contact.

biotitisation of the marginal amphibolite facies may have resulted from the introduction of Al and K (and H_2O). Conversely, the outward migration of Ca, Mg and Fe presumably caused the growth of plagioclase and, again, biotite in proximal biotite gneisses. That some sort of equilibrium was attained is indicated by the cation number distribution across the contact (fig. 22). Perhaps this wet, alkaline modification of the already existing amphibole may best be correlated with the period of extensive K-felspar pegmatisation in the biotite gneiss. Only small amounts of pegmatite are found within the amphibolites, however, although, as may be expected, thin biotiterich selvages are normally found adjacent to such veins.

3. *Schistose muscovite gneisses/biotite gneiss, foliated granite.*

Mineralogical relations. Modal analyses of all these lithologies are tabulated elsewhere (figs. 1, 4 and 5) and the «granitic mineral» components compared in figs. 23 + 24. The schistose muscovite gneisses are

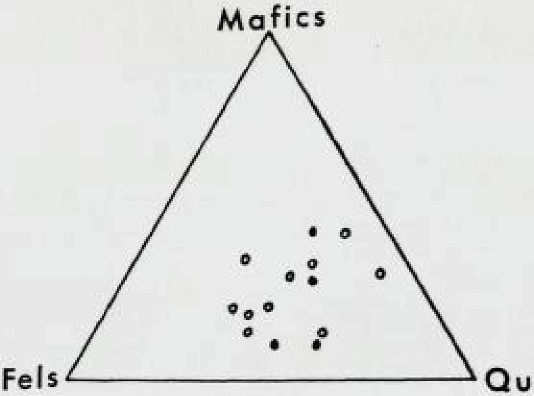


Fig. 23.

Quartz/felspar/mafic minerals diagram for muscovite gneisses: schistose muscovite gneisses — closed dots; flaggy, muscovite gneisses — open circles.

quartz enriched, compared with both the biotite gneisses and the foliated granite.

Two modal traverses have been made (figs. 25 + 26); in these, quartz and muscovite increase into the shear zones, whereas all other minerals-K-felspar, plagioclase, biotite and epidote-decrease in mode. The replacement of primary by secondary minerals is well seen in thin section, and the following reactions are thought to have occurred (in approximate order of increasing shear): —

1. 3 K-felspar + $2H_2O \longrightarrow$ Muscovite + $2K_2O + 12SiO_2$
2. 2 Albite + K-felspar + $2H_2O \longrightarrow$ Muscovite + $2Na_2O + 12SiO_2$
3. 2 Anorthite + K-felspar + $3H_2O \longrightarrow$ Muscovite + Epidote + SiO_2

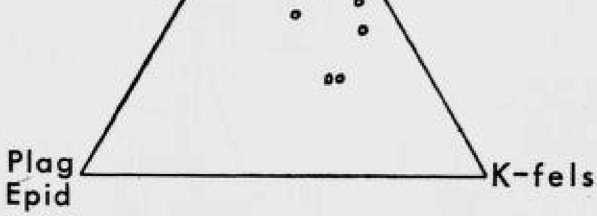


Fig. 24.

Quartz/K-felspar/plagioclase (and epidote) diagram for muscovitic gneisses: closed dots — schistose, muscovite gneisses; open circles – flaggy, muscovite gneisess.

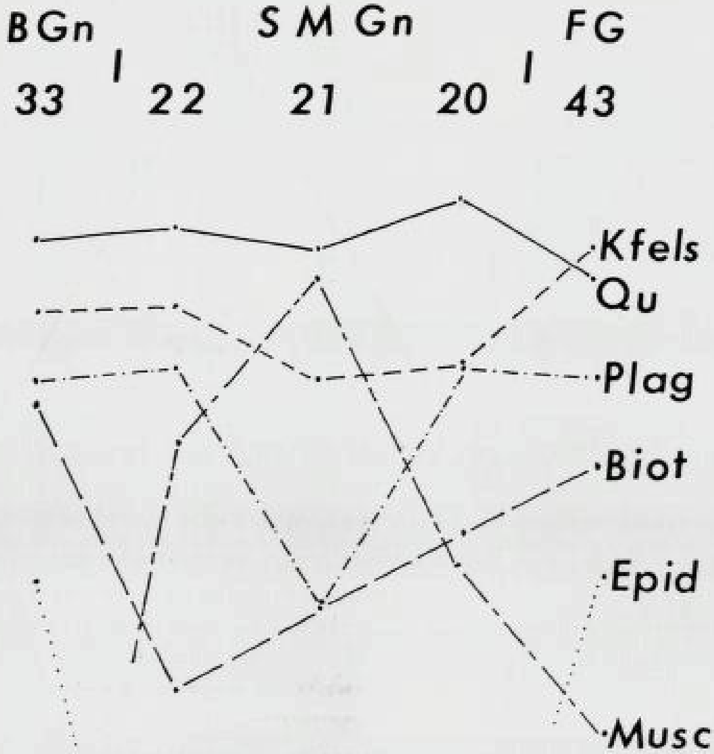


Fig. 25. Mineralogical traverse from foliated granite and biotite gneiss into schistose, muscovite gneiss.

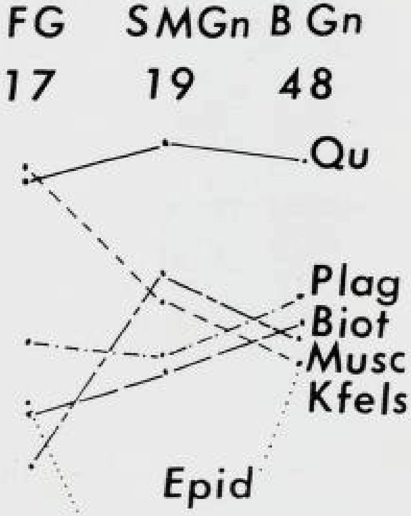


Fig. 26.

Mineralogical traverse from foliated granite and biotite gneiss into schistose, muscovite gneiss.

4. 1.6 Biotite + 1.6OH ⟶ Chlorite + 3.2 K_2O +. 8 Al_2O_3 + 6 SiO_2
5. 3 Biotite ⟶ Muscovite + 2 K_2O + 15 (MgO. FeO) + 4 H_2O + 12 SiO_2
6. 2 Biotite + Epidote ⟶ Muscovite + K_2O + 10 (MgO. FeO) + 2 (CaO. FeO) + 3 H_2O + 15 SiO_2

and possibly, in regions of extreme shear: —

7. Muscovite ⟶ 6 SiO_2 + K^2O + 3 Al_2O_3 + 2 H_2O.

It is probable that the large volume of SiO_2 expected from these reactions contributed largely to the lenses of sheared quartzite found in association with the tear faults. Other «waste products» (i.e. Al_2O_3, CaO, FeO, MgO) are believed to have migrated cut of the zone of maximum shear and to have been «fixed» in a hydrous environment as a predominantly quartz-epidote-clinochlore vein mineral assemblage in joints (Banham, 1966 a). Excess Na_2O could account for the large volumes of perthitic albite found near the shear, and, likewise, the smaller amounts of K_2O perhaps contributed to the slight, secondary K-felspar growth.

Spec.no.	21	22	13	64	95	x	s
SiO_2	71.11+	69.63+	68.1	64.13+	72.64+	69.12	3.27
TiO_2	0.20	0.18	0.29	0.29	0.29	0.25	0.07
Al_2O_3	15.22+	16.03+	16.2	17.64+	16.13+	16.24	0.87
Fe_2O_3	0.22	1.09	n.f.	n.f.	3.08	0.88	1.5
FeO	2.2	1.0	2.8	5.3	0.54	2.4	2.0
MnO	n.f.	n.f.	n.f.	n.f.	0.01	(0.01)	—
MgO	0.80	0.48	0.38	1.38	0.40	0.69	0.47
CaO	0.18	0.17	0.53	2.15	n.f.	0.61	0.95
Na_2O	3.4	5.59	3.7	3.71	3.4	4.0	1.1
K_2O	3.9	5.68	5.8	4.83	5.6	5.16	0.79
P_2O_5	0.09	0.08	0.1	0.27	0.094	0.13	0.08
H_2O	1.28+	1.34+	3.5	0.40+	0.70+	1.44	1.24
CO_2	0.12+	0.03+	0.03+	0.03+	0.05+	0.05	0.04
Totals	98.72	101.30	101.43	100.13	102.93	—	—

Fig. 27. Chemical analyses of micaceous, sheared gneisses; Key as in fig. 12.
Specimen localities are given on map 1.
Specimens 21 & 22 are schistose, muscovite gneisses; the remainder are flaggy, muscovite gneisses.

Chemical relations. Chemical analyses of the fundamental gneisses are given elsewhere (figs. 12 + 13). Two analyses of schistose muscovite gneisses are tabulated here (fig. 27). The alkalies and CaO have been

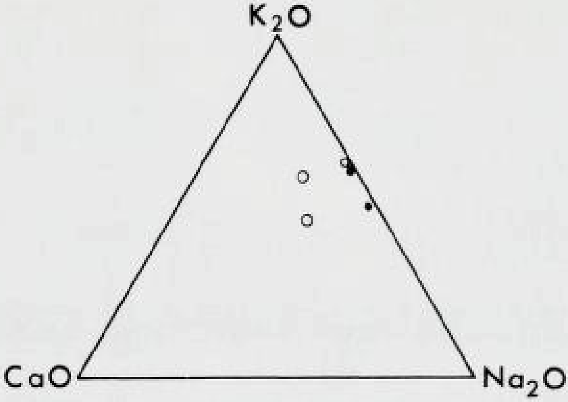


Fig. 28.

$CaO/K_2O/Na_2O$ diagram of muscovite gneisses: closed dots — schistose, muscovite gneisses; open circles — flaggy, muscovite gneisses.

plotted and indicate a relative loss of CaO (fig. 28). A chemical traverse across part of the Briedalen shear zone (fig. 29) shows that in comparison with both biotite gneisses and foliated granite the schistose muscovite gneisses have markedly less Fe_2O_3, TiO_2, P_2O_5, CaO, (and MnO). SiO_2 is slightly up in the shear zone, although the remaining oxides appear to show no significant variations, at least in this rather inadequate traverse.

4. *Schistose chlorite gneiss/amphibolite (and biotitite).*

No modal analyses of these often very fine grained, cataclastic, schistose chlorite gneisses are available.

Chemical relations. Three analyses of chlorite gneisses are given

Spec.no.	84	85	88	x	s
SiO_2	52.77+	61.9	58.0	57.6	4.6
TiO_2	0.94	1.2	2.40	1.54	0.78
Al_2O_3	16.61+	14.80	14.20	15.2	1.26
Fe_2O_3	2.60	1.17	1.41	1,73	0,80
FeO	6.8	5.4	7.7	6.6	1.16
MnO	0.10	0.15	0.08	0.06	0.05
MgO	3.15	2.35	2.92	2.81	0.42
CaO	5.24	5.46	4.79	5.16	0.33
Na_2O	2.32	2.2	2.4	2.3	0.10
K_2O	3.42	3.9	3.7	3.7	0.2
P_2O_5	1.44	0.69	1.67	1.27	0.27
H_2O	1.50+	0.75+	0.73+	0.99	0.44
CO_2	0.03+	0.03+	0.05+	0.037	0.032
Totals	96.92	100.00	100.05	—	—

Fig. 30. Chemical analyses of sheared basic gneiss (schistose chlorite gneisses). Key — fig. 12. Specimen localities on map 1.

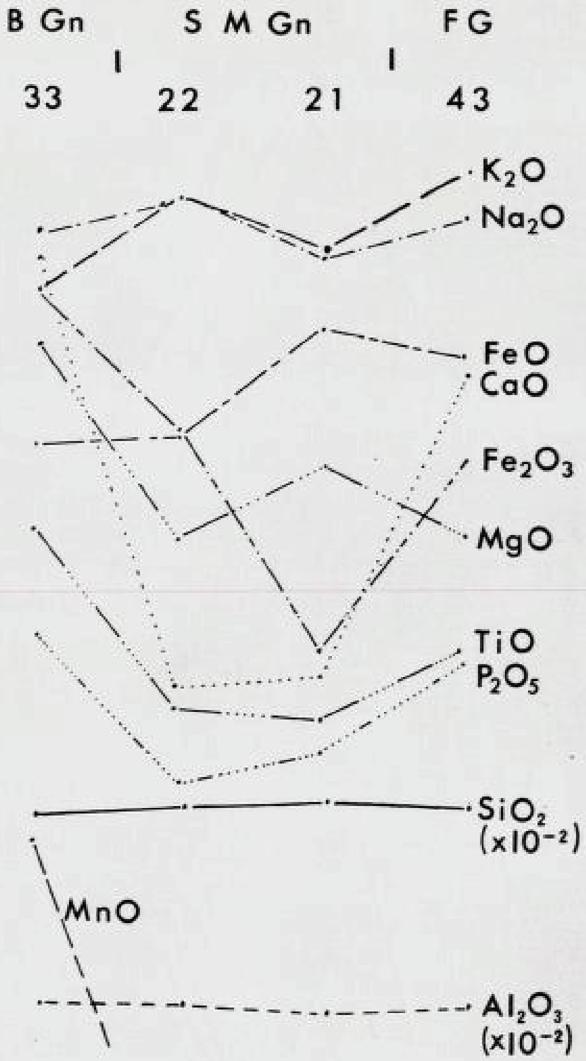


Fig. 29.

Chemical traverse from biotite gneiss and foliated granite into schistose, muscovite gneiss.

in fig. 30. A strong affinity with the marginal, biotitised portions of amphibolite bodies is shown, for example, by a plot of alkalies and CaO (fig. 31). However, the high K_2O, Al_2O_3 etc of the biotitites has resulted from metasomatic processes, whereas similar figures in the chlorite gneisses reflect the cataclastic inclusion of acid gneiss. Nevertheless, their generally similar basic chemistry is believed to show an amphibolitic parentage for the chlorite gneisses. On shearing the folowing reaction may have occurred: —

8. Hornblende + 3 SiO_2 + 2 (OH) ⟶ Chlorite + 2 CaO, Na_2O,
· 6 MgO · 4 FeO

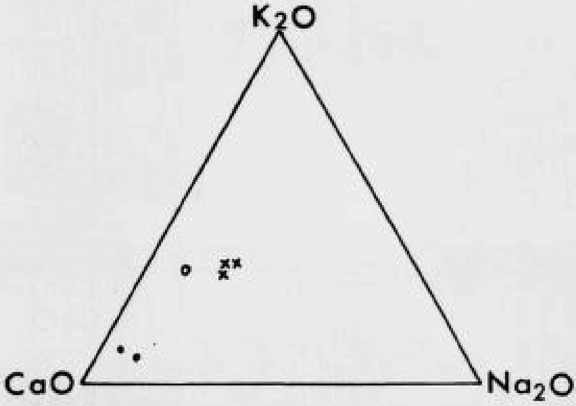


Fig. 31.

CaO/K_2O/Na_2O diagram of basic gneisses; closed dots. — amphibolites; open circle — biotite amphibolite; crosses — schistose, chlorite gneisses.

The volume and number of «waste products» is at first sight rather alarming. However, it is undoubtedly significant that in joints marginal to that part of the Briedalen shear zone which contains the chlorite gneisses, veins of epidote and clinochlore are particularly abundant. (gr. 458435).

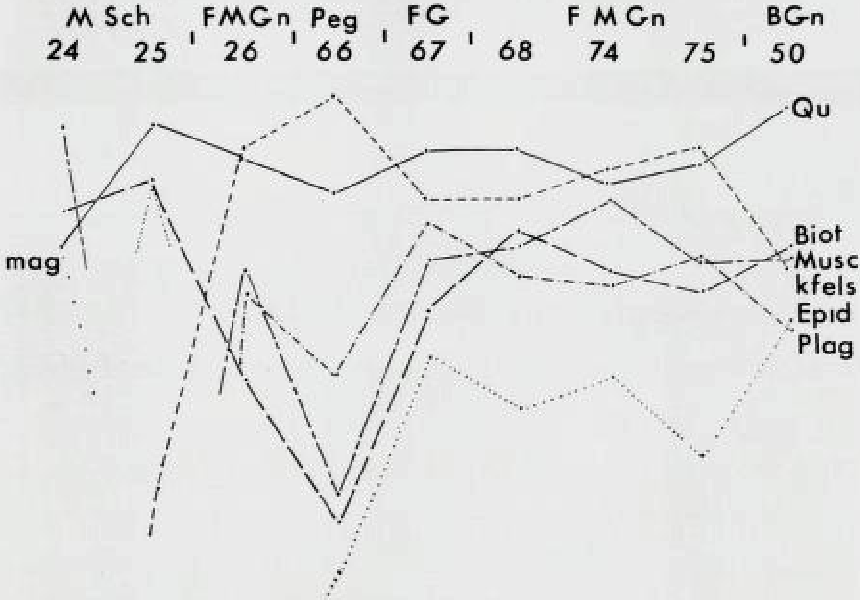


Fig. 32. Mineralogical traverse across the basement contact (mica-schist/flaggy, muscovite gneiss) and various other lithological boundaries (pegmatite, foliated granite and biotite gneiss with flaggy, muscovite gneiss).

5. *Basement Contact.*

Mineralogical relations. Modal analyses of the three lithological groups involved have been given in figs. 1—6.

Modal traverses have been made across the contact at three localities (figs. 32, 33 + 34).

1) Flaggy muscovite gneiss/biotite gneiss (etc). A comparison between these lithologies is difficult because of the variability of the fun-

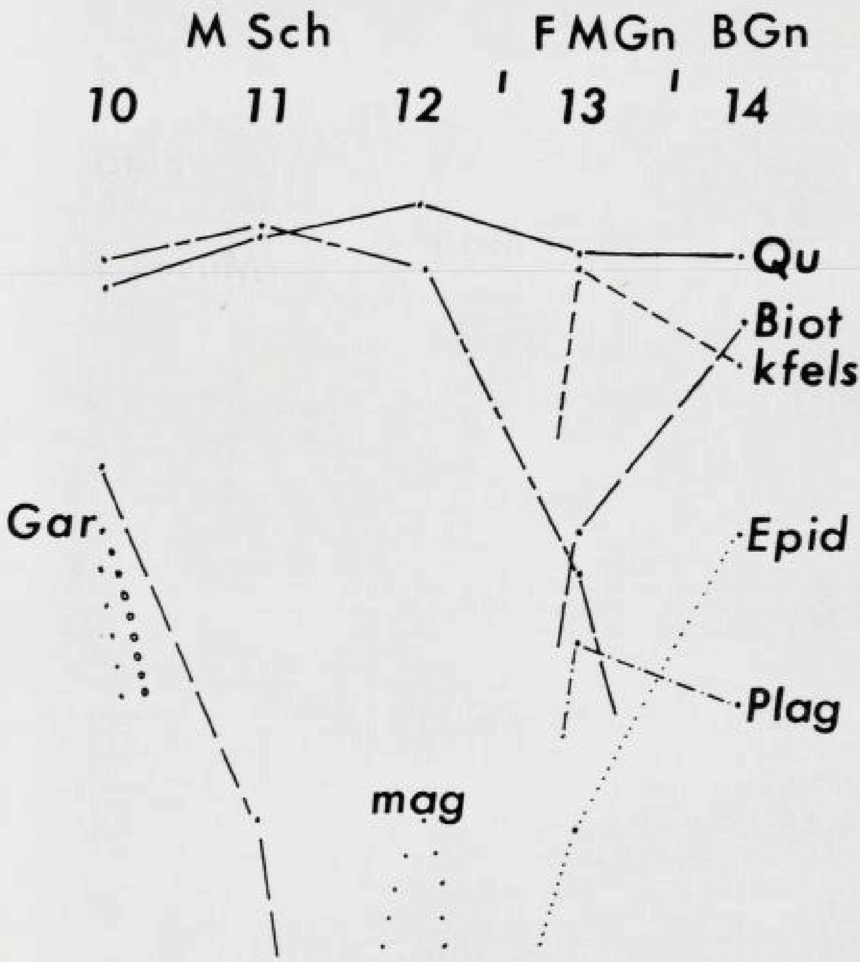


Fig. 33. Mineralogical traverse across the basement contact.

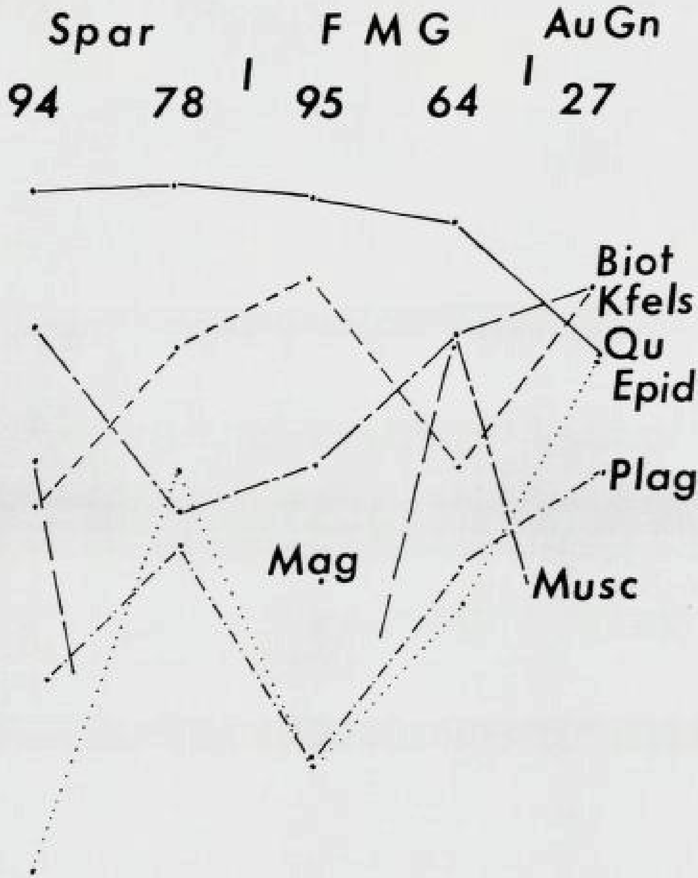


Fig. 34. Mineralogical traverse across the basement contact (Sparagmite / flaggy, muscovite gneiss / augen gneiss.)

damental gneisses in the region of the basement contact. Despite this, however, it is clear that muscovite invariably increases toward the Basal thrust, while the felspars, particularly plagioclase, with biotite and epidote, tend to decrease. It is likely that the shear-induced reactions cited for the schistose, muscovite gneisses also apply to some extent in this shearing environment.

2) Flaggy, muscovite gneisses/Psammite Group. Fig. 33 illustrates a traverse between flaggy gneiss and muscovite schist. Here the

mineralogical break is very sharp; K-felspar, plagioclase biotite and epidote do not pass from the gneiss to the schist, which consists simply of approximately equal proportions of muscovite and quartz. Fig. 32 shows rather a different case; although quartz is prominent in and felspars absent (virtually) from the mica-schist, it contains both biotite and epidote, whereas muscovite is absent. Nevertheless, the contact is sharp. The contact between sparagmite and flaggy-gneiss (fig. 34) is much less distinct, modally, however; in fact, the internal variation in both lithologies seems to be greater than that found at the contact. It is clear, at least, however, that no gradient occurs in this, albeit rather short, traverse.

Chemical relations. Chemical analyses of fundamental gneisses are given elsewhere (figs. 12, 13 + 20). Analyses of three mica-schists and three flaggy muscovite gneisses are presented here (figs. 35 + 27) A plot of alkalies and CaO (fig. 28) shows that the flaggy gneisses, like the schistose gneisses described already, are relatively deficient in CaO.

Spec.no.	10*	11*	12*	x	s
SiO_2	56.5	68.8	64.2	63.2	5.9
TiO_2	1.1	0.65	1.1	0.95	0.26
Al_2O_3	21.7	14.6	18.2	18.2	3.6
Fe_2O_3	0.92	0.54	0.70	0.72	0.20
FeO	8.8	5.6	6.2	6.9	1.6
MnO	0.81	0.07	0.08	0.32	0.42
MgO	2.2	0.78	1.1	1.36	0.75
CaO	0.97	0.53	0.12	0.54	0.43
Na_2O	1.3	0.3	0.3	0.6	0.47
K_2O	4,8	6.0	7.0	5.9	1.1
P_2O_5	0.17	0.09	0.16	0.14	0.03
H_2O	1.8	1.2	1.1	1.4	0.39
CO_2	0.06+	0.02+	0.05+	0.04	0.02
Totals	101.13	99.18	100.21	—	—

Fig. 35. Chemical analyses of Psammite Group lithologies; Key — fig. 12. Specimen localities on map 1.

A short chemical traverse across the basement contact (fig. 36) indicates that a sort of chemical convergence between fundamental gneisses and metasediments occurs in the flaggy muscovite gneisses. Na_2O and CaO, particularly, decrease towards the contact, as, less spectacularly, do Fe_2O_3,

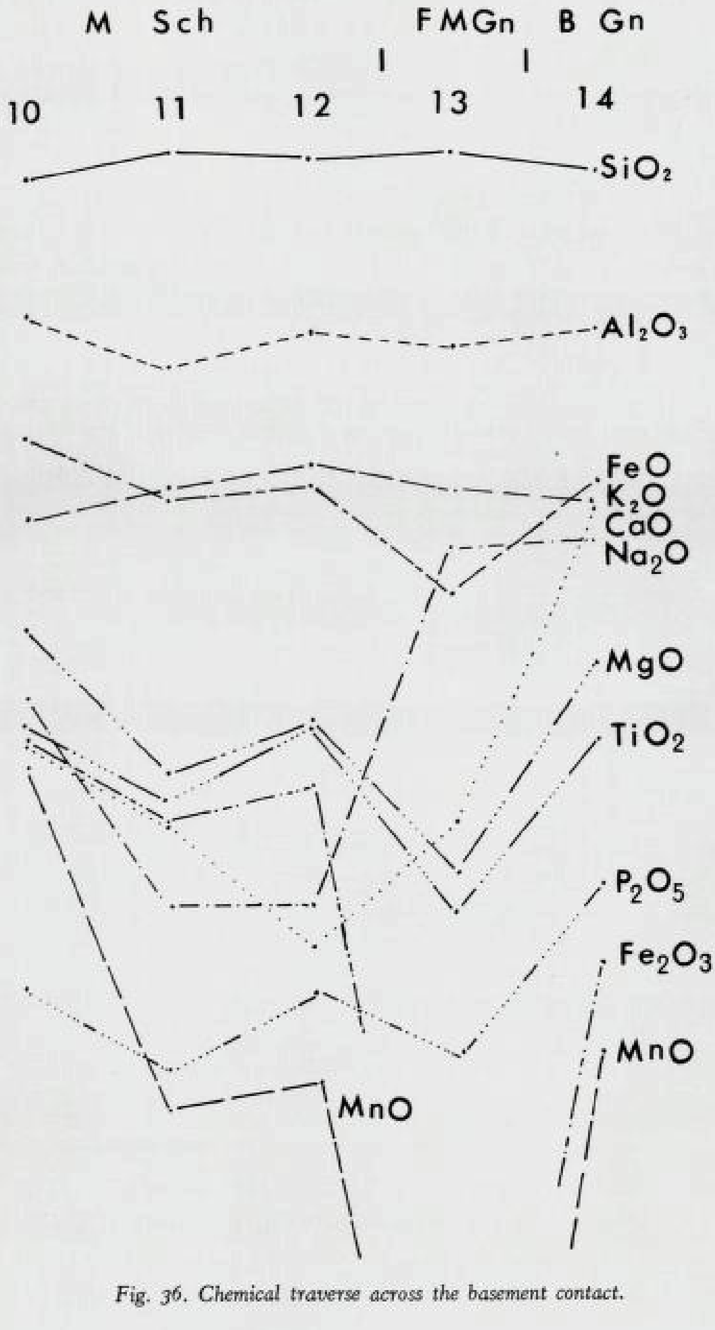


Fig. 36. Chemical traverse across the basement contact.

FeO, MgO, P_2O_5, TiO_2 and MnO. Conversely, SiO_2, Al_2O_3 and K_2O tend to increase. (cf Barth, 1938 who found in the Opdal region a complete transition from sparagmite to basement gneiss).

Spec. no	66.
SiO_2	73.39+
TiO_2	n.f.
Al_2O_3	15.83+
Fe_2O_3	0.01
FeO	0.30+
MnO	n.f.
MgO	0.17
CaO	0.53
Na_2O	2.18
K_2O	7.80
P_2O_5	0.25
H_2O	0.28+
CO_2	0.01+
Total	100.75

Fig. 37. Chemical analysis of a quartzo-felspathic pegmatite sample. Key as in fig. 12. Specimen locality on map 1.

Structure (Basal Gneisses).

Folds.

The fundamental planar element in the Basal Gneiss area is the regionally E-W striking foliation. This appears to have suffered only one phase of folding, and that about numerous axes which plunge rather uniformly 090° at 20°—30°. (Strand, 1949, has described folds of a similar orientation in the Grotli area) Folds of this orientation vary from a few metres to hundreds of metres in dimension, and, although fold styles also vary considerably, consistently «face» north (i.e. have steeper, shorter northern limbs) and have more or less steep, south-dipping axial planes.

The range of fold styles may readily be correlated with variations in the broader geological setting. To the South of the Hestbrepiggan granite the steeply-dipping biotite gneisses show rather tight, sharp crested «Z type» folds. Further north, however, in more flatly dipping biotite gneisses overlying the Hestbrepiggan granite, folds of the same trend are much more open and rounded in form. Such folds can be observed particularly well in a magnificent glacier side-wall section (Høybreen, around 504448). Here can be seen a complete lateral transition from tight folds in the south to open folds overlying granite in the north. Further, a vertical variation from open to tight folds may be observed as the section is ascended (fig. 38).

The influence of the granite during the folding of the gneisses seems clear. Possibly upward intrusion, broadly contemporaneous with earth-

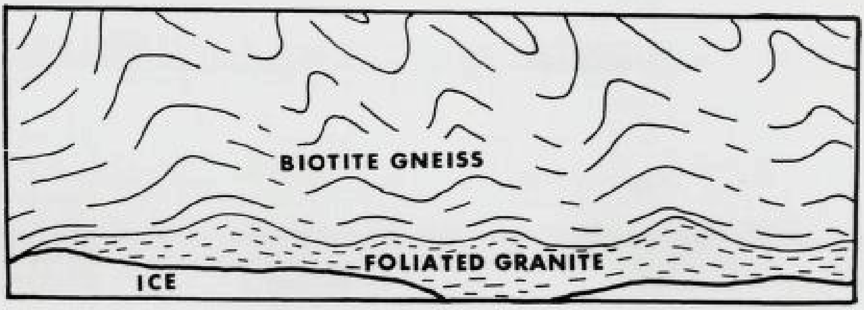


Fig. 38. The relationship between fold-styles, lithology and depth in the Høybreen side-wall section. Length of section — 300 metres.

movements, may have locally reduced lateral pressures. Further, upward heat flow, and, possibly, mineralising agents, may have made gneisses immediately above the granite more plastic and less likely to acquire or retain the tighter folds produced elsewhere. It is interesting to note that although here the gneissose and granite foliations are conformable there remains a sharp lithological break at the contact. Elsewhere, along the steep side margin of the granite, folds in biotite gneisses are truncated by the Hestbrepiggan granite (e. g. near Merrahøe, 445392).

The smaller amphibolite bodies (e.g. in Steindalen g.r. 460389) are involved in these folds, although pegmatites and micaceous gneisses are cross-cutting and clearly developed after this phase of folding.

Faults.

High-angled fractures are extremely numerous in the Hestbrepiggan area (map 3) and although most show slight lateral displacements and are marked by narrow bands of sheared, micaceous gneisses, only one major fault occurs. This is the Briedalen tear fault which strikes through the cliff-bounded valley of that name at 040°, and passes out of the area to both south-west and north-east.

This fault displaces, to an unknown extent, the Hestbrepiggan granite and biotite gneiss, and a zone up to 1000 metres wide containing schistose gneisses and quartzite ribs has been developed as the result of shear-induced recrystallisation of these rocks. Not only has the biotite foliation been disrupted and replaced within the shear zone by a muscovite foliation, but the fundamental gneisses have been rotated on a large scale about a near-vertical axis (map 2). In fact, the fault replaces the middle limb of this sinistral flexure, and indicates thereby the sense of (first) movement of the fault. This rotation of large volumes of gneiss is not consistent, perhaps, with the essentially much more brittle deformation in and around the shear zone. It is possible that rotation, at least, occurred during the declining stages of the main folding episode of the Basal Gneisses.

The only other dislocation of any size is the Hålåtinden (presumed) tear fault, which strikes at 140° through the ridge of that name, and probably continues south-east along the well-marked line of the lake Svartdalsvatn. The widest portion of the shear zone (about 300 metres) cuts through much basic material near Hålåtinden (around 405445). The strike of this fault and the suggestion of a dextral rotation of granite foliation in Midtdalen (415428) may indicate that this is the dextral complement of the Briedalen tear fault. The wide angle (80°) enclosed by these faults perhaps supports the suggestion that at least initial movements occurred when the Basal Gneisses were still relatively mobile, with low internal friction.

Of the minor tear faults, some strike parallel to the major faults, although a more important set strikes 015°—020°, particularly in the area immediately to the south of Briedalen. Faults of this orientation may also account for apparent abrupt dislocations of the southern margin of the Hestbrepiggan granite, although this is very poorly exposed.

Further minor faults striking 065° (approx.) are most conspicuously developed around Høybreen (e.g. 490441) where amphibolites have been sheared, and on Svartdalshøe within the granite, where shear zones are normally less than a few cms. wide.

Two high-angled faults of strike 080°—090° with shear zones up to a few metres wide occur near the southern margin of the granite, and are well exposed on Svartdalshøe and Steindalshøe. Possibly these dislocations are marginal lags associated with the later stages of the intrusion of the granite, the foliation of which they approximately parallel.

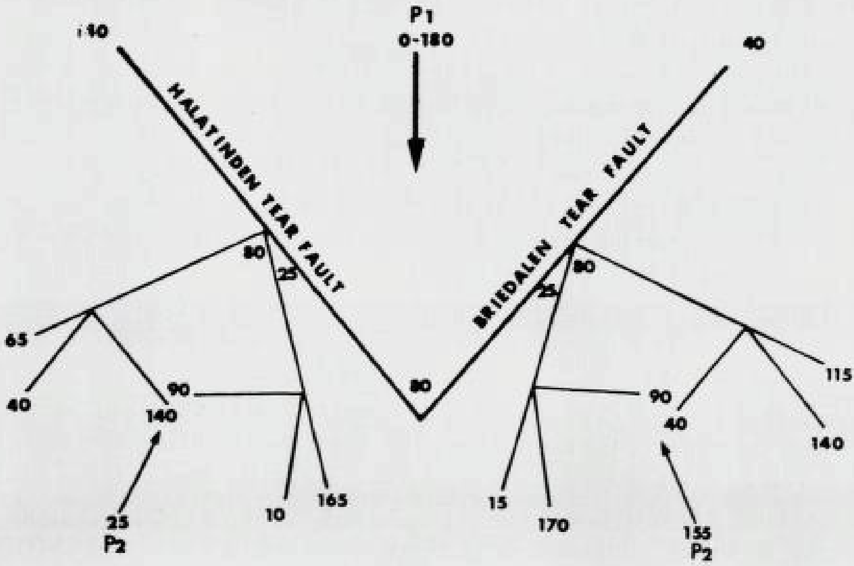


Fig. 39. Predicted pattern of 1st—3rd order, high-angled shears in the Basal gneisses.

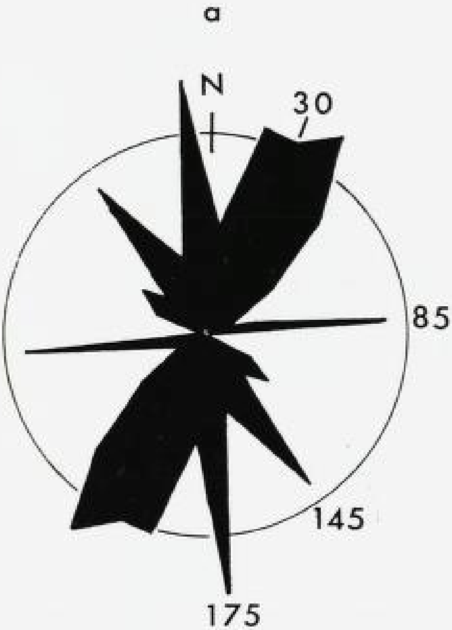
All other faults so far noted are believed to be genetically related, for they can, without too great an act of faith, be attributed to a scheme of 1st to 3rd order shears such as that put forward by McKinstrey (1953) and Moody and Hill (1956). (Fig. 39).

That the Briedalen, and other, tear faults had at least one major phase of activity after the early metamorphism (etc) of the gneisses, is indicated not only by associated retrograde metamorphism, but also by the manner in which the metasediments in the western part of the area appear to have been truncated and rotated.

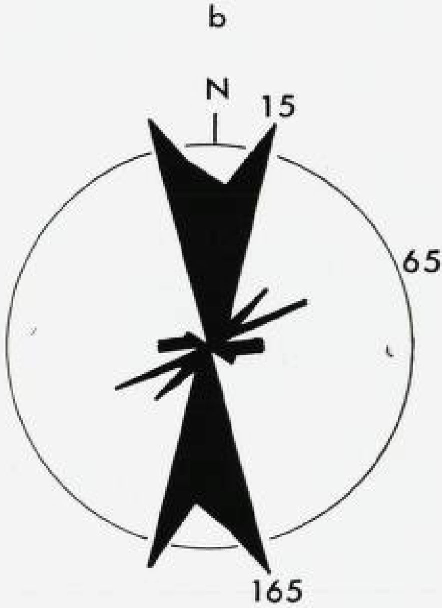
Joints.

At least 100 joint orientation measurements have been made at each of 30 stations throughout the area. Only 10 of these are within the Basal Gneiss area however. A rose diagram of all joints (high-angled, i. e.) shows a confusion of peaks; individual stations show simpler, although varying patterns (fig. 40), reflecting, presumably, their differing positions

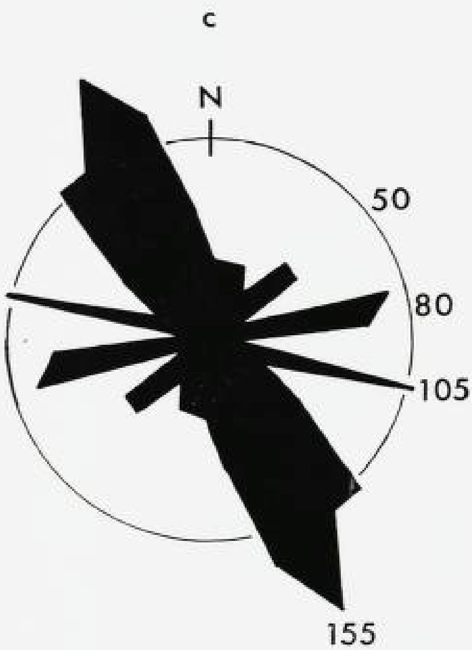
Fig. 40. High-angled joints in the Basal Gneiss area.



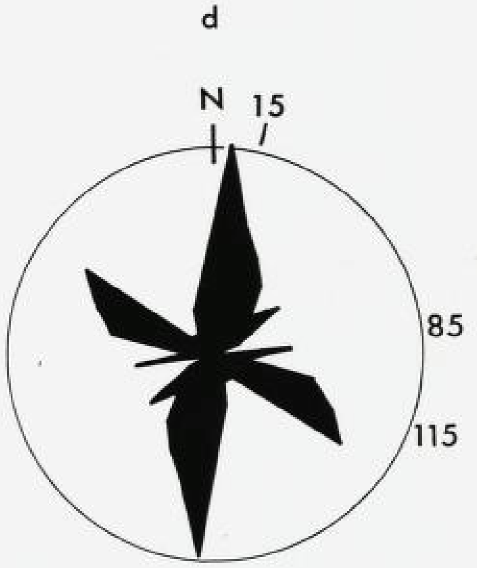
a) g. r. 452428 (82 readings),



b) g. r. 461412 (50 readings),

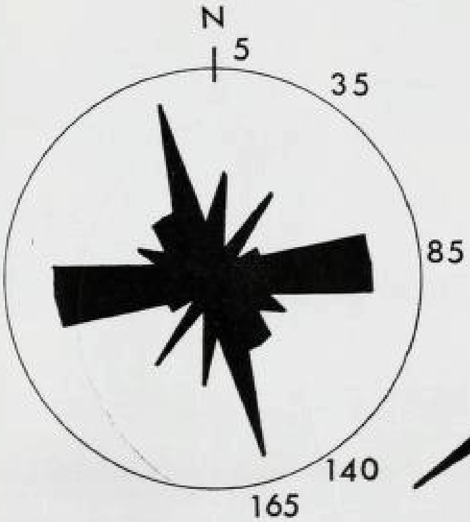


c) g. r. 471400 (82 readings),



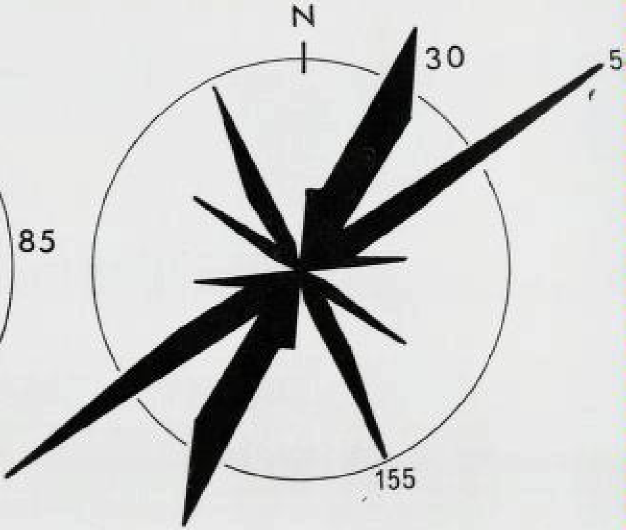
d) g. r. 470414 (53 readings),

e



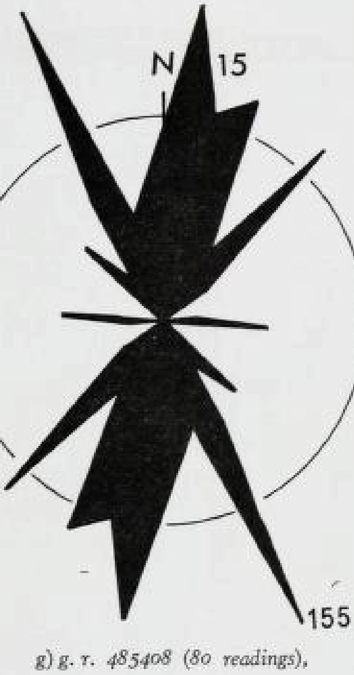
e) g. r. *460406 (60 readings),*

f



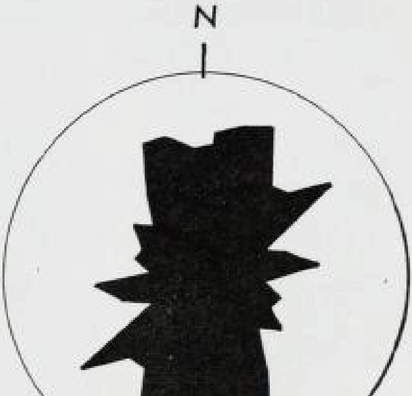
f) g. r. *484407 (80 readings),*

g



g) g. r. *485408 (80 readings),*

h



h) *Total high-angled joints — 487.*

in relation to the major faults. Two distinct peaks are common at 135°—165° and 005°—025°, while smaller, less frequent peaks occur at 050°—055° and 110°—120°, with an even weaker peak at 075°—085°. Conclusions must remain tentative in view of the complexity of the problem and the scarcity of the data and of the wide choice of possible shear directions available theoretically.

Nevertheless, there does seem to be some degree of correlation between the joint patterns on the one hand and actual tear faults plus predicted shear directions on the other. On balance, therefore, a study of joints has tended to confirm the system of 1st—3rd order shears already suggested.

Thrusts.

Two major thrusts occur in the Hestbrepiggan area, both towards the base of the metasediments. The upper, Gjeitaa thrust is best exposed in the east, around Gjeitaabreen, where it appears to divide the Psammtie Group from the Limestone-Pelite Group above (Banham and Elliott, 1965) As a structure entirely within the metasediments it will not be further considered here.

The lower, Basal thrust is developed, normally, precisely at the lithological contactbetween Basasl Gneisses and metasediments (as noted nearly by Landark, 1949; see alreof Skjerli's description (1957) of an area near Leikanger). In reality, therefore this «thrust» would perhaps be better described as a plane of décollement. It should be noted, however, that in the west of the area (around 432383) the thrust plane appears to lie well abovo the base of the Psammite Group. Elsewhere, a considerable variety of ithologies occurs tmmediately above the plane of the thrust, perhaps indicating that the plane of dislocation «wandered» somewhat through the succession Mianly, however and particularly in the west, the thrust is developed within micaceous schists.

Wihtin 10—15 metres above the thrust quartzites are well banded or flaggy and schists display a coarse cleavage sub-parallel to the thrust plane. Below the thrust the Basal gneisses have been sheared to form the «flaggy-muscovite-gneisses» to a varying degree, depending on the frequency of imdrication thrusts within a zone 10—70 metres in vertical extent. The detailed nature of the thrust is indicated in fig. 41; imbrication slices tenb to be occluded to the east. (cf. Strand's (1951) comment on the Sel and Vågå area (p. 13) «The gneisses have sharp contacts to the overlying Sparagmites, but there is no unconformity at the contact»).

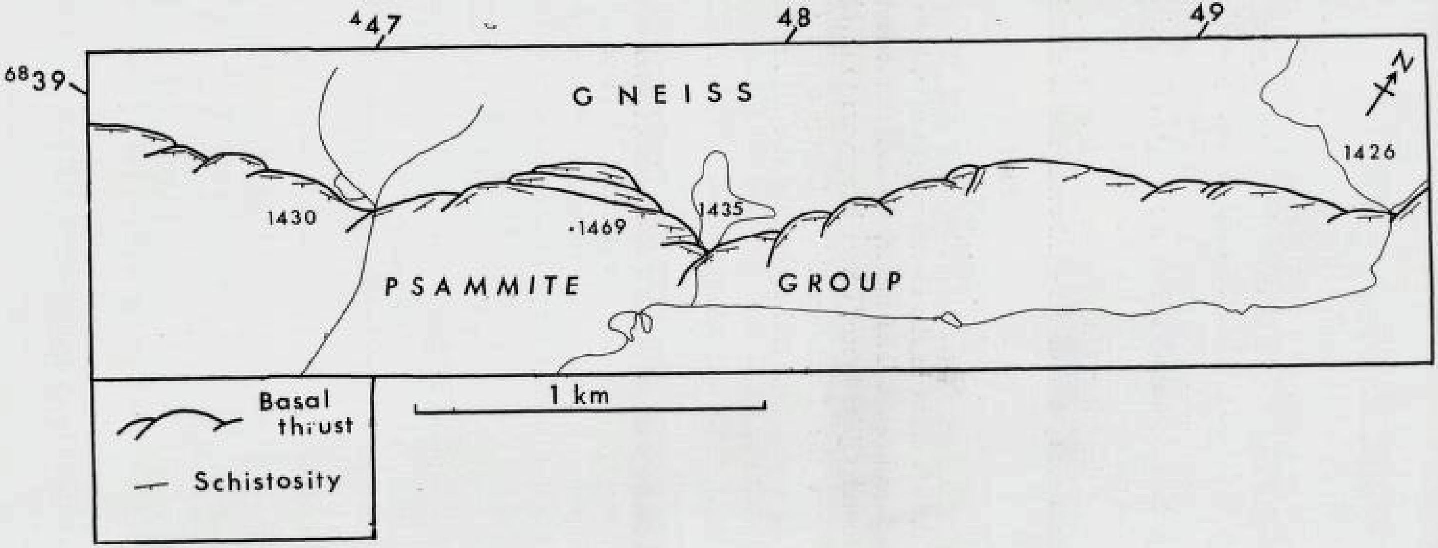


Fig. 41. A detailed map of a portion of the Basal thrust outcrop.

Photo No. 20. «Stripey lineation» developed near the Gjeitaa thrust. (g.r. 525426).

The Basal thrust zone throughout its outcrop has as the dominant minor structure a «stripey», sometimes rodded, (see photo. no. 20) lineation which trends 110°—130° at 25°—45° (fig. 42) Rather open, minor folds which trend 030°—050° are associated with the lineation. These folds

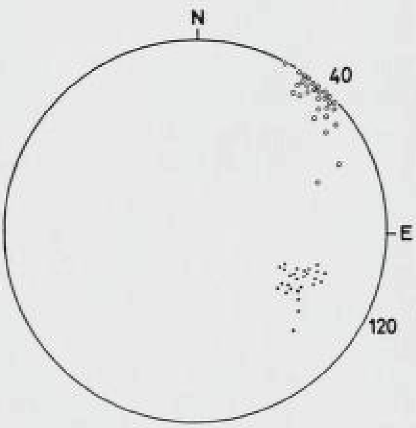


Fig. 42.

Equi-angular projection of poles to minor folds developed in part of the outcrop of the Psammite Group (g. r. 527430) between the Basal and Gjeittaa thrusts. Dots — ««stripey lineation»; open circles — open folds.

consistently face south-east. The rodding is taken to indicate the direction of thrust movement, and the sense of movement from the north-west is indicated by the overturning of the minor folds to the south-east. If it is assumed that the thrust plane was originally sub-horizontal, then an original sense of movement may be determined by removing the rotation imposed by later broad warps (Banham and Elliott, 1965). Thrust, or sliding, décollement movements from the west-noth-west accord well with evidence from other, marginal parts of the Basal Gneiss complex.

(The full, rather complex structural history of the metasediments is to be the subject of a later article).

Geological History and Conclusions.

Basal Gneisses.

The earliest event in the area for which evidence remains was the deposition of a variable sequence of sediments (the proto-biotite gneisses). Basic igneous bodies, the least altered portions of which chemically resemble picrite-basalt, were then intruded (extruded?) into this sequence.

Then began the major phase of folding of the area about E-W axes; it is likely that at this time the basic bodies became deformed into the small, elongate (E-W) pods now observable. Almost certainly penecontemporaneously the area was metamorphosed and felspathised in the almandine-amphibolite facies to form acid biotite gneisses from the sediments, and amphibolites from the basic bodies. This metamorphism was probably accompanied by the development of the regional quartzo-felspathic pegmatite which penetrated and replaced biotite gneisses without marked disturbance, and caused the biotitisation of the marginal portions of the amphibolites, and the development of augen in more basic biotite gneisses. The main, Hestbrepiggan granite (and the other, smaller bodies) was intruded into the biotite gneiss etc. complex and has sharp, sometimes agmatitic contacts, but no metamorphic aureole. That the same general earth pressures continued to operate at the time of granite intrusion is indicated not only by the E-W orientation of the granite mass itself, but also by the fact that the styles of the E-W trending biotite gneiss folds vary according to the position of these folds in relation to the granite.

Further, a post-metamorphism/granite intrusion continuation of these (N-S) pressures may be indicated by the sinistral and dextral rotations of the biotite (gneiss) foliation near the Briedalen and Hålåtinden tear faults respectively. The angle between the fault planes is 80°, and this presumably indicates a low angle of internal friction at the time of initial movement. This, in turn, may have been the consequence of the continued deep burial of the area.

Retrograde metamorphism of the Basal Gneisses to the (middle) greenschist facies is general. In association with minor shears below the Basal Thrust, and in a pronounced zone on either side of the Briedalen and other tear faults occur more or less micaceous and chloritic schists which may be in an even further retrograded state (lowest greenschist subfacies). A suite of vein minerals occurs in joints associated with the tear faults.

Metasediments. (Psammite Group)

Conclusions here must be very incomplete and tentative, for only the narrow outcrop of the basal group (the Psammite Group) has been considered.

The sandstones, shales and arkoses which, with little doubt, originally constituted the Psammite Group, were probably deposited upon Basal Gneisses, Certainly, the present day contact is unconformable and it is possible that a conglomerate was the first deposit, at least in places. Since that time, however, the bulk of the Psammite Group has been moved into the area from a WNW direction, principally along a major, subhorizontal dislocation, the Basal Thrust, which normally follows the surface of the unconformity at the base of the Psammite Group.

These movements probably preceded metamorphism of the sediments in the (middle) greenschist facies. Certainly, the sediments were emplaced and metamorphosed(?) before late, major movements along the Briedalen tear fault dislocated and rotated them in the western part of the area. Some slight retrograde metamorphism associated with parts of the Basal Thrust may indicate that further small movements occurred along this plane of décollement at this time.

The metasedimentary succession of the Hestbrepiggan area has been correlated (Banham and Elliott, 1965) with the Eocambrian—Silurian succession of the Otta nappe of the Sel and Vågå area (Strand, 1951). If this is accepted, then the main Basal Gneiss deformation, metamorphism and granitisation occurred during the Precambrian. Further, the main metasediment thrusting (and folding) and metamorphism are likely to be of «Caledonian» age. Possibly, therefore, the latest movements along the tear faults are of Svalbardian, or at any rate, late or post Caledonian age. (cf Strand, 1951, who also has suggested Svalbardian movements in the area).

Summary.

Precambrian

1. Deposition of the proto-biotite gneisses
2. Intrusion (extrusion?) of basic igneous roks
3. Folding about E-W axes, metamorphism, pegmatisation and granite intrusion in the almandine amphibolite facies.
4. Rotation of fundamental gneisses and incipient movements along tear faults.

Pre- and Lower Palaeozoic

1. Deposition of Eocambrian (and later) sediments unconformably upon eroded Basal Gneisses.
2. Movement of sediments from WNW on Basal Thrusts, and superficial shearing of Basal Gneisses
3. Metamorphism of the sediments and retrograde metamorphism of the Basal Gneisses in the (middle) greenschist facies.

Post Lower Palaeozoic (Middle — Upper Devonian?)

1. Movement along the Briedalen (and other) tear fault(s) and the local, shear-induced retrograde metamorphism to the lowest greenschist sub-facies with associated vein minerals. (Also some slight movement and retrograding along Basal Thrust).

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Appendix I-Mineral chemistry and X-Ray data.

Chemical and X-ray data on minerals from the Hestbrepiggan area

Chemical analyses were carried out as for the rocks, although difficulties were encountered in dissolving some of the mineral powders and in estimating dilution factors. For these reasons partial analyses containing only the most reliable determinations are often given. (Analyst PHB).

X-ray photographs were obtained with a Phillips 11.46 powder camera; cobalt radiation used throughout. Film reference numbers are those of the Departement of Geology, Nottingham University.

Mineral samples for analysis were separated by various methods, including handpicking, heavy liquids, shaking tables and magnetic separator (Appendix 2).

Felspars.

Chemistry. The compositions of bulk felspar samples (fig. A1) from 7 acid Basal Gneisses were determined by the analysis of felspar plus quartz samples very readily separated from ferromagnesian minerals using the

Spec.no.	F4	F14	F17	F19	F33	F36	F38
SiO_2	76.47	67.8	76.39*	82.21*	72.08*	74.17*	74.55*
TiO_2	0.19	0.63	0.23	0.16	0.53	0.35	0.22
Al_2O_3	15.36	17.6	13.86	9.68	14.96	14.1	13.9
Fe_2O_3	0.18	0.54	0.31	0.32	0.54	0.43	0.31
FeO	0.38	0.68	0.32	0.66	0.22	0.34	0.35
MnO	0.08	0.04	nd	nd	nd	nd	nd
MgO	nf	0.48	nf	0.48	0.51	nf	nf
CaO	2.8	3.18	1.02	0.57	3.27	1.37	0.98
Na_2O	4.7	4.4	3.7	2.6	5,3	3.25	3.6
K_2O	0.52	4.25	4.00	3.15	2.2	5.9	6.0
P_2O_5	0.21	0.47	0.17	0.17	0.39	0.09	0.09
H_2O	not determined.						
Totals	100.9	99.9	100.00*	100.00*	100.00*	100.00*	100.00*

* — *SiO_2 by difference.*

Fig. A1. Chemical analyses of felspars; F4, F4 and F33 — biotite gneiss, F7, F9, F36 and F38 foliated granite.

magnetic separator. From these analyses the proportions of Or, Ab and An have been calculated. These «normative» proportions used together with felspar modes allow reliable estimates of the temperature of formation of the rocks to be made (Banham, 1966 b). Comparison with the data of Bowen and Tuttle (1958, p. 136) indicates the normality of the Hestbrepiggan granite felspar proportions (samples 36, 38 and 17, fig. A2). Biotite

Spec.no.	F36	F38	F17	F4	F14	F33	F19
Or	51	51	50	6	33	18	44
Ab	40	43	42	71	48	61	50
An	9	6	8	23	19	21	6

Fig. A2. «Normative» felspar percentages recalculated from information in Fig. A1.

gneiss felspars (4, 14, 33 fig. ?) show a remarkably consistent An content, although the Or: Ab ratio varies considerably. Sample 19 is a slightly sheared granite and the deficiency in Or is probably the result of replacement of microcline by muscovite.

Biotites.

Chemistry. Partial analyses of 9 biotites are given in fig. A3. A triangular plot of «diagnostic cations» (fig. A4; i. e. Fe, Mg and K) indicates that biotites from all over the area are generally intermediate in type.

Spec.no.	B4	B5	B10	B14	B17	B33	B36	B38	B89
SiO_2	36.1	nd	nd	nd	nd	nd	nd	nd	38.1
TiO_2	1.7	0.59	1.15	1.60	1.95	1.44	1.15	1.40	1.90
Al_2O_3	12.4	nd	nd	nd	nd	nd	nd	nd	17.0
Fe_2O_3	20.4	15.7	16.1	15.6	13.4	17.1	21.4	20.4	19.2
FeO	not determined; total Fe as Fe_2O_3.								
MnO	0.09	0.15	0.62	0.23	0.18	0.29	0.22	0.37	0.12
MgO	10.1	10.8	6.3	7.4	5.9	6.0	6.7	5.2	10.9
CaO	1.5	3.0	0.9	2.0	0.9	3.1	3.0	1.8	0.21
Na_2O	4.9	5.2	5.3	2.0	2.8	1.3	2.0	1.9	0.61
K_2O	9.6	7.2	4.4	9.0	7.8	6.8	6.0	8.8	7.7
P_2O_5	0.22	0.22	0.17	0.10	0.18	0.09	0.24	0.18	0.21
H_2O	not determined.								

Fig. A3. Partial chemical analyses of biotites; B10-garnet-mica-schist, B4, B14 and B33-biotite gneisses, B5-amphibolite (marginal), B89-biotitite, B17, B36 and B38-foliated granite.

This is confirmed by the additional plot (fig. A5) of samples B4 and B89 on an Al, Mg, Fe diagram. Biotites from granites are relatively enriched in Fe (siderophyllite-annite mol), however, and biotites from amphibolites and biotitites show the highest Mg content (phlogopite-eastonite mol.), whereas biotite gneiss and mica-schist biotites are intermediate. It is noteworthy that biotite from the granodioritic biotite gneiss (B4) from

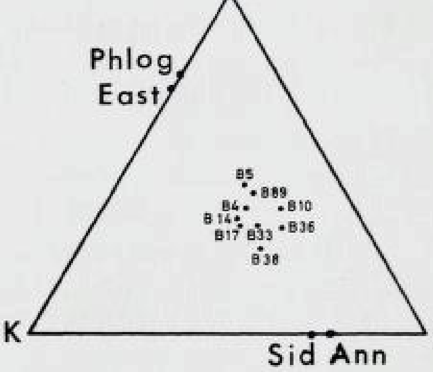

Fig. A4. Mg/Fe/K plot for 9 biotites.

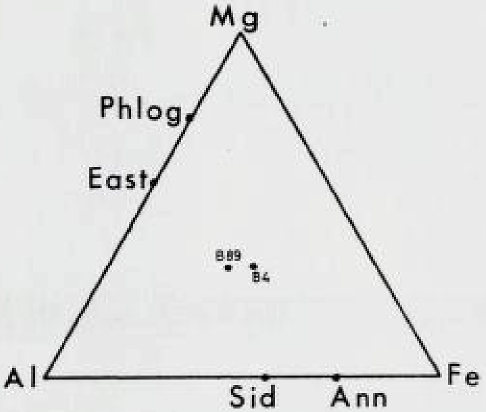

Fig. A5. Mg/Al/Fe plot for two biotites.

within cms. of the Steindalen amphibolite is also enriched in Mg and closely approaches the composition of a biotite from a biotitite. The mica-schist biotite is deficient in K relative to the gneissose biotites.

X-ray data have been obtained for all of the 9 biotites chemically analysed; throughout, the d-values are quite normal (10.48, 3.37, 2.66, 2.45, 2.18, 1.55) Chlorite is present in all samples (line d-value 7.41 is commonly among the 6 most intense lines) but particularly in biotite

Spec.no.	B4	B5	B10	B14	B17	B33	B36	B38	B89
Fe	35	32	45	35	36	42	48	45	36
Mg	36	43	34	32	31	29	29	23	40
K	29	25	21	33	34	28	23	32	24
Fe:Mg	0.97	0.75	1.32	1.10	1.16	1.45	1.65	1.96	0.90

Fig. A6. Certain cation proportions of biotites calculated from information in fig. A3.

(B10) from a garnet mica-schist close to the Basal thrust. The presence of goethite (FeO(OH)) is possibly indicated in biotite gneiss, foliated granite and biotitite (film nos. 221—223) by a line of d-value 4.17.

Muscovites.

Chemistry Only one muscovite sample, from a garnet-mica-schist within the Psammite group, has been analysed (fig. A7). This appears to be a normal muscovite ($(KNa)_2Al_4Si_6(Al_2)O_{20}$), with, possibly, some Fe and Mg substituting for Al. Slight contamination of the sample with

Spec.no.	H8	M10	E39
SiO_2	48.87	51.97	nd
TiO_2	0.39	0.49	nd
Al_2O_3	12.0	27.25	20.5
Fe_2O_3	9.2	4.3	12.3
FeO	not determined; total Fe as Fe_2O_3.		
Mno	0.36	0.26	nd
MgO	14.3	1.8	nd
CaO	12.1	nf	nd
Na_2O	1.5	1.7	nd
K_2O	0.65	9.2	nd
P_2O_5	0.041	nf	nd
H_2O	0.40	3.01*	nd
Totals	99.82	100.00*	—

* — *H_2O by difference.*

Fig. A7. Chemical analyses of three minerals; H8-hornblende; M10 — muscovite from garnet-mica-schist; E39 — vein epidote from the Høybreen backwall

magnetite and biotite would be difficult to disprove, however. Similarly, a slight contamination with albitic material is possibly indicated by the rather high Na content, which if expressed entirely as paragonite would in ratio with the muscovite, suggest a temperature too high for the observed facies of the rock (Eugster and Yoder, 1954, p. 125).

Epidote.

Chemistry Al_2O_3 and Fe_2O_3 only, have been determined for a vein epidote from the backwall of Høybreen (fig. A7). The $Fe^{+++}:Al^{+++}$-ratio is 37.5 % and thus this particular epidote is an iron rich pistacite (Winchell, 1956, 10—40 % Fe^{+++} for Al^{+++}, pistacite).

Hornblende.

Chemistry The analysis of a hornblende separated from the central part of the large, Steindalen amphibolite (fig. A7) would seem to give the approximate, general formula: —

$$NaCa_2\ (Mg_3Fe_2)_5\ (OH)_2\ Si_6Al_2O_{22}$$

Garnet.

X-ray data. X-ray photographs of five (3 metasedimentary and 2 gneissose) garnets show practically identical series of d-values, each indicative of virtually pure almandine (2.59, 1.55, 2.90, 1.60, 2.35).

Stilbite.

X-ray data. A white mineral with radiating crystal structure found in a few, small (5 cms) vesicles in the Briedalen zone of shear mineralisation (Banham, 1966a) has a powder photograph recognisable as that of the zeolite stilbite (4.07, 9.20, 4,65, 3.03, 3.39, 3.19, film no. 284).

Magnetite-ilmenite.

X-ray data. A massive, apparently amorphous, brownish metallic mineral found in small, irregular veins in heavily pegmatised biotite gneisses (sample from 481410) has been found to consist of a «mixture» of magnetite and ilmenite (film no. 286; magnetite lines — 2.54, 1.47, 2.98; ilmenite lines — 2.75, 2.54, 1.72. The shared 2.54 line is very intense, although not so heavy as the 2.75 ilmenite line).

Monazite.

X-ray data One sample from the metamict core of a mica (mainly biotite) vesicle in heavily pegmatised biotite gneiss (480439) gave faint lines against a fogged background almost certainly indicative of monazite (film no. 288; 3.08, 3.29, 287, with some chlorite possibly indicated by a faint line at 4.17).

Appendix II-Magnetic separation of minerals.

Method used for separation of Minerals using magnetic separator.

1. Crush sufficient rock sample to powder of 60—100 mesh (avoid dust); jaw and roller crushers used.
2. Magnetically separate. The Nottingham University Department of Geology magnetic separator was set at a forward slope of 25° and a side slope of 15° throughout this work, and minerals were separated by repeated runs at the following amperages (approx. -depending on precise composition): —

almandine garnet	0.4 amps
iron rich biotite	0.6—0.7 amps.
magnesium rich biotite	0.8—0.85 amps
epidote	0.95 amps
hornblende	1.5 amps
muscovite	1.3—2.0 amps

quartz and felspars remain in the non-magnetic channel throughout. (The Nottingham Geology separator is approximately half as powerful as the standard Franz Isodynamic Magnetic Separator as is indicated by the amps. quoted above (cf Rosenblum, 1958).)

3. Check sample for purity microscopically; hand pick, if necessary.

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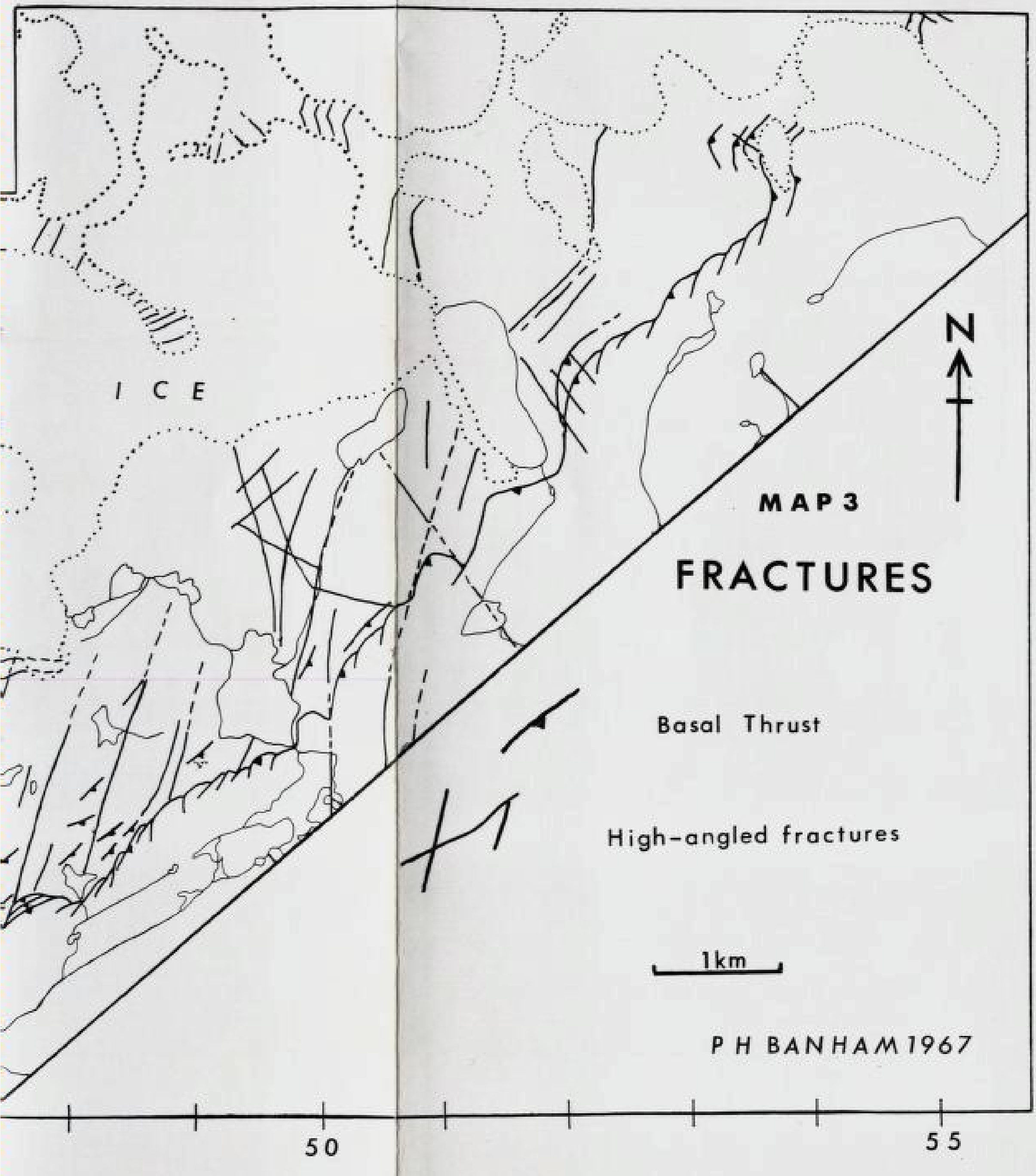

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MAP 3
FRACTURES
ICE
Basal Thrust
High-angled fractures
1km
P H BANHAM 1967
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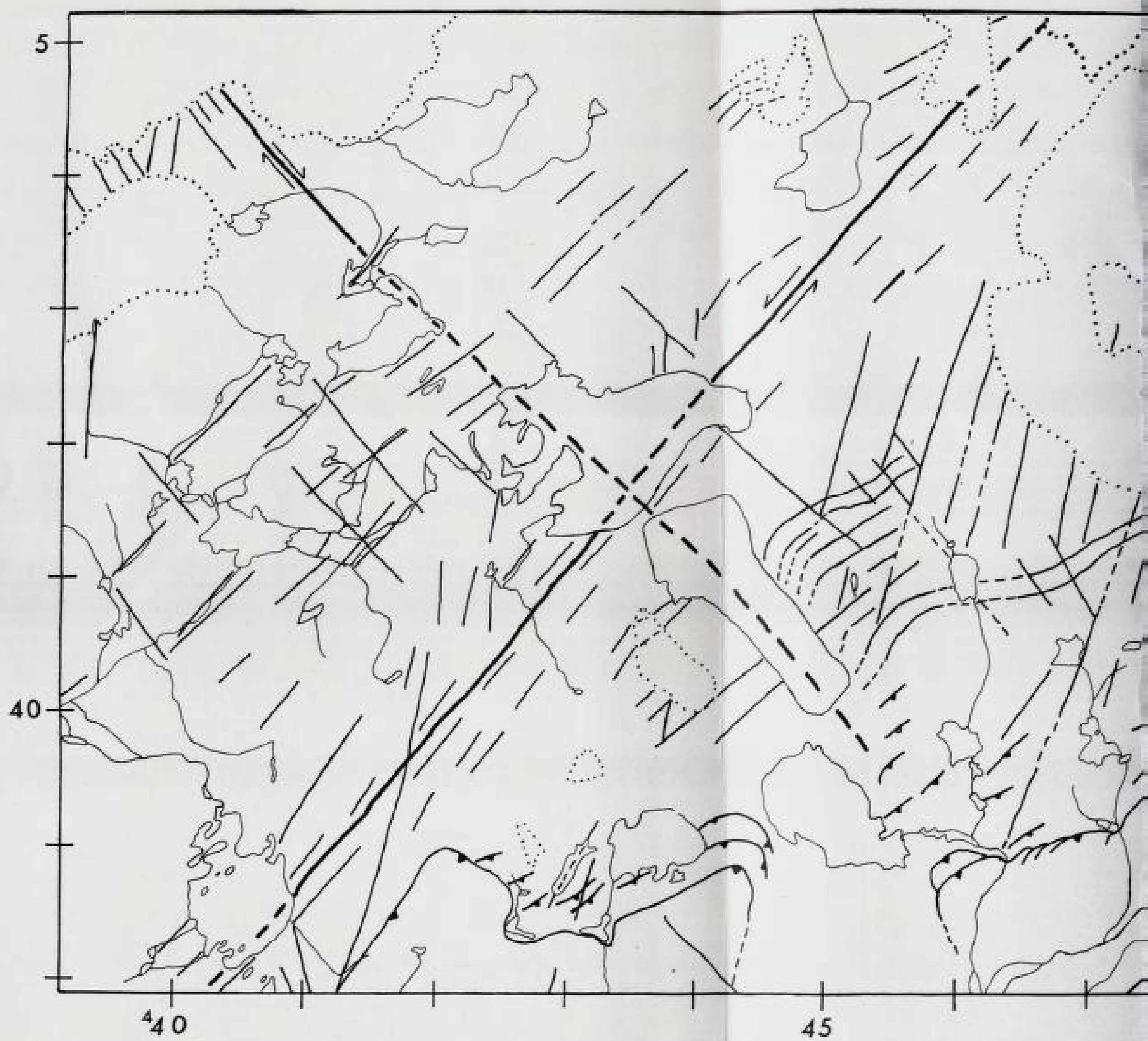

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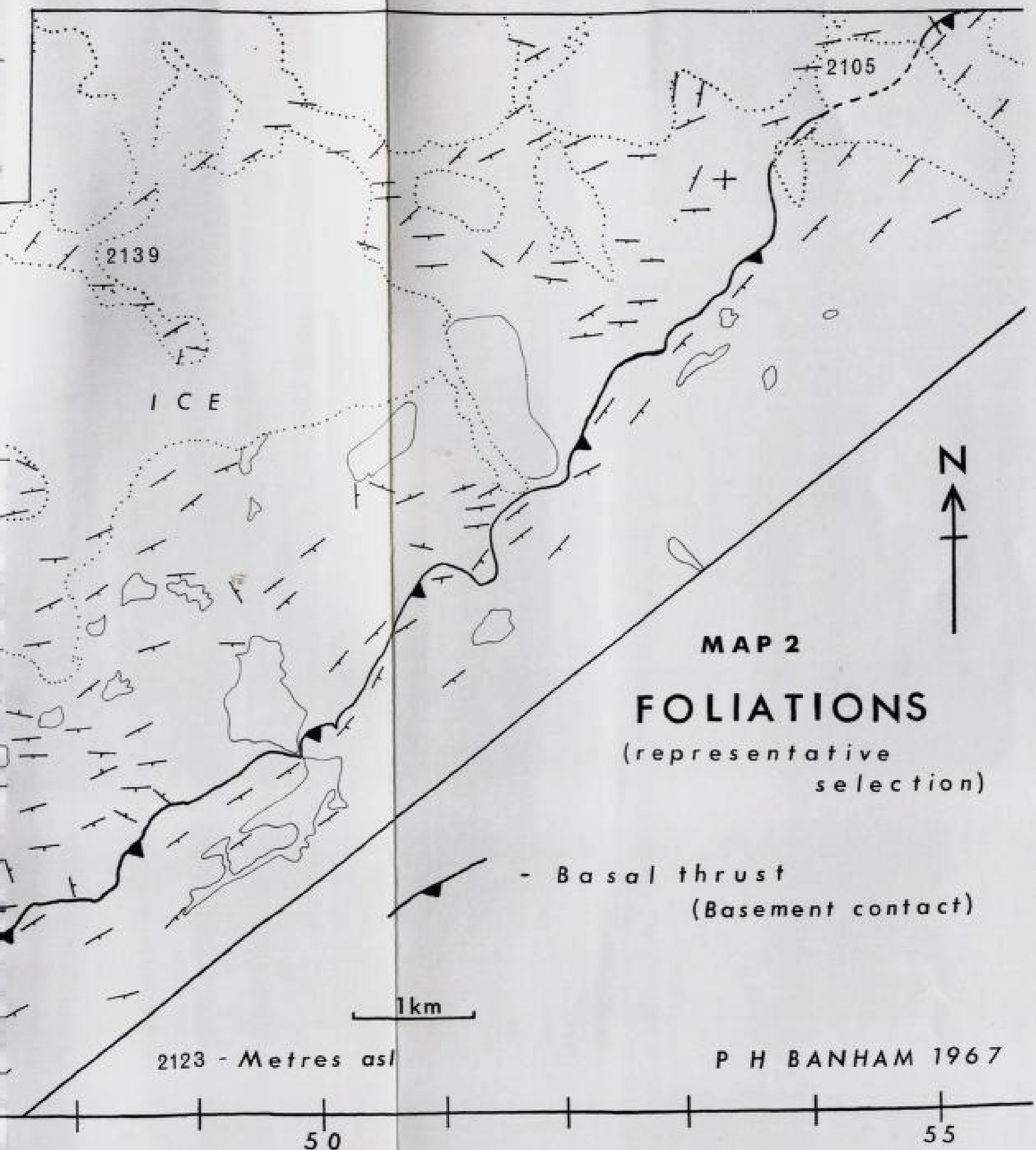
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MAP 2
FOLIATIONS
(representative selection)
- Basal thrust (Basement contact)
1km
2123 - Metres asl
P H BANHAM 1967
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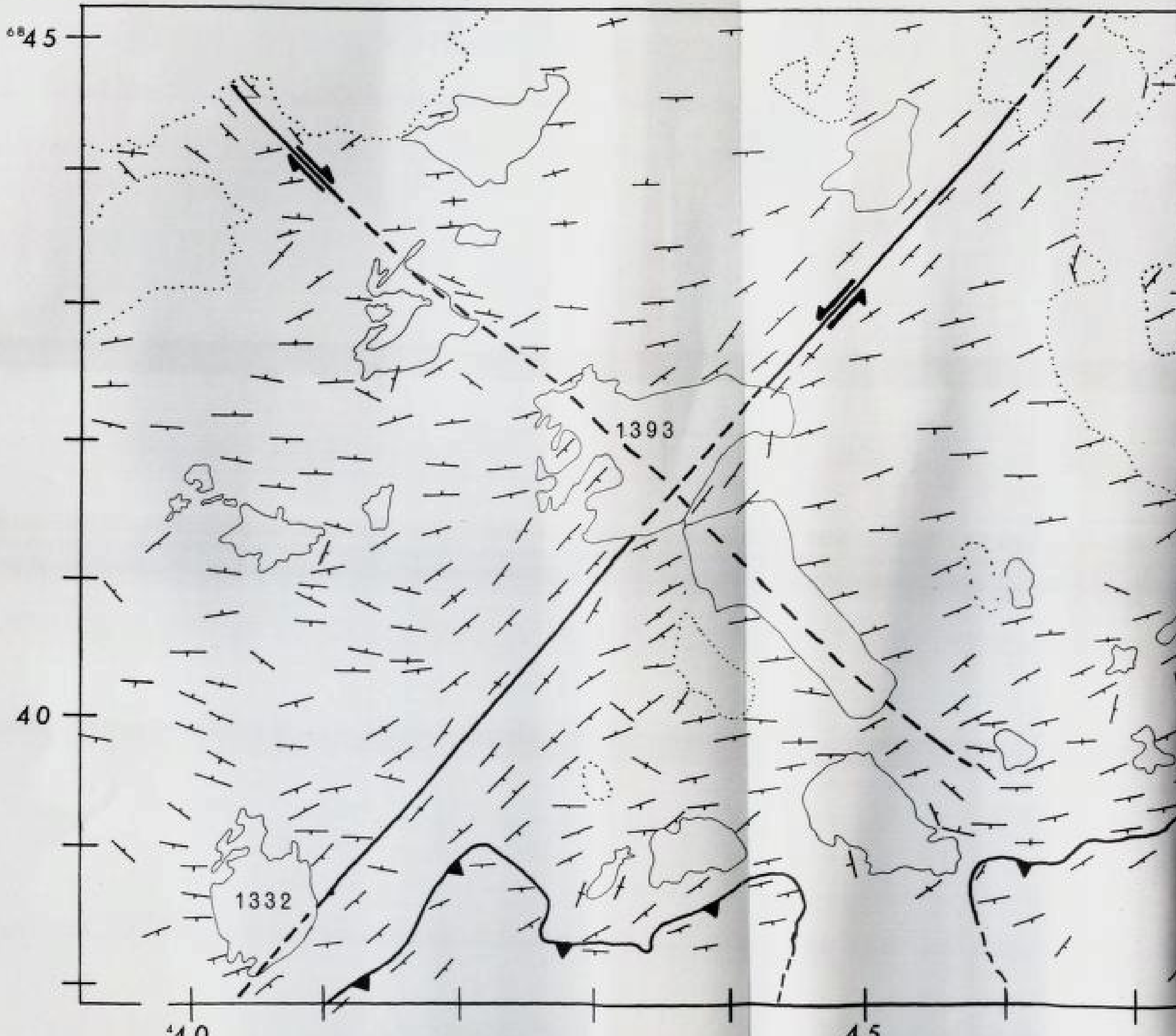

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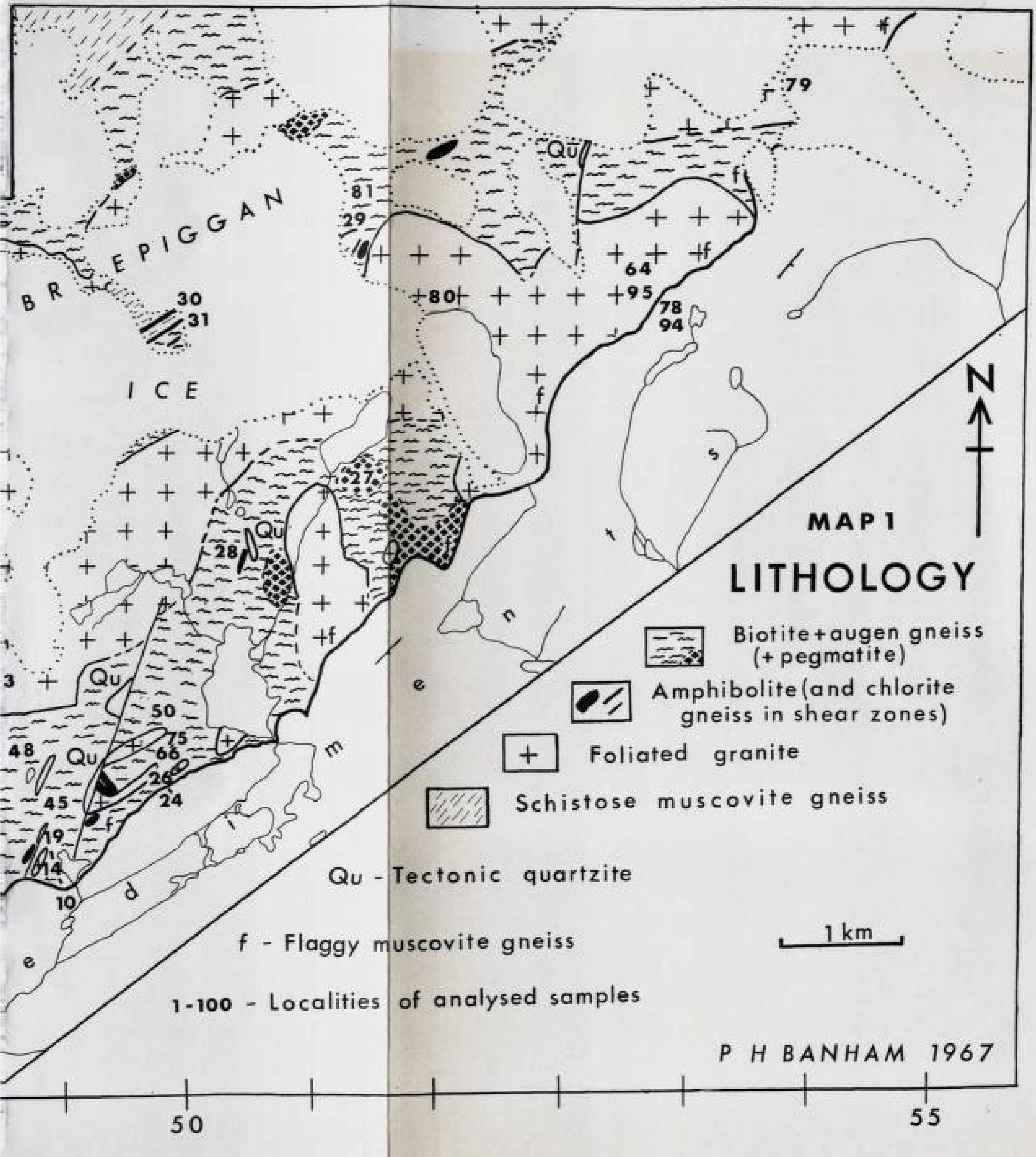
MAP 1
LITHOLOGY
N
BREPIGGAN
ICE
Biotite+augen gneiss (+pegmatite)
Amphibolite (and chlorite gneiss in shear zones)
Foliated granite
Schistose muscovite gneiss
Qu - Tectonic quartzite
f - Flaggy muscovite gneiss
1-100 - Localities of analysed samples
1 km
P H BANHAM 1967
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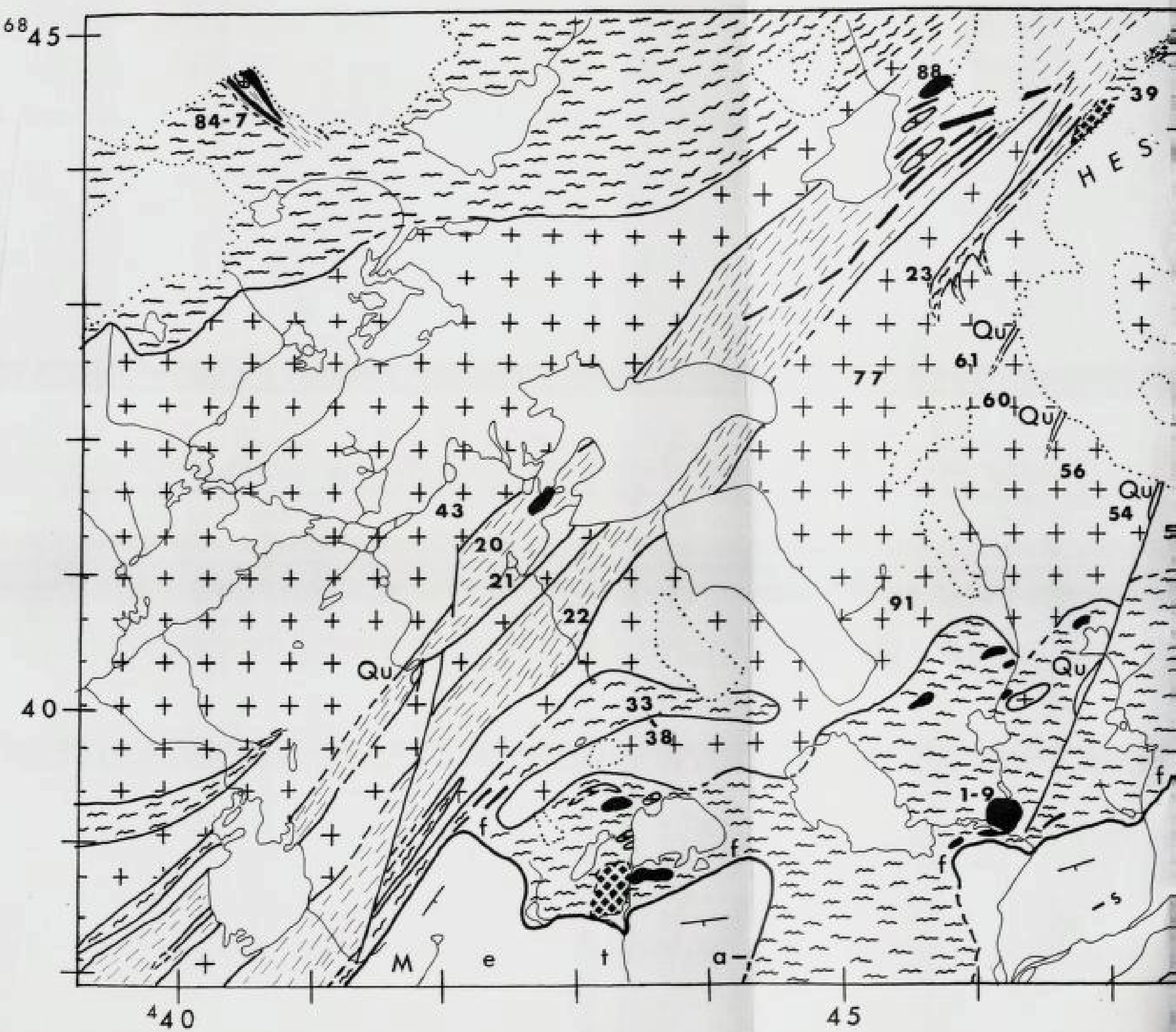

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MAP 1
LITHOLOGY
Biotite+augen gneiss (+ pegmatite)
Amphibolite (and chlorite gneiss in shear zones)
Foliated granite
Schistose muscovite gneiss
Qu - Tectonic quartzite
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1-100 - Localities of analysed samples
1 km
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HESTBREPIGGAN ICE
Meledalen
P H BANHAM 1967


ICE
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MAP 3
FRACTURES
Basal Thrust
High-angled fractures
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(representative selection)
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