Geological Investigations in the Bamble Sector of the Fennoscandian Shield South Norway

1. The Geology of Eastern Bamble

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With 19 figures in the text, 9 plates, 10 tables and one geological map at the end of the paper.

ABSTRACT

This paper, based upon a recent survey on a scale of 1 : 15,000, constitutes a description of the geology and broad structural aspects of the E. Bamble region, S. Norway. Two principal groups of Precambrian metamorphics and intrusives are recognized, namely: (1) those exhibiting only localized, minor cataclasis and (2) characterized by cataclasis. The latter group occupies a 4-5 km. wide zone in the north of the region. All of these rocks have undergone regional metamorphism under the P-T conditions of the almandine-amphibolite facies. Assemblages diagnostic of both the sillimanite-almandine-orthoclase subfacies and the sillimanite-almandine-muscovite subfacies of the almandine-amphibolite facies are common. Occasionally assemblages suggestive of the hornblende-granulite- or the pyroxene-granulite-subfacies of the granulite facies were noted. Retrograde metamorphism or distinct, lowergrade thermal regimes are indicated by the presence of epidote, chlorite and prehnite.

A group of metasediments, representing pre-existing sandstones, arkoses and argillaceous rocks, has been partially mobilized and affected by injection of syntectonic granitic and gabbroic rocks. Granitic, granodioritic and quartz-dioritic gneisses are common throughout the region and are thought to have been derived by anatexis within a meta-sedimentary-metavolcanic sequence. The resultant anatectic melts gave rise to large granitic masses by diapiric intrusion and to some gneisses by lit-par-lit injection. Augen gneisses in the sequence are envisaged as the result of small scale diffusion under special stress conditions. The 'nodular' sillimanite gneisses probably owe their origin to multiple boudinage of pre-existing arkosic sediments. Banded gneisses are interpreted as layered metasediments and metavolcanics whose banding has been emphasized by some degree of metamorphic differentiation. Limited occurrences of rapakivi granite probably represent pretectonic intrusives.

Lenticular, or sill-like, concordant bodies of amphibolite are predominantly ortho-amphibolites. These represent either metamorphosed basic volcanics or syntectonic mafic intrusives which crystallized as 'primary' amphibolites under high PH_2O conditions. Geochemical studies have been performed on 6 samples.

A group of Precambrian, syn- to late-kinematic gabbros, norites and olivine norites, intrusive into the metamorphic sequence are suggested to represent differentiates of two parent magmas, namely: (1) a nepheline normative magma and (2) a high-hypersthene or quartz-normative magma. Previous theories on the origin of corona structures commonly developed in the gabbroic suite are questioned and it is concluded that they have probably developed by simple reactions between such minerals as olivine

and plagioclase under the PH_2O-T conditions of the almandine amphibolite facies of regional metamorphism, without the addition of silica. 23 members of the gabbroic suite were analysed and C.I.P.W. norms and Niggli values are presented for these.

A group of hornblende-pyroxene gneisses signify either localized transgressions of metamorphic grade from the almandine-amphibolite facies to the pyroxene-granulite subfacies (or the hornblende-granulite subfacies) of the Granulite facies or merely localized variations in PH_2O during a relatively constant thermal regime.

Anthophylite-cordierite and sillimanite-cordierite rocks within the district are thought to have originated by metamorphism of a quartz-chlorite assemblages, derived by previous low-grade alteration of basic volcanics, rather than by intensive Mg-metasomatism during higher grade regional metamorphism.

The numerous granitic, granodioritic and quartz-dioritic pegmatites show a distribution closely related to host rock composition. As with some of the acid gneisses, these rocks represent mobile fractions derived by partial anatexis of the metamorphic suite.

Brief descriptions are given regarding the nature of the basal members of the Cambro-Silurian in E. Bamble. A basal arkosic member is overlain by a fine grained, well sorted sandstone unit.

Permian vulcanicity in the district is represented by sills and dykes of dolerite and syenite. Three occurrences of explosion breccia represent vents where gas-rich basaltic magma rose by a fluidization process.

An initial phase of Precambrian deformation resulted in NE-SW trending, shallow plunging, similar folds. These folds are open near the coast but become isoclinal northwards. Shear folding was the dominant deforming mechanism and in most cases the foliation conforms to original stratification. No direct evidence of a second phase of N-S trending folds (as observed to the SW of the area in W. Bamble and Aust-Agder) was found.

Two dominant, steeply dipping, fault sets were recorded, namely an older NE-SW trending group and a younger NNW-SSE trending group. It is postulated that the NE-SW trending Porsgrunn-Kristiansand fault is merely a late-stage dislocation of normal character, whose trend and attitude were determined by the anisotropy of the cataclastite belt, which itself represents an ancient Precambrian transcurrent fault zone.

The traditional concept of the western margin of the Oslo Graben being sited in the eastern portion of Bamble is refuted and it is suggested that the graben trends south-westward through S. Norway. The Porsgrunn-Kristiansand fault is therefore thought to represent the NW margin of the graben and it is felt that a SE boundary structure probably lies below the Skagerak floor to the SE.

The metalliferous ore deposits of E. Bamble include minor concentrations of Fe, Ni, Cu, Mo, Ti and Pb ores belonging to the Precambrian and Permian-Igneous metallogenic provinces. Three sectors of vein and disseminated Fe-Cu-Ni sulphide mineralization are associated with noritic and gabbroic intrusions. Low grade, disseminated pyrrhotite-pentlandite-pyrite-chalcopyrite ores and higher grade, pyrrhotite-pentlandite-pyrite-chalcopyrite ores (containing abundant silicate blebs) are considered to have originated by liquid immiscibility, which resulted from differentiation or sulfurization of the Precambrian noritic magmas.

The results of a previous magnetometer survey are discussed and suggestions are given for renewed exploration within the district.

INTRODUCTION

Geographical setting

The region described is situated within the Skagerak coastal region of S. Norway, some 130 km. S.W. of Oslo; (see Fig. 1). Eastern Bamble is characterized by a low, undulating, highly dissected plateau rising gradually from the coast to a maximum elevation of around 200 m.a.s.l. in the northern portion of the map area. Despite its relatively low elevation, the region is extremely rugged and its smooth walled, steep valleys and rounded glaciated hills are difficult to traverse away from the highways. Survey progress is also hampered severely by the heavy forest cover. Only on rare occasions is the forest broken by small arable and pastoral areas in the valley bottoms.

The predominantly coniferous vegetation is particularly dense in those areas underlain by mafic lithologies such as amphibolite, gabbro and metagabbro. However, those areas underlain by more granitic lithologies are often covered by thick scrub-oak and birch forest. There is a noticeable paucity of vegetation in those portions of the area occupied by quartzitic horizons.

Geological environment

The E. Bamble district is occupied for the most part by outcrops of metamorphic and igneous rocks belonging to the Fennoscandian shield.

However, the eastern edge of the area is underlain by sediments of Cambro-Silurian age which unconformably overly the Precambrian lithologies. The northern boundary of the area surveyed is demarcated partly by rocks associated with the major fault zone which stretches from Porsgrunn, in the N.E., to Kristiansand in the S.W. The major dislocation of this fault zone has for many years been referred to as the Great Friction Breccia; Bugge (1928).

Previous literature

A tremendous volume of literature exists concerning the geology of this portion of the shield. However, comprehensive areal descriptions are very few in number and the major publications have dealt only with broad regional aspects or with selected lithologies. Bugge (1943) published a regional description of the whole of the Kongsberg-Bamble portion of the shield; which has been enlarged upon and somewhat modified in subsequent papers by Holtedahl (1960), Barth & Reitan (in Rankama 1963) and Bugge (1965).
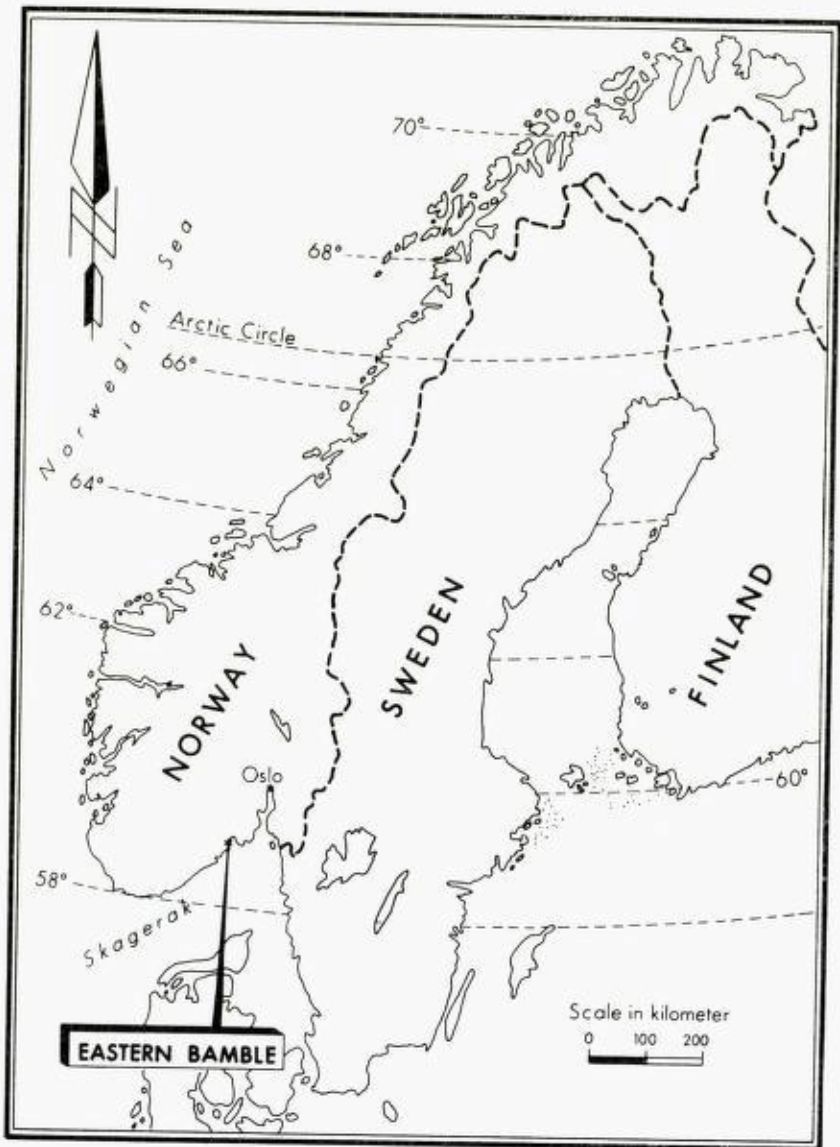
Fig. 1: Location Map.

Neumann (1960), Nilssen (1963) and Broch (1964) have summarized the existing data on age determinations from a few lithologies in Bamble.

Several authors have studied the gabbroic rocks of Bamble; the most comprehensive accounts being those of Brøgger (1934, 1935). Bugge (1943) and Reynolds & Fredrickson (1962) published short accounts concerning hyperites from S. Norway; the latter authors being primarily concerned with the origin of the corona structures so often developed in these rocks.

Granites and the so-called 'nodular granites' from S. Norway have been the subject of a number of publications; the most pertinent being those by Brøgger (1933d), Hofseth (1942), Barth (1947, 1955, 1956), Christie et al. (1965), Nilssen & Smithson (1965), Elliott & Morton (1965), Smithson (1963, 1964) and Smithson & Barth (1967).

The nature and origin of gneisses and banded gneisses from S. Norway has been discussed in numerous publications. The two major works on this topic are those of Dietrich (1960) and Barth (1956). The pegmatites associated with these lithologies have also been discussed at length in papers by Anderson (1931), Bjørlykke (1937, 1939), Brøgger (1922), Oftedahl (1958) and Reitan (1956, 1958, 1959a, 1959b).

The problematic origin and nature of albitites in S. Norway have been covered by Brøgger (1935), Green (1956), Elliott (1966) and Bodart (1966).

A number of papers on the structural geology of the region have been published; the most noteworthy being those of Bugge (1928), Wegmann (1960), Barth (1947), Selmer Olsen (1950), Elders (1963) and Smithson (1963).

Surprisingly few publications have emerged directly concerned with the distribution of economically significant mineral desposits in this portion of the shield; especially when one considers the intensity of mineral exploration within analogous portions of the Canadian shield. The two most pertinent papers in this respect are those by Foslie (1925) and Vokes (1958). Work on specific parochial mineral deposits has been published by Neumann (1944a, 1944b), Adamson (1952), Barth (1947a), Bjørlykke (1947), Heier (1955) and Bugge (1951, 1954).

The post-Precambrian rocks of this region, too, have been the topic of numerous publications. The basal sediments of the Cambro-Silurian in E. Bamble have been described by Vogt (1929) and Henningsmoen (1946). The Permian intrusives of S. Norway were studied by Brøgger

(1890, 1894, 1899, 1931a, 1931b, 1933a, 1933b, 1933c), Dons (1952), Barth (1945, 1954) and Oftedahl (1946, 1948, 1952, 1953, 1957a, 1957b, 1959, 1960).

The state of knowledge prior to 1968

Previous authors have recognized three geographical provinces within the Fennoscandian shield in S. Norway; namely those of Østfold, Telemark and Kongsberg-Bamble, (see Fig. 2). Subsequent to the publication by Brøgger (1900), the Precambrian rocks of the Skagerak coastal margin between Kristiansand and Langesund have been referred to as the Bamble 'formation'; (the authors now propose to discontinue the use of this latter, stratigraphically erroneous, title noun). The northern boundary of the Bamble sector was regarded by Bugge (1928, 1936) to be demarcated by a major, N.E. - S.W. striking fault which extended from Kristiansand in the S.W. to Porsgrunn in the N.E. This major fault structure was endowed with the unfortunate title of "The Great Friction Breccia".

The artifically geographical nature of the subdivision of this portion of the shield into 3 provinces was soon recognized by authors such as Barth (1933, 1947), who postulated that the Telemark and Bamble provinces probably represented two mutually related portions of one geologically homogeneous Precambrian complex. Subsequently, Holtedahl (1945) supported this view and stated that the extensively granitized and migmatized rocks of the Telemark sector might simply represent deeper crustal levels than the less mobilized rocks of the Bamble sector.

Smithson's studies (1963), together with the observations of Selmer Olsen (1950) and Elders (1961, 1963), suggested that a wedge of denser Bamble rocks along the coastal region, were underlain in depth by Telemark migmatites and granites. It was also concluded that the Porsgrunn-Kristiansand fault had effected a downthrow to the S.E. of approximately 0.5 km. (near Hynnekleiv), together with some degree of displacement to the N.E.

The numerous petrographical investigations had revealed that Bamble was occupied by a series of metasediments and metavolcanics affected in part by migmatisation and metasomatism, and extensively intruded by basic igneous rocks, pegmatites and both post- and syn-kinematic granites. The metamorphic grades within these rocks had been shown by early workers to be at a maximum in the district adjacent to Arendal, where rocks of the granulite facies occur. As one proceeded north eastward towards E. Bamble from Arendal, the metamorphic grade was suggested
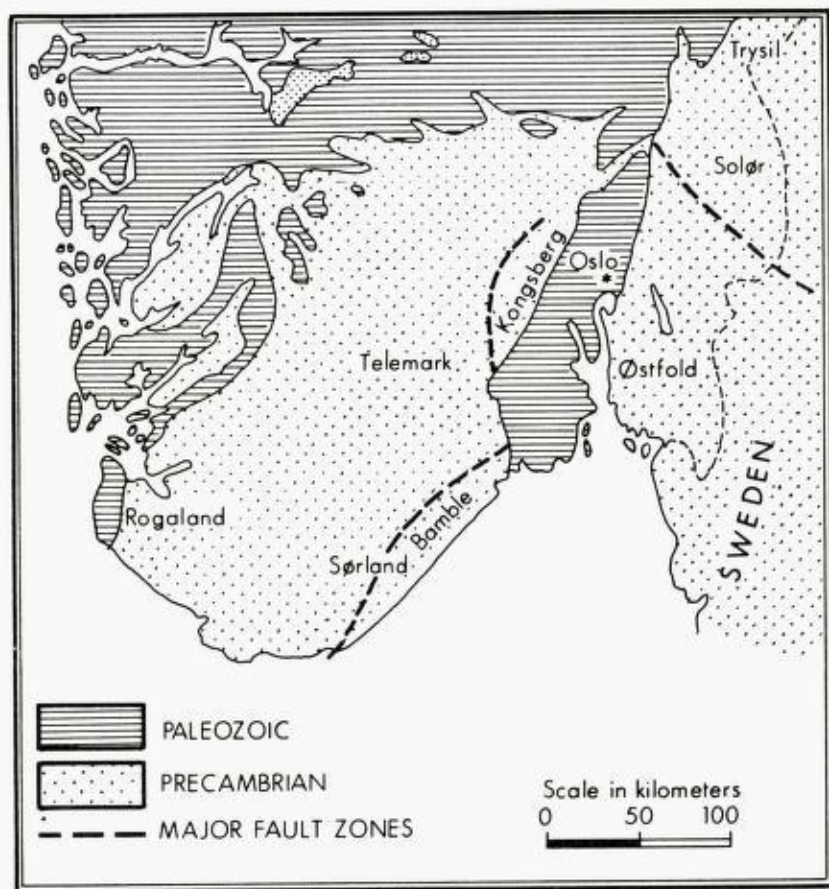
Fig. 2: The geographical provinces of the Precambrian in S. Norway.

to decrease to the upper amphibolite facies. However, recent work by Touret (1961) has shown that gneisses of charnockitic affinity occur well outside the Arendal district, in the Vegårshei-Gjerstad area.

Some 36 age determinations on minerals from the metamorphic rocks of the Bamble sector have been published by Neumann (1960), Nilsson (1963) and Broch (1963). Twenty-six of these dates are K/Ar ages from micas. Thus the interpretation of a younger phase at 900-950 m.y. and a older phase at ～ 1100 m.y. can only be accepted as tentative and possibly erroneous.

Objectives of the present study

Despite almost a century of work within this sector of the Fennoscandian shield, our knowledge of the detailed geological pattern is surprisingly meagre. Few regional cartographic studies have ever been performed and consequently recent summaries, such as those presented by Barth, Dons & Wegmann (1960), and Barth & Reitan (1963), tend to give a false impression of complete familiarity based upon limited parochial hypotheses. The objectives of this series of studies in the N.E. portion of the Bamble sector, initiated by R. D. Morton, were:

A. To provide some of the first large scale geological maps of the region.
B. To outline the broad structural aspects of the district and to determine the number of orogenic phases represented in the obviously polymetamorphic terrain.
C. To determine feasible hypotheses as to the origin of certain problematic lithologies such as albitites, cordierite-anthophyllite horizons, the so-called 'nodular granites' and the coronite-gabbros and norites.
D. To investigate the distribution and nature of the principal metalliferous ore deposits within this region and to combine this information with other field data in the planning of future exploratory programs.
E. To intiate the first complete geochronological study of this group of Precambrian rocks, based upon stratigraphic relationships established during the surveys.
F. To determine the structural nature of the western margins of the Oslo graben which were supposed to exist in this part of the shield.
G. To investigate the nature of the basal Cambro-Silurian strata and their relationships to the underlying basement in Bamble.

The cartographic basis of the geological survey project

No suitable, large scale, topographic maps of S. Norway exist, which would permit geological surveys of such detail as those described in this series. Therefore, vertical aerial photographs, on a scale of 1 : 15,000 (supplied by Widerøe's Flyveselskap, Oslo) were employed during the field surveys. The final geological maps produced herein were compiled utilizing an uncontrolled photographic mosaic (scale 1 : 15,000) and the U. S. Army Map Service's topographic sheets (scale 1 : 50,000).

Acknowledgements

THE LITHOLOGICAL GROUPINGS

Within the following lithological accounts, the various lithological types recognized have been described under the following headings:

1. The Normal Precambrian metamorphics and Intrusives
2. The Cataclastite Belt
3. The Post-Precambrian

The former group is composed of all those metamorphics and intrusives of Precambrian age which exhibit only localized cataclasis. The second group, in contrast to this, comprises a belt of rocks, outcropping in the north of the area, whose lithologies are equivalent in almost every respect to those of the normal metamorphics and intrusives, but which in most cases are characterized by cataclastic textures. The latter group includes all rocks of either Cambro-Silurian or Permian age occurring within the region.

THE NORMAL PRECAMBRIAN METAMORPHICS AND INTRUSIVES

The Metasediments

Lithologies, field relationships
and petrography

(1) Quartzites and feldspathic micaceous quartzites

Quartzite horizons occur principally in the southern portion of the map area, adjacent to the coast, where they are interbedded with amphibolitic lithologies. The quartzites occasionally form layers which are traceable for some distance, but more often they are of a lenticular nature. These rocks are also extensively developed within the Bamble synclinal area and adjacent to the Vissestad gabbro. However, the latter horizons have suf-

fered extensive deformation, particularly in the neighbourhood of Bamble.

Whilst the major occurrences of quartzites are as described above, small, discontinuous lensoid bodies are almost ubiquitous throughout the banded-gneisses and the general gneiss sequence.

In the field, the quartzites are normally white or grey, weathering to a pale buff or grey colour. Most quartzite horizons are massive and foliation is only developed in those which contain significant amounts of sillimanite, muscovite or biotite. In some instances a distinct flattening of the quartz grains does produce a very poor foliation in relatively pure quartzites. Despite a careful search, no relict sedimentary structures were observed within members of this group.

The feldspathic, micaceous quartzites vary greatly in their composition and are lithologically gradational on the one hand into pure quartzites and on the other hand into biotite schists and biotite granite gneisses. These rocks, as their mineralogy suggests, are usually well foliated. In the field members of this group are very difficult to trace laterally, owing to their variable composition. However, they appear to particularly predominant in the southern sector of this area, where they underly areas of low ground. Near Tveitan, east of Hønstjern, feldspathic biotite quartzites contain abundant graphite.

The mineral assemblages observed in the Bamble quartzites were as follows:

Quartz + Muscovite

Quartz + Muscovite + Magnetite

Quartz + Muscovite + Biotite + Apatite + Magnetite

Quartz + Biotite + Sillimanite → (Muscovite) + Tourmaline
    + Zircon

Quartz + Chlorite + Tourmaline + Magnetite

The feldspathic quartzite horizons exhibit a considerable variation in their mineral assemblages:

Quartz + Microcline + Biotite → (Chlorite) + Zircon

Quartz + Microcline + Biotite → (Chlorite) + Prehnite
    + Zircon + Magnetite

Quartz + Microcline + Plagioclase + Biotite → (Chlorite)
    + Sillimanite + Tourmaline

Quartz + Microcline + Plagioclase + Biotite → (Chlorite)
    + Apatite + Graphite

The fabric of the quartzite lithologies varies as follows:

Texture: Crystalloblastic, granoblastic, weakly or strongly lepidoblastic.

Grain size: 0.5 to 4.0 mm.

Planar and linear elements: Normally, in well foliated members, the biotite, sillimanite and muscovite are aligned sub-parallel to the foliation. However, in certain specimens, acicular sillimanite crystals can be observed at right angles to the main foliation.

(2) Biotite schists

Biotite schists are quite common in E. Bamble, although most of them occur as thin, lensoid intercalations within the quartzites, amphibolites and gneisses. Only two biotite schist horizons are of sufficiently large dimensions to be represented in the accompanying map. The map occurrence of these schists is exposed for some 3 km. along the E-18 highway to the S.W. of Åby and to the north of Kjærs. Here, a conformable biotite schist horizon, some 250 m. thick, strikes on a N.E. - S.W. azimuth. To the N.W. of Kjærs, the horizon bifurcates and transgresses into a granitic gneiss.

A smaller, conformable band of biotite schist, some 50 to 180 m. thick, is interlayered with amphibolites to the S.W. of Rognstranda and to the N. of Kåsene.

The biotite schists grade laterally into biotite-rich granitic gneisses on the one hand and into micaceous quartzites on the other. They are normally medium to coarse grained and well foliated, with the mica aligned parallel to the schistosity. The assemblages noted were:

Biotite + Quartz + Muscovite + Apatite + Magnetite

Biotite → (Chlorite) + Quartz + Magnetite

Biotite + Quartz + Microcline + Graphite + Apatite

Biotite → (Chlorite) + Quartz + Microcline + Apatite

Biotite + Quartz + Microcline + Garnet + Magnetite + Apatite

Mineralogy and Modal Proportions

(see Table 1) of the metasediments.

Quartz: Xenoblastic, eliptical grains which are invariably strained, exhibiting undulose extinction. Those horizons which have undergone a minimum of shearing have crystals 2 to 4 mm. in diameter. In the quartzites the mineral may exceed 90 % of the mode, and in the feldspathic, micaceous quartzites the amount of quartz is never below 40 %.

Microcline: Xenoblastic, flattened. In general the grains are smaller than those of quartz in the same rock. Often full of inclusions. May exceed 20 % of the mode.

Muscovite: Xenoblastic. 0.25 to 1.0 mm. diameter. Only obserevd in those lithologies where microcline is absent. Replaces both sillimanite and biotite; (see Plate 2).

Biotite: Xenoblastic, occasionally extensively altered.

Plagioclase: Xenoblastic, usually highly sericitised and consequently it is impossible to determine its composition optically.

Sillimanite: Subidioblastic to idioblastic, acicular or fibrous (fibrolite). Occasionally larger prisms can be seen with cross sectional dimensions of ~ 0.1 mm.

Chlorite: Commonly occurs as an alteration product after biotite.

Tourmaline (var. Schorl): Subidioblastic to xenoblastic. Maximum cross section ~ 0.25 mm. Strongly pleochroic: grey — deep tourquoise.

Zircon: Rounded grains, < 0.05 mm. diameter. Very variable in modal concentration.

Prehnite: Occasionally this mineral can be seen as lenticular inclusions between the cleavage of biotite.

Accessories: Magnetite, rutile, apatite occur as minute rounded grains.

Metamorphic facies and origins.

The mineral assemblages exhibited by the metasediments of this group are in part diagnostic of both the Sillimanite-almandine-orthoclase sub-facies and the Sillimanite-almandine-muscovite subfacies of the Almandine-amphibolite facies of regional metamorphism. The replacement of biotite by chlorite and the presence of prehnite in some samples could be interpreted either as retrograde phenomena or as indications of later, distinct, lower-grade thermal events.

Both petrographic studies and field observations imply that these rocks must have been derived by regional metamorphism of sandstones, arkoses, argillaceous sandstones and argillaceous sediments which constituted part of a thick sedimentary sequence.

The Granitic, Granodioritic and Quartz Dioritic Gneisses

Although widespread throughout the map area, rocks of this group do predominate in the north and central sectors. The composition of these gneisses is highly variable, but four main types have been included under this title, namely:

1. Granite gneisses; including augen gneisses and 'nodular' sillimanite granite gneiss.
2. Granodiorite gneisses.
3. Quartz diorite gneisses.
4. Banded gneisses; undifferentiated.

These broad lithological groups, although easily recognizable in the field, could not easily be mapped as discrete entities on the scale of 1 : 15,000, owing to a combination of small scale banding and rapid lateral gradations from one type to the other. The granite gneisses were found to predominate in the northern and central portions of the area, especially around the Bjørkeset-Hønstjern Norites, the Skogen Norite and in the region to the north of the latter intrusion. Augen gneisses were particularly

abundant in the vicinity of Skogen. 'Nodular' sillimanite gneisses are concentrated within the region adjacent to the coastal quartzites. Banded gneisses too are well developed along the coastal area and can be best observed at Rognstranda. This latter locality was described in detail by Elders (1960).

Rocks of this gneissic group occur either as large conformable, irregular or lensoid masses or as thinner, conformable to mildly transgressive bands in more mafic schists and gneisses. The rocks are medium to coarse grained, usually strongly foliated and gneissose and rarely contain more than 15 % coloured minerals.

Petrography

The mineral assemblages observed within rocks of this group are:

Quartz + Microcline + Plagioclase + Muscovite

Quartz + Microcline + Plagioclase + Sillimanite

Quartz + Microcline + Plagioclase + Biotite → (Chlorite)

Quartz + Microcline + Plagioclase + Biotite + Hornblende

Quartz + Microcline + Plagioclase + Biotite
+ Hornblende + Garnet

Quartz + Microcline + Plagioclase + Biotite + Garnet

Quartz + Microcline + Plagioclase + Biotite + Garnet
+ Sillimanite

Quartz + Plagioclase + Biotite

Quartz + Plagioclase + Biotite + Garnet

Quartz + Plagioclase + Biotite + Hornblende

Quartz + Plagioclase → (Chlorite) + Garnet

Quartz + Plagioclase + Biotite + Epidote

Accessory minerals: Diopside (rare), Apatite, Zircon, Tourmaline, Sphene, Magnetite, Ilmenite, Pyrite and Calcite.

The texture of these gneisses is crystalloblastic, occasionally granoblastic and usually to some degree lepidoblastic. Minor cataclastic textures are quite common. The grain size is rather variable but is generally between 0.5 mm. and 4 mm.

Mineralogy

Quartz: The quartz may be strongly granoblastic or weakly lepidoblastic. The grains usually exhibit sutured margins and strongly undulose extinction. Myrmekitic inter-growths with microcline and plagioclase have been observed. Blebs of quartz are commonly enclosed poikiloblastically within garnet porphyroblasts.

Plagioclase: The plagioclase is invariably xenoblastic and usually shows a high degree of sericitisation. The composition of the plagioclase is normally difficult to estimate, but the majority measured fell in the range An_8 to An_{14}. The maximum value recorded was An_{42} in the quartz-diorite gneisses.

Microcline: Xenoblastic microcline occurs in typically lenticular masses or streaks. The grain size ranges from 0.5 mm. - 4 mm. Undulose extinction is common. In many instances the grains are partially replaced by plagioclase either along their peripheries or along twin lamellae. Alteration to sericite is very frequently seen.

Hornblende: This mineral generally occurs in lath-like xenoblastic grains or fibrous aggregates. The grain size is usually less than 2 mm. In all cases, the hornblende was strongly pleochroic with x = yellow-green, light-green or colourless; y = dark-green, green or brown; z = dark-green or olive-green. In some instances the hornblende is partially altered to chlorite or biotite.

Biotite: The biotite normally occurs as xenoblastic or subidioblastic crystals which are seldom in excess of 1 mm. in diameter. The crystals are strongly pleochroic. with x = yellow or pale brown and y and z = dark-brown, red-brown or black. The biotite normally contains minute inclusions of zircon surrounded by pleochroic haloes. Alterations to chlorite is very common. Occasionally the biotite is partially replaced by either muscovite or prehnite; see plate 3.

Muscovite: Minute xenoblastic, occasionally poikiloblastic, grains usually occur as alteration products of biotite and sillimanite. Only rarely are larger flakes present to the exclusion of biotite.

Garnet: Pink, almandine garnet occurs as xenoblastic to subioblastic, crystals.

Diopside: 2-3 mm. diameter xenoblastic masses of altered diopside were occasionally observed in the quartz diorite gneisses.

Apatite: $\sim$ 0.5 mm. long idioblastic or subidioblastic crystals are almost ubiquitous.

Ilmenite and *Magnetite*: Usually present as small subidioblastic masses associated with chlorite and garnet.

Pyrite: Xenoblastic to subidioblastic blebs associated with biotites. In one locality, this mineral constituted approximately 7 % of the mode.

Zircon, Tourmaline and *Sphene*: These accessory minerals are seen in small and variable amounts throughout the gneisses. They are generally subidioblastic and rarely exceed 0.25 mm. diameter. In some gneisses the zircons are distinctly rounded and appear to have suffered transport.

Epidote and *Calcite*: Xenoblastic masses of these minerals are associated with post-foliation veining. The epidote is of the pistachite variety.

Sillimanite (var. fibrolite): occurs as felted masses aligned parallel to the foliation planes.

The geochemistry of certain gneisses

Thirteen gneisses of this group, representing differing types from various environments were chemically analysed. The partial analyses and Niggli values are presented in Table 5. It will be seen from Figure 3 that there is a trend towards the fm + c apex of the triangular diagram. The afore-mentioned diagram also lends some support to the validity of the original
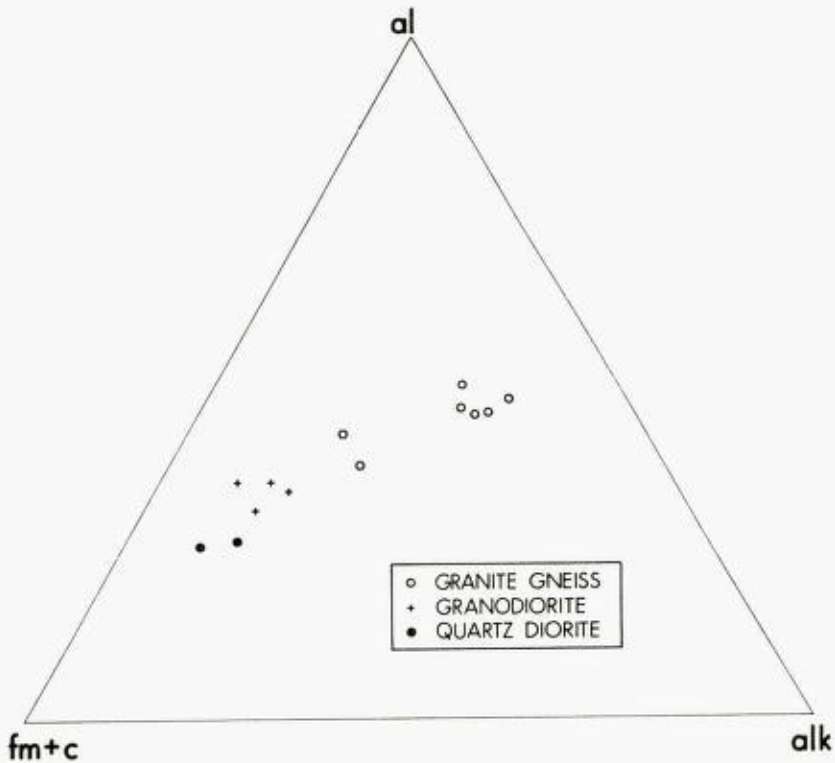
Variation Diagram (NIGGLI VALUES) For The
Leucocratic Gneisses

Fig. 3.

modal classification of these gneisses; but at the same time illustrates
how each type may be gradational into the other. In the field, this modal
and chemical distinction is in part linked to the environment and mode
of occurrence of each type. The granite gneisses occur as lenticular or
sub-rounded masses, which are poorly foliated and often of igneous texture.
In contrast to these, the granodiorite gneisses are located at the peripheries
of larger granitic gneiss units, where they are adjacent to amphibolites or
biotite schists. The quartz diorite gneisses were sampled from bands and
lenses of gneissic material directly adjacent to, or within, amphibolites
or biotite schists.

Metamorphic facies and petrogenesis

The prevalence of the assemblage: Quartz + Microcline + Plagioclase, together with Biotite, Almandine and Hornblende, suggests that these gneisses formed well within the Almandine Amphibolite facies of regional metamorphism. The isolated occurrence of sillimanite and diopside suggest that the metamorphic grade reached the extreme conditions of the upper Amphibolite facies (Sillimanite-Almandine-Orthoclase subfacies) and perhaps encroached into the Hornblende-granulite facies locally.

The presence of epidote and chlorite suggests that retrograde metamorphism or later thermal events subsequently effected mineralogic changes under the conditions of the Greenschist facies.

It seems probable that both the larger masses of poorly foliated gneiss and the better foliated, smaller masses of gneiss which occur intimately associated with more mafic lithologies in E. Bamble, were derived, for the most part, by anatexis within a sequence of metasediments and meta volcanics. The resultant migmatitic melts would give rise to the larger masses of granite gneiss by a process of diapiric intrusion and to some leucocratic gneiss bands by lit - par - lit injections. Wherever this process of anatexis was 'arrested' prior to the stage where the coalescence of the melts effected the formation of the larger bodies of gneiss, the resultant lithologic sequence would be one of finely banded gneisses. Augen gneisses are envisaged as representing petrogenetic instances where widespread small scale diffusion under special stress conditions promoted elipsoidal porphyroblast growth without attaining a migmatitic stage.

With respect to the so-called 'nodular' sillimanite granite gneisses and other normal granitic gneisses, it is possible that these might owe their origin, in part, to an almost isochemical metamorphism of pre-existing arkosic sediments; see Elliott & Morton (1965).

Finally, those banded gneisses which predominate within the southern portion of the area are thought to represent a metamorphosed, interlayered sequence of sediments and volcanics whose banding is in part original, but which has probably been emphasized to some degree by metamorphic differentiation. The interpretation of such banding as representing, to some degree, original stratification, is in accordance with the view expressed by Dietrich (1960), who studied a similar, banded gneissic sequence in the Randesund area of S. Norway, to the south west of Bamble.

The Amphibolites

Lithologies and field relationships

The term amphibolite is herein restricted to those medium to coarse grained, melanocratic, metamorphic rocks which are composed essentially of plagioclase and hornblende in a proportional ratio of approximately 1 : 1. In addition to these two minerals, variable amounts of biotite, garnet and quartz may be present.

Rocks of amphibolitic nature are present throughout the E. Bamble region, but tend to show their highest concentration in the south and east, where a series of complex fold structures are developed. The rocks of this group vary from almost massive to well foliated. Some of the thicker amphibolite masses are less foliated towards their central portions and exhibit distinct palimpsest igneous textures which point to a gabbroic origin. Banding is quite common in these lithologies, and may vary from a megascopic scale to a microscopic scale.

In general the amphibolitic horizons occur as lenticular or sill-like bodies, more or less concordant with the foliation of the surrounding metamorphics. The larger bodies tend to bifurcate or even undergo repeated branching into the surrounding gneisses.

Petrography

The following mineral assemblages were noted within members of this group:

Plagioclase + Hornblende
Plagioclase + Hornblende + Garnet
Plagioclase + Hornblende + Garnet + Ilmenite
Plagioclase + Hornblende + Quartz
Plagioclase + Hornblende + Quartz + Magnetite
Plagioclase + Hornblende + Quartz + Biotite
Plagioclase + Hornblende + Quartz + Biotite + Garnet
Plagioclase + Hornblende + Diopside → (Serpentine)

Accessory minerals: Sphene, Epidote, Apatite, Carbonates

Texture: Textures vary from relict igneous (gabbroic or doleritic) to strongly granoblastic and lepidoblastic. Poikiloblastic textures are common in the garnets.

Grain-size: The grain size rarely exceeds 2 mm. and is usually 0.5 - 1.0 mm.

Mineralogy and Modal proportions (see Table 3).

Plagioclase: Xenoblastic, subidioblastic or idioblastic (laths). Lamellar twinning well developed. Composition: An_{30} to An_{50}. Often cloudy due to myriads of inclusions. Constitutes 30-60 % of mode.

Hornblende: Xenoblastic or subidioblastic. Strongly pleochroic, with $x =$ pale brown, yellow or yellow-green; $y =$ olive green, or deep blue-green; $z =$ brown or dark green. Rarely exceeds 2 mm., often $<$ 1 mm. Occasionally partially replaced by biotite.

Biotite: Xenoblastic, 1 mm. av. diameter. Strongly pleochroic, with $x =$ yellow; y, $z =$ dark red-brown to almost black. Often altered to chlorite. Particularly common where the amphibolite surrounds a gabbroic mass.

Quartz: Xenoblastic, invariably strained, showing undulose extinction. Occasionally $<$ 10 % of mode.

Garnet: Xenoblastic. poikiloblastic. Pink to colourless in thin-section. Almandine-pyrope (see Table 10). Crystals up to 23 mm. in diameter.

Ilmenite and *Magnetite*: Xenoblastic, digitate skeletal or granular masses. Usually associated with hornblende. Constitute approximately 2 % of mode.

Apatite: Idioblastic, short prisms ubiquitous.

Diopside: Xenoblastic, rounded grains as relict patches in serpentine.

Epidote: Xenoblastic pistachite occasionally present in hornblende.

Metamorphic facies

The dominance of the assemblage: Hornblende + Plagioclase (An_{30-50}) + Almandine + (Quartz + Biotite) within the Bamble amphibolites indicates regional metamorphism under the conditions of the Almandine Amphibolite facies. The presence of clinopyroxene (diopside) does not indicate any higher grade of metamorphism, as this mineral, too, is a stable member of the Almandine Amphibolite facies assemblage of basic rocks, Winkler (1965). The presence of epidote and chlorite in certain horizons is a sure indication of local retrograde effects.

The geochemistry of certain amphibolites

Six amphibolites were analysed. Two samples (54a and 89) were of amphibolites associated with gabbros and four samples (40, 48, 30 and 18a) were amphibolites apparently independent of gabbroic masses. The analyses are presented in Table 6 and Niggli values plotted in Figure 4.

Leake (1964) has suggested that the plot of mg against c ist the best indication as to whether a particular group of amphibolites owe their origin to the metamorphism of igneous or of sedimentary rocks. The direction of trend in the case of para-amphibolites would be radial, whereas the plot for ortho-amphibolites would be similar to that followed by the differentiation sequence of the Karoo dolerites. On this basis it is concluded
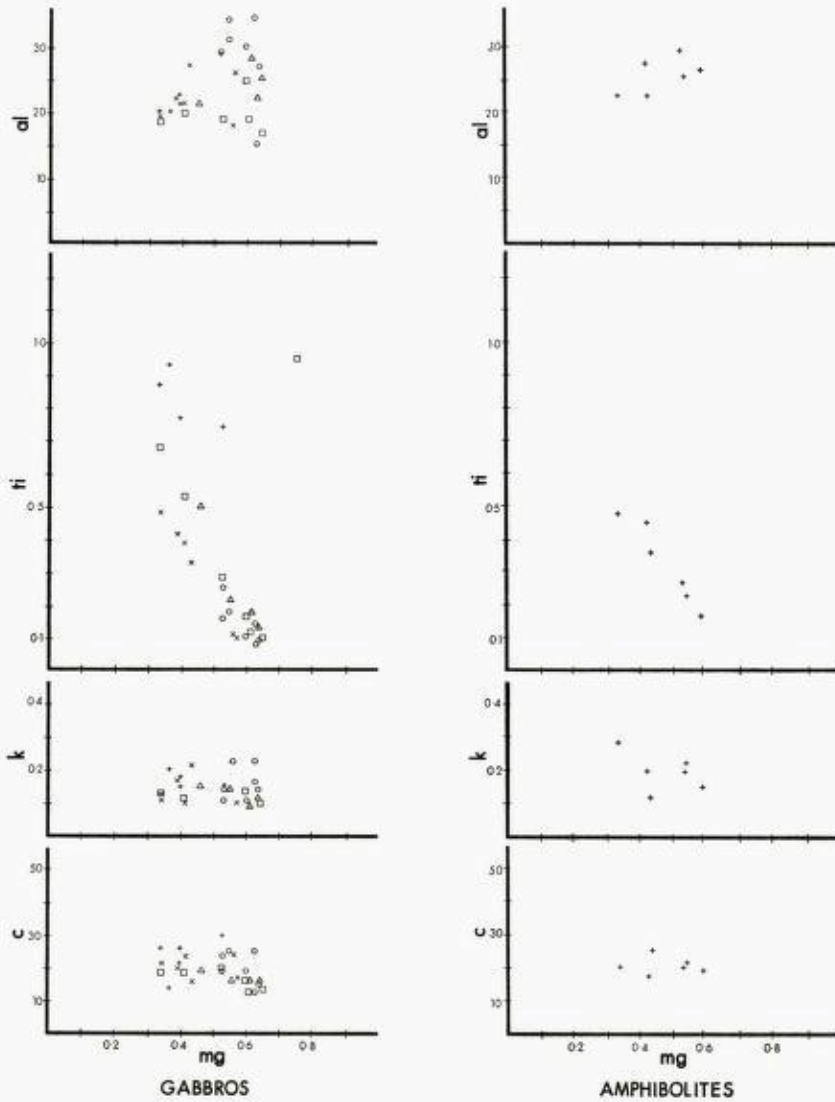
Various Plots against mg
(Niggli Values)

Fig. 4:

that the Bamble amphibolites are probably ortho-amphibolites, for they closely parallel the Karoo trend.

It is also noteworthy that the plot of Niggli values for the amphibolites closely parallels that for gabbroic rocks of E. Bamble shown in the same figure.

Petrogenesis of the Amphibolites

Almost every student of Precambrian metamorphic petrology is ultimately faced with the problem of deciding upon the origin of conformable amphibolites. With little evidence from Eastern Bamble of intensive metasomatic activity, one is forced to postulate an almost isochemical origin for such lithologies. The possible origins are therefore:

1. Regional metamorphism of basic igneous rocks.
2. Regional metamorphism of basic pyroclastics.
3. Regional metamorphism of impure limestones or impure dolomites.
4. Syntectonic mafic intrusives.

On the basis of the cursory geochemical investigation and field observations of such phenomena as palimpsest igneous textures, it is felt that the amphibolites of this portion of the shield are predominantly ortho-amphibolites. These would represent either, a regionally metamorphosed, differentiated sequence of basic igneous rocks and pyroclastics, or a differentiated sequence of syntectonic mafic intrusives. The latter case might be possible where basic melts, injected into an environment of Almandine Amphibolite facies conditions, (and sufficiently high H_2O pressure), crystallized as 'primary' amphibolites. Such an origin was recently proposed for similar lithologies in N.W. Connecticut by Gates (1967).

The Gabbros and Norites

Rocks of gabbroic composition occur throughout the area as lensoid masses, concordant with the foliation of the surrounding metasediments and metavolcanics. Commonly they are elongated parallel to the strike of the foliation. Compositionally the gabbroic rocks are divisible into gabbro (sensu stricto), norite, and olivine norite. The term hyperite has been used by many Scandinavian geologists (Bugge, 1943, Holtedahl, 1960) to include all gabbroic rocks and their transitions into ortho-amphibolite.

Norite and olivine norite occur in three principle masses; the Bjørkeset and Hønstjern norites along the coast and the Skogen norite in the central part of the map area. The Vissestad gabbro is the principle gabbro body in

the coastal region. In the Bjørkeset-Hønstjern and Skogen norites, the common mineral assemblages is:

Plagioclase + Orthopyroxene + Hornblende ± Clinopyroxene ± Olivine ± Spinel ± Garnet ± Ilmenite
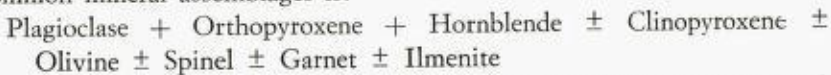
Texturally they are ophitic with incipient corona development, the secondary corona-minerals tending to be granoblastic to xenoblastic in habit. Plagioclase, pyroxene and olivine often show evidence of deformation, such as bending of grains and brecciation of crystal margins.

Mineralogy

Plagioclase: Primary plagioclase, often exceeding 5 mm., may compose as much as 60 % of the rock (see Table 4). Compositionally the plagioclase varies from An_{45} to An_{60} (andesine - labradorite). Individual crystals are lath-shaped with rounded and corroded margins and show well-marked albite and pericline twinning. Inclusions (possibly Fe oxides) occurring in the central part of the grains and often aligned parallel to the twinning, and impart a cloudy appearance to the feldspars. Plagioclase with undulose extinction is a common feature of the Skogen norite.

Orthopyroxene: Primary orthopyroxene occurs as anhedral to subhedral grains. Pleochroism is usually pink to green, characteristic of hypersthene. Such primary hypersthene may be surrounded by a narrow corona of secondary subidioblastic to xenoblastic, granular or fibrous masses of orthopyroxene, forming the inner of a double corona around olivine.

Olivine: Olivine, when present in the norites, occurs as relict anhedral grains surrounded by an inner corona of orthopyroxene and an outer corona of hornblende and spinel. Occasionally a third corona of garnet may be present around the hornblende-spinel corona. Serpentine alteration of olivine is common and may constitute up to 5 % of the mode.

Clinopyroxene: Clinopyroxene in the gabbros occurs as anhedral to subhedral masses often having a sub-triangular, polygonal or digitate form. Clinopyroxene may be completely absent from rocks of noritic composition.

Hornblende: Hornblende is always secondary and occurs as xenoblastic, subidioblastic or occasionally poikiloblastic masses. As an outer corona around olivine, hornblende may form a symplectite with spinel. Hornblende may also form a wide diffuse corona around magnetite and ilmenite.

Garnet: Garnet, in xenoblastic, subidioblastic and poikiloblastic forms, may form a third incomplete corona around olivine. Garnet is present in variable amounts and may be as much as 10 modal per cent in the Bjørkeset norite.

Spinel: Spinel occurs as xenoblastic grains forming a symplectite with hornblende in the second corona around olivine. Spinel is only well seen when olivine is present and does not occur in the Vissestad gabbro and other minor gabbros.

Biotite: Biotite occurs as xenoblastic to subidioblastic masses often associated with ilmenite as the centre of a corona structure.
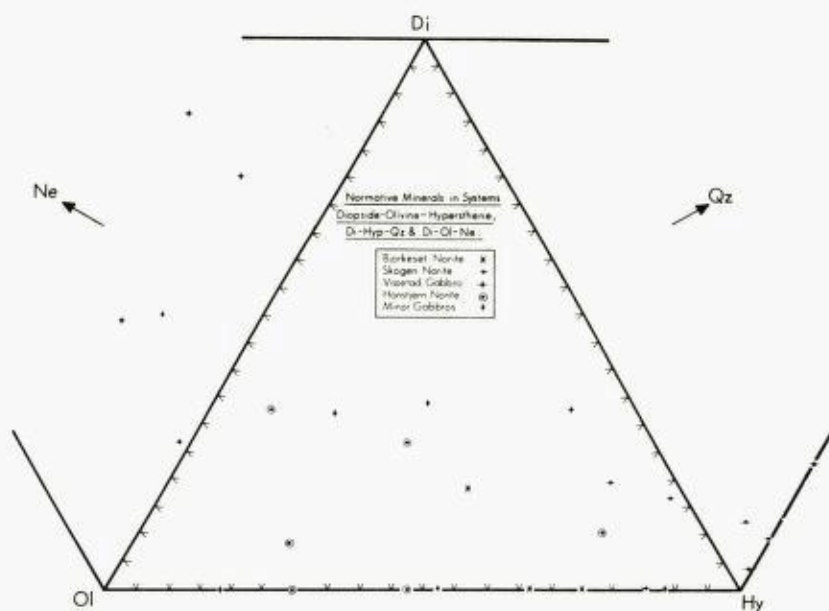
Fig. 5.

The geochemistry of the gabbroic rocks

Twenty-seven partial analyses have been carried out in order to establish whether compositional differences exist between the gabbroic bodies and within the gabbroic bodies themselves. C.I.P.W. norms and Niggli values are presented for each of these (see Tables 7 and 8).

Consideration of the analyses of major and minor gabbroic rocks indicates some compositional variation from north to south. Gabbroic rocks appear to be more silica-and alumina-rich towards the north, and richer in iron, titanium and phosphorous to the south; possibly linked with the increased plagioclase content northwards, and the abundance of hornblende and ore minerals in the coastal gabbros. In Figure 5, normative proportions of Di, Ol and Hy have been plotted together with Qz and Ne in the systems Ne-Di-Ol, Di-Ol-Hy, and Hy-Di-Qz. Comparing Figure 5 with the generalized system for rocks of basaltic chemistry by Yoder and Tilley (1962, p. 325), the gabbroic rocks of Bamble are seen to range from the alkali basalt group, through olivine tholeiite to the tholeiite group. Relating the above analyses to a simple system of differentiation from a nepheline normative magma may be erroneous. It is perhaps more likely that the
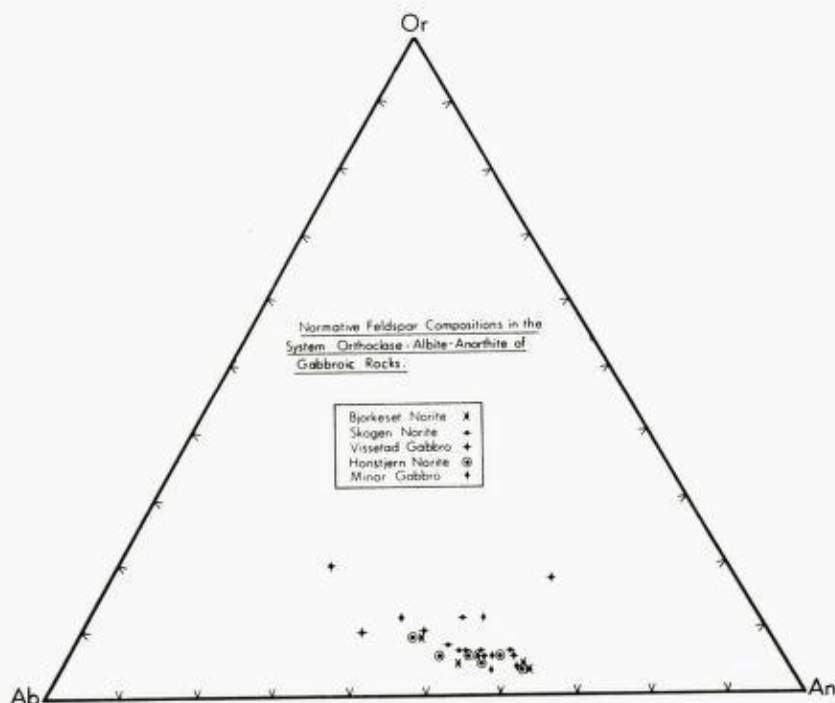
Fig. 6.

norites and gabbros are related to different parent magmas; a nepheline normative magma and a high -hypersthene or quartz-normative magma. Field evidence (deformation structures) indicates that the Skogen norite is perhaps syntectonic, whereas other undeformed gabbro masses are probably late tectonic. Other workers in the Bamble region (Ryan, 1966) have suggested different phases of intrusion for gabbroic rocks nearby at Øde-gaardens-verk. Normative feldspar compositions in the system Or-Ab-An (see Fig. 6) form a tight grouping, with the exception of the Vissestad gabbro. The wide variation in the Vissestad gabbro suggests a greater degree of differentiation. Field studies, petrographical evidence and chemical analyses suggest that the Bjørkeset and Hønstjern norites are very closely allied and in fact may be members of a single norite mass, which has sheared into two parts.

Niggli mg values have been plotted with c, k, ti and al in Figure 4. The ti-plot is of particular interest since it indicates an increase in ti/mg ratio from norite in the north to Vissestad gabbro in the south. This variation

is probably related to greater amounts of sphene, magnetite and ilmenite in the coastal gabbros. Traverses have been conducted across all the major gabbroic bodies with the exception of the Vissestad gabbro. Niggli al, fm, c and alk values (see Figure 7) show comparatively little variation over the traverses from one mass to another. fm shows an increase in the centres accompanied by a sympathetic decrease in al and c. In Figure 8, Niggli 100 p and ti show a marked, but not uniform variation across the gabbroic masses, with the margins having consistently higher values than the centres. In Fig. 9 Niggli mg values have been plotted for the Skogen, Bjørkeset and Hønstjern norites in relation to distance from the northern margin. All of the norites show higher mg values at their centres, which may indicate emplacement as 'stocks' rather than sill-like bodies.

Fig. 7.

Fig. 8.

mg Variation in the Norite Traverses
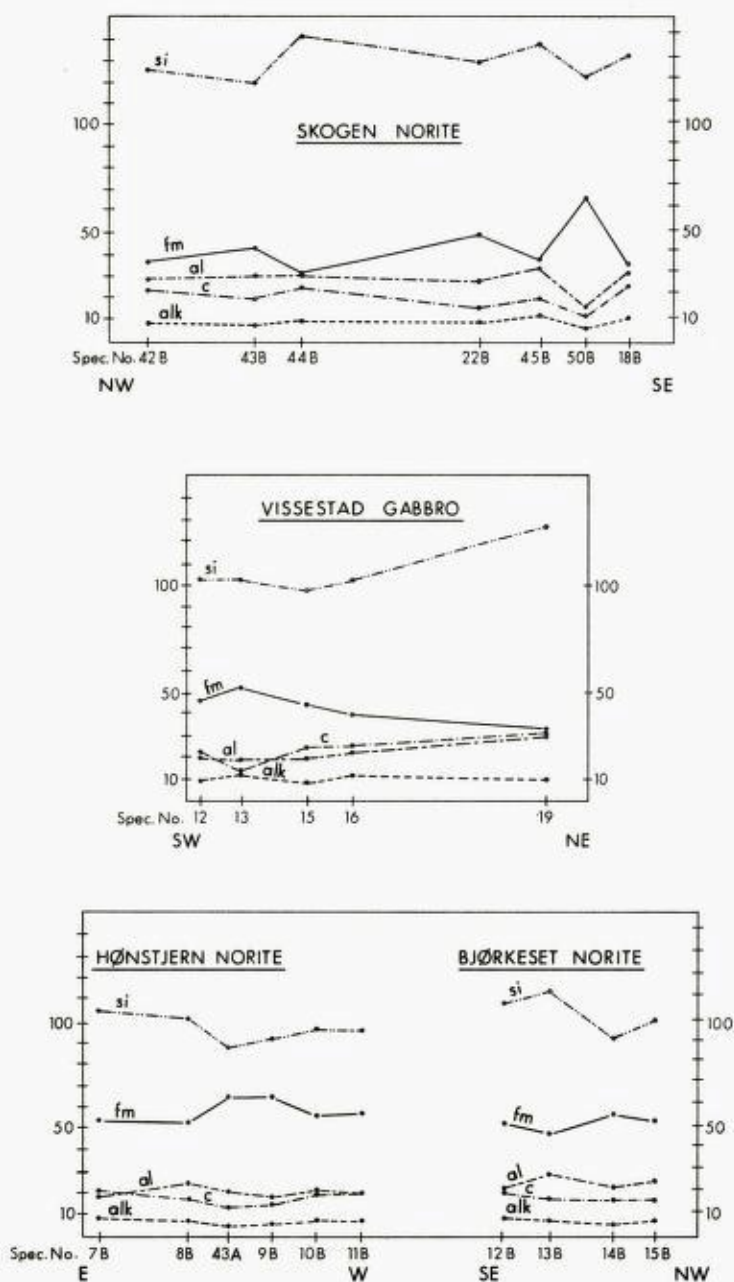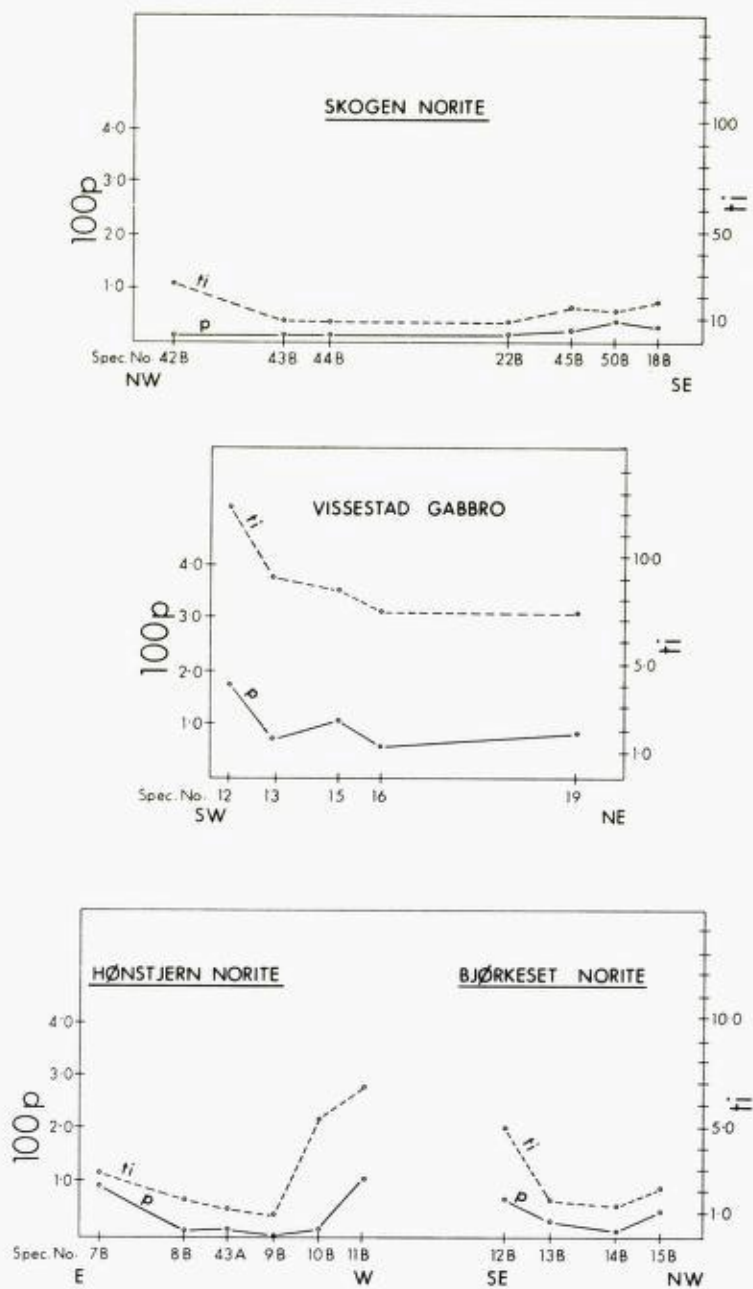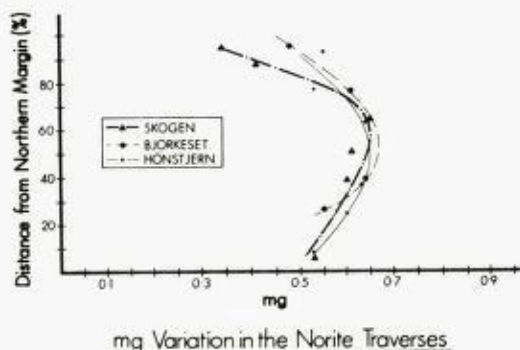
Fig. 9.

Corona structures and metamorphic facies

Corona structures occur in the majority of the gabbroic bodies in the Bamble region with the notable exception of the Skogen norite. Similar coronites have been described from elsewhere in South Norway (Brøgger, 1934, Gjelsvik, 1952, Ryan, 1966) and in northern Norway (Vogt, 1927, Mason, 1967).

In Bamble, relict olivine is rimmed by an orthopyroxene corona and a second symplectite corona of hornblende and spinel. Reynolds and Frederickson (1962) described similar coronite gabbros from the Valberg peninsula, Kragerø, and maintain that garnet is not found in rocks where fresh olivine persits. However, in Bamble a third narrow garnet corona is occasionally observed.

Most workers have agreed that corona formation is a metamorphic phenomenon (Reynolds & Frederickson, 1962, Gjelsvik, 1952, Oosterom 1963), but the reactions which have taken place remain a subject of controversy. Reynolds & Frederickson (op. cit., 1962) maintain that during metamorphism, subsequent to intrusion, aqueous silica-bearing solutions were introduced into the rock, resulting in transformation of olivine to bronzite. This reaction released Mg and Fe permitting the formation of hornblende and spinel from the feldspars; the plagioclase containing more Al_2O_3 than could be incorporated into the hornblende. For these reactions to occur, Reynolds & Frederickson suggest ten weight per cent silica must be added to the rock mass. From a consideration of normative proportions of Di, Hy, Or, Qz and Ne (see Figure 5) in the gabbroic masses, one may expect those with corona development would lie outside the Ne-normative

field in the Hy or Qz-normative field. In fact, the only gabbroic body lacking corona structures is the Skogen norite, analyses of which lie in the Qz-normative field. Thus, addition of silica may not be necessary for corona development.

Petrographic studies indicate that corona formation results from reaction between olivine and plagioclase. A reaction of the following kind after Deer, Howie and Zussman (1966) may pertain:

$$7Mg_2SiO_4 + 2CaAl_2Si_2O_8 + NaAlSi_3O_8 + H_2O \rightarrow NaCa_2Mg_5Si_7AlO_{22}(OH)_2$$

olivine   plagioclase ss (labradorite)   Edenitic hornblende

$$+ 7MgSiO_3 + 2MgAl_2O_4$$

enstatite   spinel
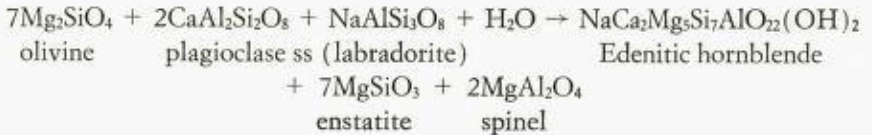
Green and Ringwood (1967) have studied anhydrous reactions in under-saturated alkali-olivine basalts and olivine tholeiites. Reaction between olivine and plagioclase becomes important at about 7 kb and 1100° C. In starting compositions with 100 $Mg/(Mg + Fe'')$ 60-70, reactions between 7-9 kb yield spinel and pyroxene at the expense of olivine and plagioclase. The appearance of garnet in anhydrous runs on quartz tholeiite and alkali olivine basalts was found to be at lower pressure in more iron-rich compositions. Such compositional control on the appearance of garnet may be important in Bamble. The reaction for hydrous conditions may be expected to occur at lower pressures and temperatures than Green and Ringwood's anhydrous reactions.

Mason (1967) has studied similar coronites from Sulitjelma, northern Norway, using electron microprobe techniques. He concludes that a simple process of two-way diffusion across the olivine-plagioclase interface, with iron and magnesium diffusing into the plagioclase, and a little aluminium and calcium diffusing into the olivine suffices to explain the corona composition. The presence of hornblende in the coronas indicates that water must have been available at the time of formation. Water would most likely be derived from the country rocks into which the gabbro was emplaced.

The corona mineralogy is consistent with the prevailing P_{H_2O} - T conditions of the country rocks into which they are emplaced. The absence of corona structures in the Skogen norite may result from low P_{H_2O} conditions of the local country rocks indicated by the local development of low-pressure granulites, and the absence of amphibolitized margins to the north.

Petrogenesis

The term "hyperite" has been used to refer to all rocks of gabbroic chemistry and their common ortho-amphibolite margins. It is generally agreed (Bugge, 1943, Brøgger, 1935) that the ortho-amphibolite margins result from metamorphism of gabbroic intrusives of varying composition, which had achieved some degree of differentiation within themselves.

In eastern Bamble there appear to be two major intrusive types, gabbro and norite, possibly related to Ne-normative and high Hy-, or Qz-normative magmas. Field relations suggest that these are syn- to late- kinematic and have been subjected to regional metamorphic P_{H_2O} - T conditions, characteristic of the Almandine amphibolite facies, under which conditions olivine and plagioclase are unstable and react to form corona structures.

The Hornblende-Pyroxene Gneisses

Lithologies and field relationships

Occasional thick bands of medium grained, melanocratic rock occur within the gneisses just to the south of the Skogen Norite. These lithologies possess an almost gabbroic texture in certain instances and are interpreted as, syntectonic conformable bodies of igneous origin.

Petrography

Within lithologies of this group, the following mineral assemblages were observed:

Plagioclase + Diopside + Hypersthene + Hornblende + Garnet
+ Opaques

These rocks are characterized by a rather uniform grain size of 0.25 mm. to 0.50 mm. Rare 3.00 mm. porphyroblasts of feldspar were observed. The texture of the rocks is granulitic and only poorly developed planar elements can be seen.

Mineralogy

Plagioclase: Crystalloblastic, granoblastic and rarely porphyroblastic. Grains usually 0.25 - 0.50 mm. Composition: Andesine An_{34}.

Microcline: Rare xenoblastic, small crystals.

Hypersthene: Xenoblastic relict patches usually altered in part to diopside and hornblende. Moderately pleochroic, pink-green.

Diopside: Xenoblastic or idioblastic. Pale green. Usually partly altered to hornblende.

Hornblende: Xenoblastic masses, replacing both diopside and hypersthene. Strongly pleochroic: olive green-dark green.

Garnet: Large, irregular aggregates of xenoblastic or subidioblastic, poikiloblastic crystals. Usually pale pink in colour.

Metamorphic facies and petrogenesis

The ubiquitous granulitic texture of rocks of this group, together with the presence of assemblages including hypersthene, diopside, hornblende, garnet and microcline suggest that such lithologies might owe their origin to either:

(i) Localized transgression of metamorphic grade from Almandine-Amphibolite facies into the conditions of the Pyroxene-granulite sub-facies or the Hornblende-granulite sub-facies of the Granulitic facies.

or (ii) Local variation in H_2O pressure during a relatively constant thermal regime which permitted parochial development of more 'anhydrous', orthopyroxene bearing assemblages.

The Anthophyllite-Cordierite and Sillimanite-Cordierite Rocks

Anthophyllite-cordierite rocks are of very limited occurrence in Eastern Bamble, generally occurring as lenticular bodies within amphibolite sequenches. Included in this section are the corderite-sillimanite schists which occur within the metasedimentary sequence. Characteristically anthophyllite occurs as radiating or feather-shaped masses lying in planes separated by cordierite and quartz bands.

Petrography

In thin-section the following assemblages have been noted:

Anthophyllite + Cordierite + Hornblende + Phlogopite
Anthophyllite + Cordierite + Mica + Quartz
Anthophyllite + Cordierite + Mica + Quartz + Plagioclase
Anthophyllite + Cordierite + Mica
Sillimanite + Cordierite + Biotite + Quartz

Anthophyllite, phlogopite and sillimanite produce a strongly lepidoblastic or nematoblastic texture. Anthophyllite frequently exceeds 0.5 cms. in long dimension, but may be extremely variably when shearing is present. Quartz and cordierite rarely exceed 2 mm. and generally fall between 0.2 mm. and 2 mm.

Mineralogy

Anthophyllite occurs as large xenoblastic to subidioblastic and occasionally poikiloblastic masses, which may be aggregated into bands. Occasional alteration of anthophyllite to *chlorite* and *talc* is observed. In some instances the orthoamphibole is of the more aluminous *gedrite* variety.

Cordierite: Cordierite is generally subidioblastic and tends to form equidimensional grains. Invariably the cordierite shows some alteration either peripherally or along cracks. The secondary minerals such as muscovite, chlorite and serpentine are collectively grouped as pinite.

Phlogopite: Usually xenoblastic and occasionally poikiloblastic in habit. Normally the phlogopite is aggregated in bands.

Quartz: Xenoblastic, rounded quartz grains are found in nearly all sections, although amounts are generally small. Undulose extinction is common.

Sillimanite: Sillimanite is only observed in cordierite schists where anthophyllite is deficient or absent. Generally it is of the fibrolite variety, forming masses of minute accicular crystalloblasts arranged in streaks and bundles aligned paralled to the foliation.

Tourmaline: Tourmaline has a subidioblastic to idioblastic habit and is very variable in size, but rarely exceeds 0.25 mm.

Accessories: Minor amounts of rutile may be present and these are commonly enclosed in ilmenite. Plagioclase and hornblende are of a very limited occurrence.

Petrogenesis of Anthophyllite-Cordierite Rocks

The cordierite-anthophyllite paragenesis has been described from a number of localities throughout the world, e.g. Cornwall (Tilley, 1937), Orijärvi (Eskola, 1914), South Norway (Brøgger, 1934; Bugge, 1943), Western Norway (Sørbye, 1964), Western Australia (Prider, 1944). The bulk chemistry of anthophyllite-cordierite rocks does not correspond to any known sedimentary or igneous rocks. Thus, previous workers (Bugge, op. cit.), have invoked processes involving Mg metasomatism of country rocks, the source of Mg being amphibolites and gabbros. Anthophyllite-cordierite rocks are not in all instances spatially related to gabbros and ortho-amphibolites and a scheme of Mg metasomatism would not appear to be a sufficient explanation.

Vallance (1967) and Akella & Winkler (1966) have suggested that an assemblage equivalent to chlorite and quartz in bulk chemistry may, under conditions of isochemical metamorphism, give rise to the paragenesis anthophyllite-cordierite. Vallance (op. cit.) has shown that low-grade alteration of basic volcanic rocks may give rise to the necessary bulk chemistry. The anthophyllite-cordierite rocks of Eastern Bamble may, thus, have resulted from isochemical upper amphibolite facies metamorphism of basic volcanic rocks which underwent sufficient low-grade, pre-metamorphic alteration to produce an assemblage equivalent in bulk chemistry to aluminous chlorite plus quartz.

The Albitites

Lithologies and field relationships

Leucocratic rocks of a granulitic or saccharoidal aspect with little evidence of foliation were ocasionally observed as small lenses or irregular masses within amphibolitic horizons. These rocks are characterized by a predominance of sodic plagioclase. They are described herein under the common title of 'albitites', but it must be admitted that other terms, such as 'sodic plagioclasite', might be preferred as the plagioclase does have a compositional range between albite and oligoclase.

Within these masses, streaks or augen of dark brown rutile are often seen. The marginal sectors are often somewhat more melanocratic and their contacts with the amphibolites are either gradational or quite sharp.

Petrography

The mineral assemblages observed within rocks of this group were:

Plagioclase + Quartz + Diopside + Chlorite + Ilmenite

Plagioclase + Hornblende + Rutile + Apatite

Plagioclase + Garnet + Chlorite + Ilmenite + Apatite

The texture of these rocks was crystalloblastic and granoblastic with a medium grain size of 0.25 to 3.00 mm.

Mineralogy

Plagioclase: The plagioclase varies in composition between albite and oligoclase and is generally xenoblastic with distinctly sutured margin. Alteration to sericite is quite common.

Quartz: This mineral occurs as subidioblastic, rather equidimensional grains (usually less than 0.25 mm. in diameter).

Diopside: The clinopyroxene is colourless in thin section, xenoblastic and is usually altered to some degree to hornblende.

Rutile: The rutile occurs as large porphyroblastic clumps which are usually associated with ilmenite. The mineral is deep brown in thin section and exhibits marked lamellar twinning.

Garnet: This mineral was occasionally seen within the albitites and was usually altered in part to chlorite along cracks and at the peripheries of the crystals.

Ilmenite: The ilmenite was almost ubiquitous within the albitites. It was xenoblastic and usually occurred as fine-grained aggregates of crystals.

Apatite: Apatite occurred either a small, idioblastic, prisms or as rather altered, larger aggregates.

Petrogenesis

The origins of the so-called albitites have, for many years, occassioned much discussion and dispute. They have been thought of in the past as either differentiates of gabbroic magmas or as some product of regional metamorphism and / or anatexis.

Brøgger (1934) believed that the albitites and rutile albitites (Kragerø-ites) represented sodic, residual fluids derived by differentiation of the 'hyperite' intrusive suite. This theory owed its origin, in part, to the French school (in particular Michel Lévy) in the latter part of the 19th century. Green (1956) disputed this hypothesis and noted that all rocks included within this group did not correspond, by virtue of their low potassium content, to any 'low temperature residuum'. Green therefore envisaged some metasomatic process, involving sodic emanations from nearby gabbroic intrusions, which effected transformation of pre-existing amphibolites into albitites.

Elliott (1966) suggested that albitites might have been derived during simple regional metamorphism of upper amphibolite facies. It was postulated that the initial mobile fraction derived by partial anatexis of amphibolites would be highly sodic and could consequently give rise to an albite-rich lithology. Whilst the authors accept this theory as feasible, certain aspects of albitites remain unexplained by such an hypothesis. For example, no evidence has so far been forwarded, which points to any higher concentration of such lithologies within the regions towards Risør and Arendal, where the grade of regional metamorphism must have been somewhat higher than in E. Bamble.

Recently Bodart (1966, 1969) has rejected the partial melting hypothesis of Elliott (op. cit.) on the ground of much higher Na_2O/K_2O ratios (~ 8) of the albitites compared with such melts in the Qz-Ab-An-Or-H_2O system ($Na_2O/K_2O \gtrsim 1$) and the high-temperatures probably required to melt sphene ($> 800°$ C) in order to produce the observed high TiO_2 contents (e.g. kragerøite). Bodart alternatively proposes an origin by liquid immiscibility, whereby a crystallizing gabbroic magma, rich in Cl, P and CO_2, forms two immiscible liquids: an Na-Si-rich liquid (albitite) and an Fe-P-oxide liquid which later forms immiscible apatite and iron oxide phase (c.f. Philpotts, 1967).

In view of the frequent spatial association of gabbro albitite, and the less common association of gabbro-albitite-apatite (Ødegaarden), an hypothesis involving liquid immiscibility would appear to be the most plausible to the present authors.

It is felt that, as yet, no one has proven conclusively that all albitites are consanguineous. Consequently the following origins for albitites remain to be proven or disproven by future publications:

1. Fluid magmatic differentiates intruded into the metamorphic sequence.
2. Metasomatic fluids diffused outward from nearby gabbroic intrusions.
3. The result of partial anatexis of amphibolites during regional metamorphism.
4. Products of almost isochemical metamorphism (and perhaps partial mobilization) of rocks belonging to the spilite-keratophyre suite.

Pegmatites

Lithologies and field relationships

The pegmatites of Eastern Bamble vary greatly in form and dimension, but may be classified into two, broad morphological groups namely:

(1) Rounded or elliptical lensoid masses, possessing sharp, discordant boundaries.
(2) Small, lensoid masses or veins, frequently conformable with the foliation.

Pegmatites of the first group are the only ones of sufficiently large dimensions to be included in the accompanying map. These pegmatites are mainly confined to the amphibolite-metasedimentary sequence within the southern and south-central portions of the mapped area. It is noteworthy that the majority of the larger pegmatite masses occur within that belt of gabbroic intrusions which runs between Bamble and Vissestad.

Petrography

The pegmatites, naturally, are coarse grained, but within any one sample the range may be as great as from 0.5 cm. to over 6.0 cm. Foliation is absent except in the marginal, usually more micaceous, portions.

The composition of the pegmatites of both groups varies from granitic, through granodioritic to dioritic and in most instances there is a distinct relationship between pegmatite type and host lithology. Where the host is of a siliceous or granitic aspect, the pegmatite is usually of granitic composition, whereas more mafic lithologies tend to host dioritic or granodioritic pegmatites. It was also noted that smaller pegmatites associated with gabbroic or metagabbroic rocks tended to be rich in albite, sphene and tourmaline.

The mineral assemblages observed within the E. Bamble pegmatites were:

Quartz + Plagioclase + Biotite

Quartz + Plagioclase + Microcline + Biotite

Quartz + Plagioclase + Microcline + Biotite + Sphene + Ilmenite

Quartz + Plagioclase + Microcline + Biotite + (Pyroxene) → Chlorite

Quartz + Plagioclase + Tourmaline

Sulphides (pyrite and chalcopyrite) were occasionally seen as accessories.

Mineralogy

Few detailed mineralogical studies were performed on this most interesting group during the present survey. It is hoped that detailed studies will be initiated in the future. However the following observations are pertinent:

Quartz: This mineral is usually xenoblastic and is often graphically intergrown with the feldspars. In a few localitites, adjacent to the Vissestad gabbro, rose-quartz is quite abundant.

Plagioclase: Plagioclase occurs as subidioblastic, xenoblastic or rarely idioblastic crystals, exhibiting megascopic lamellar twinning. The composition of the plagioclase is apparently normally within the range Albite-Oligoclase. In many instances the plagioclase is clouded by abundant microscopic inclusions.

Microcline: This mineral is usually red in colour, subidioblastic and intimately intergrown with plagioclase. Megascopic perthites are common.

Biotite and *Muscovite*: Brown or black subidioblastic to idioblastic biotite is ubiquitous within the pegmatites. Muscovite is far less common.

Petrogenesis

The mineral assemblages, agmatitic textures and the lack of chilled margins exhibited by the pegmatites of Eastern Bamble, suggest that they must have been derived during the main metamorphic phase. It is therefore concluded that these rocks represent mobile fractions derived by partial anatexis of the metasedimentary and metavolcanic sequence during the upper Amphibolite facies metamorphism.

THE CATACLASTITE BELT

Within Eastern Bamble, in the northern portion of the present map area, a N.E. - S.W. trending zone has been recognized which is characterized by a predominance or cataclastic rocks. The zone, occupying the area immediately to the south east of the Porsgrunn-Kristiansand fault, has a

width of 4.0 to 4.5 km. Most of the rocks within this belt have suffered some degree of cataclasis due to movements related to the aforementioned fault. The southern limit of the cataclastite belt is somewhat difficult to define, as cataclasis decreases gradually to the south east. Consequently an arbitrary southern boundary has been placed at the fault which runs from the region north of Kroktjern towards Garstad.

The cataclastites of E. Bamble are characteristically fine or very fine grained, well foliated and strongly banded rocks which exhibit a ubiquitous cataclastic texture in thin section. These rocks also possess, in many instances, remarkably strong lineations on their foliation planes. Compositionally, rocks within the cataclastite belt include representatives of all those lithological variations already described within the normal gneiss sequence.

Lithological cartography within the belt of cataclastites, (particularly in its southern portion, where fine banding is developed), is extremely difficult. Consequently a compromise 'grouping' had to be agreed upon and where amphibolitic lithologies predominated over granitic, quartzitic or schistose members within a banded sequence, the term 'basic' cataclastite was utilized.

The Gabbroic Rocks

Included within this group are all gabbroic rocks north of the fault line from Fisketjern to Asdal. Field relations of the gabbros are essentially identical to those further south, but differ in two aspects:

(i) The degree of dynamic metamorphism. Cataclasis and shearing are common features of the gabbroic rocks of the Cataclastite Belt, resulting in a reduction of grain size to about 2 mm.

(ii) The degree of amphibolitization. The response of the gabbroic rocks to P_{H_2O} - T conditions of the upper amphibolite facies is more complete.

The increasing intensity of folding northwards into the Cataclastite Belt and the amount of shearing associated with the Porsgrunn-Kristiansand fault is responsible for the above mentioned differences in the gabbroic rocks. Intense shearing and cataclasis facilitated the entry of fluids (predominantly H_2O) into the gabbroic bodies resulting in a virtually complete conversion of the former gabbroic mineralogy, into plagioclase and hornblende.

Basic and Leucocratic Gneisses

The term basic gneiss is used to designate gneisses dark in colour and composed of alternating fine-grained dark and light bands. Minute augen structures impart a mottled megascopic texture to the rock. They are

considered to be the normal amphibolites in the southern part of the area.

The leucocratic gneisses are very fine-grained (mostly 0.24 mm. or less), intensely banded, invariably lepidoblastic and occasionally porphyroblastic. Mineralogically they are similar to the previously described leucocratic gneisses in the normal sequence, and are considered to be their cataclasite equivalents.

The Pretectonic Granite Group

Included here are a group of rocks, outcropping on the east and west side of Flaatevatn, interpreted to have been derived from a pretectonic granite mass by varying degrees of cataclasis and shearing. The group includes:

1. Igneous granite (sensu stricto)
2. Rapakivi granite (sensu lato)
3. Augen granite gneiss
4. Granite gneiss

Only those rocks classified under (1) still retain a true granitic texture.

Mineralogy and Petrography

The grain size varies from medium in the igneous granite (sensu stricto) to coarse in the rapakivi granite.

The quartz is granoblastic to xenoblastic, and frequently shows sutured margins and undulose extinction in the sheared gneisses. Microcline occurs as individual granoblastic to xenoblastic grains, 0.25 mm. to 0.50 mm. in diameter, and in the case of rapakivi granite as cores of larger plagioclase grains. Microcline augen may be surrounded by a zone of plagioclase in the augen gneisses. Plagioclase may be present as individual, xenoblastic flattened grains, up to 3.0 mm in diameter, and as a mantle around microcline in remnants of rapakivi texture. Biotite is generally present as small xenoblastic ragged plates. Minute quantities have been observed in some of the rapakivi granites.

Petrogenesis

The rapakivi granite and the true igneous granite appear to be associated in the field. Rapakivi granite is always subordinate, and apparently a marginal relict feature of the granite. Augen granite grades laterally into granite and rapakivi granite.

It seems probable that the granite-granite gneiss area north of the Fiske-tjern-Asdal fault represents an area of pretectonic granite, which has suf-

fered severe brecciation and regional metamorphism resulting in the conversion of the majority of the granite into augen and granite gneiss.

The origin of the classic rapakivi granites of Finland and Sweden has for years been a point of conjecture amongst Scandinavian geologists; some advocating a metamorphic origin, others an origin by liquid immiscibility (Holmqvist, 1901) or order of crystallization (Wahl, 1925). Experimental work of Tuttle & Bowen (1958) lends support to a magmatic origin for the rapakivi texture. They suggest that a liquid with normative composition $qz + ab + or$ may crystallize quartz and alkali feldspar until the residual melt contains around 10 weight per cent H_2O and reaches the solvus in the binary Ab-Or system, at which point plagioclase and alkali feldspar crystallize and form mantles on previously crystallized alkalifeldspar.

Such an origin is consistent with the present indications of a pretectonic granite in parts of which the mode of crystallization resulted in a rapakivi texture.

Quartzites

Quartzitic material occurs interbanded within the gneiss sequence in the Cataclastic Belt. A thick quartzite band, very uniform in appearance, extends for 2 km. from the east end of the Fisketjern-Asdal fault.

Mineralogically the quartzites are similar to their far less sheared counterparts to the south, but are much finer grained. The average grain size varies between 0.25 mm. and 1.0 mm. As with the 'normal' quartzites farther south a metasedimentary origin is the most likely.

Mylonites

Mylonite is best developed to the north of the map area where it occurs as sporadic lenticles along the Porsgrunn-Kristiansand fault. Texturally the mylonites are porphyroblastic or extremely fine clastic, varying in grain size from 0.25 mm. to 4.0 mm.

Where the mylonite has been derived from granite gneiss, it is seen to consist of rolled and streaked feldspar fragments. The quartz has become finely granular and often appears to "flow" around the rolled feldspar grains. In some instances sericitic material forms fine partings between the minute quartz grains. Where mylonites have been derived from quartzite, streaked out lenticles of finely granular quartz are readily distinguishable.

THE POST PRECAMBRIAN

Cambro-Silurian Sediments

Rocks of Cambro-Silurian age occur in the eastern part of the map area. The precipitous Cambro-Silurian escarpment extending from Omborsnes to Rognstranda, forming a prominent physiographic feature of the area, has been previously interpreted as the line of the Oslo graben fault. Present work, however, refutes this interpretation.

Within the sector of the Cambro-Silurian mapped, only arkose and sandstones were encountered.

The Basal Arkose

An arkosic unit unconformably overlies the Precambrian of a number of localities, but is best developed in the environs of Rugtveitmyra near the Stathelle tunnel, and at the southern end of Stokkevann.

The arkose is a poorly sorted deposit of variable grain size. In certain instances it grades laterally into a pebble conglomerate. Angular to subrounded fragments of quartz (often with unlulose extinction) and microcline, varying from sand to pebbles in grain size, are contained in a medium to fine-grained matrix of quartz, feldspar and some organic material, with a calcite cement.

Sandstones

Sandstone is extensively exposed around the north and south shores of Stokkevann, where it conformably overlies the basal arkose. The sandstones are composed of extremely fine-graned (0.1 mm.), well-sorted, angular grains of quartz together with a small amount of detrital organic matter.

The rapid vertical transition from coarse poorly-sorted arkosic sediments to fine well-sorted sandstones suggests that rapidly changing surface conditions prevailed at the time of formation of these deposits.

The Precambrian-Cambrian Unconformity

In 1946 three bore holes were put down in the Omborsnes-Stathelle-Langesund region under the auspices of the Forsvarets Forskningsinstitutt. Only the borehole near Rognstrand actually intersected the Precambrian basement (see Figure 10).

If the boreholes and the observed dip (10° to 15°) of the Cambro-Silurian west of Stokkevann are plotted on a section (see Figure 10), it
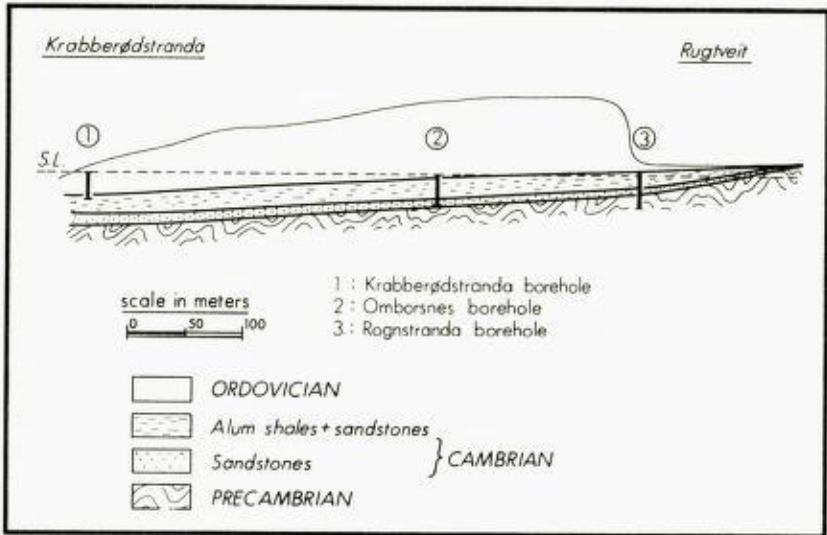
Fig. 10.

can be seen that there is no apparent fault or dislocation between the exposed Precambrian west of Stokkevann and the Precambrian basement underlying the Stathelle-Langesund area. There is, therefore, no evidence for the placement of any Oslo graben fault along the site of the Cambro-Silurian escarpment in E. Bamble.

Permian (?) Volcanic Rocks

Dolerite Dykes and Sills

Small dykes, generally less than one metre in thickness, occur sporadically throughout the area. They have a preferred N.N.W. - S.S.E. strike orientation. Sills are present only within the post-Precambrian sequence.

Petrography and Mineralogy:

In thin section the following assemblages have been recorded:

Plagioclase + Biotite + Chlorite + Serpentine + Ilmenite

Plagioclase + Pyroxene + Chlorite + Ilmenite

Plagioclase + Chlorite + Serpentine + Ilmenite + Pyrite

Plagioclase + Chlorite + Ilmenite + Pyrite

Plagioclase + Pyroxene + Biotite + Apatite + Chlorite
    + Ilmenite

The plagioclase is typically labradorite and occurs as subhedral lath-shaped crystals arranged in a decussate manner. Occasionally the feldspar may be completely altered. The interstices between the plagioclase laths are often filled with anhedral to subhedral augite laths, and commonly chlorite, serpentine and ilmenite. Serpentine is possibly replacing olivine. Occasionally biotite is present. Rarely is the texture sufficiently aligned to be termed trachytic.

Syenite Dykes

Syenite dykes have a very limited occurrence and are restricted to the area north of Flåtevatn. Like the dolerite dykes they may occur as single dykes or as an en echelon series of small dykes.

Petrography and Mineralogy:

The major syenite dyke which crosses the south arm of Flåtevatn is finegrained and occasionally contains orthoclase phenocrysts producing a distinctly porphyritic texture.

Usually subhedral to anhedral orthoclase laths form a well-defined decussate structure. Often the laths are strongly altered. Anhedral quartz together with plagioclase forms the dominant intersitial material. Chlorite, when present, is usually associated with opaques and exhibits a well-defined radiating fibrous structure.

Petrogenesis of the Syenites and Dolerites

It has long been thought that the doleritic intrusions of the Bamble area are associated with the Oslo graben. Vogt (1907) believed that the intrusion of the dolerites occured at the end of the Oslo eruptive epoch, and were older than the ore-forming solutions of Tråk and its environs.

Sills are present within the Cambro-Silurian deposits. Boreholes in the Langesund-Stathelle area reveal sills of varying thickness throughout their length, which are younger than lower Ordovician.

The dykes of the area are commonly aligned roughly parallel with the N.N.W. - S.S.E. group of faults, and it seems likely that the dykes were emplaced in fractures associated with these faults.

Sæther (1947) and Dons (1952) have concluded that dolerite dykes and sills make up an early group, whilst the quartz-porphyry and syenite dykes were intruded at a later date. Some of the larger porphyritic dykes may have served as feeders to Permian lavas similar to those which occur to the N.E. of Bamble.

Preliminary geochemical work of Christie (1964) on basic dyke swarms near Kragerø suggests that the dykes did not result from simple crystal differentiation of a basic magma, although they may have been derived from a single basaltic mass. Christie suggests that variations within single dykes may be due to some thermal diffusion process, which affected the melt during its upward migration from a deep-seated magma source.

Explosion Breccias

Irregular to circular outcrops of volcanic-vent breccias occur within the map area. Their outcrop is normally between 50 to 80 metres in diameter, and they occur at three localities approximately on a straight line oriented E.N.E. - W.S.W.:

1. West of Stokkevann
2. Tveitan
3. Hønstjern

Usually these breccias consist of irregular masses of angular gneiss fragments set within a fine-grained, dark groundmass, which may contain basic dyke stringers.

Mineralogy and Petrology:

The breccias are extremely coarse (due to large phenoclasts) between 10-12 cms. in diameter. Occasionally fragments as large as 30 cms. occur. The following lithologies have been recorded among the fragments:

1. Granite gneiss (Plagioclase + Microcline (sericitized) + Quartz + Biotite)
2. Augen gneiss (Plagioclase + Microcline + Quartz + Biotite)
3. Banded Gneiss (Plagioclase + Microcline + Quartz + Biotite + Amphibole)

The matrix is a fine-grained admixture of quartz, plagioclase and chlorite with a carbonate cement. Irregular grains of opaque iron oxides also can be seen.

Petrogenesis

It is most likely that the explosion breccias of E. Bamble are associated with the Permian volcanic activity of the Oslo graben. Their occurrence along a line approximately parallel to the Porsgrunn-Kristiansand fault is noteworthy.

It is felt that the breccias represent vents through which a gas-charged basaltic magma rose by a process of fluidization of the country rock and

erupted explosively at the surface. Similar volcanic vent breccias have been described from elsewhere in the Oslo area by Brøgger (1931) & Sæther (1945a).

THE GEOLOGICAL STRUCTURE

Structural Relationships Between Bamble and Upper Telemark

The Bamble sector of the Precambrian Shield in South Norway is separated from the Telemark sector by the Porsgrunn-Kristiansand fault (often loosely referred to as "the Great Friction Breccia"). The nature of the Porsgrunn-Kristiansand fault and the structural relationships between the Bamble and Telemark areas, have recently been the subject of considerable interest.

Subsequent to the initial work of Bugge (1928) on the nature of the Porsgrunn-Kristiansand fault, Barth (1947) and Elders (1963) have both suggested that the total relative movement was of a normal nature and that the N.W. side was moved upward relative to the S.E. side. Smithson (1963) has calculated a minimum vertical normal displacement of 0.5 km. on the basis of gravity measurements north of Herefoss, where granitic Telemark gneisses are faulted against Bamble rocks.

Although Bugge (1928) believed that the Bamble series represented an older and deeper group of rocks than those of Telemark, the converse is now widely accepted. Gravity studies carried out by Smithson (1963, 1965) have revealed the presence of a positive Bouguer anomaly increasing markedly from the Porsgrunn-Kristiansand fault to the coast. The anomaly probably results from the overall denser nature of the Bamble series compared with the Telemark gneisses, together with gradual coastward thickening of the series (see Figure 11).

Finally, it should be emphasized that the recent surveys in Bamble and Aust Agder, performed by members of this research group, have in all cases revealed the presence of a 4-5 km. wide belt of cataclastic rocks on the S.W. side of the Porsgrunn-Kristiansand fault. The genesis of the cataclastite belt and the fault itself are thought to have followed the sequence:

(1) Intense deformation and tight isoclinal folding in the north of the area, adjacent to the site of the present fault, resulted in the production of cataclastites when the elastic limit of the rocks was
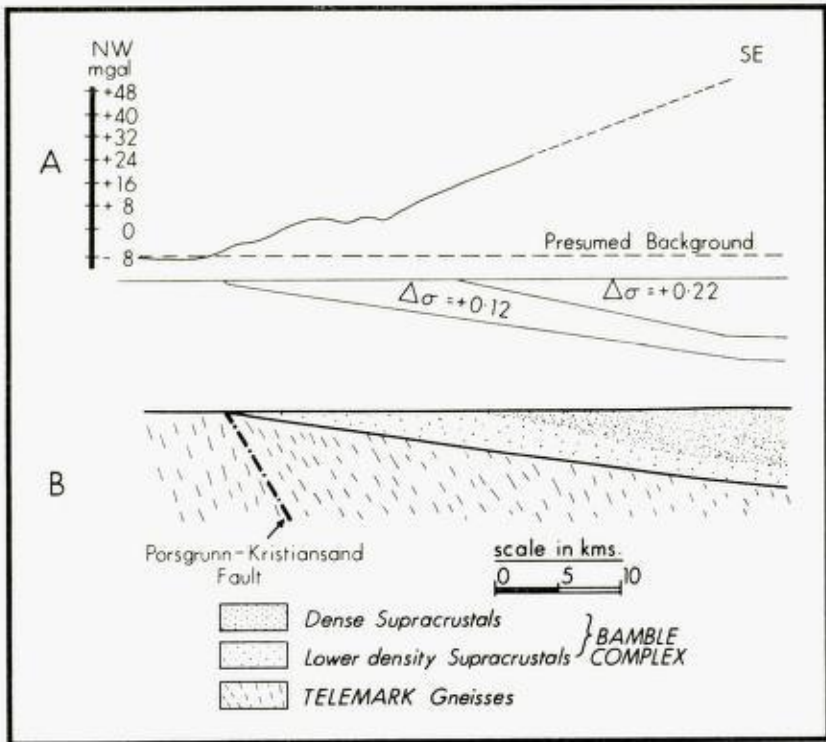
Fig. 11.

exceeded. The cataclastite belt thus marks the site of a major Precambrian transcurrent fault zone.

(2) Subsequent to the transcurrent movement along this zone, normal movement set in, at some phase between late Precambrian and Permian times.

It is therefore postulated that the present Porsgrunn-Kristiansand fault is a late-stage structure of normal character whose trend and attitude were determined by the anisotropy of the cataclastite associated with an older Precambrian transcurrent fault zone.

The Structure of Eastern Bamble

Wegmann (in Holtedahl, 1960) has recognized three major stages of deformation in Bamble . . .

1. Fairly shallow folding during which granodiorites were intruded.
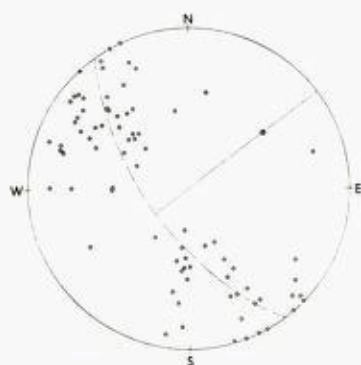
Plot of poles to foliation planes BAMBLE FOLD
Bearing 54°, Plunge 30°

Fig. 12.
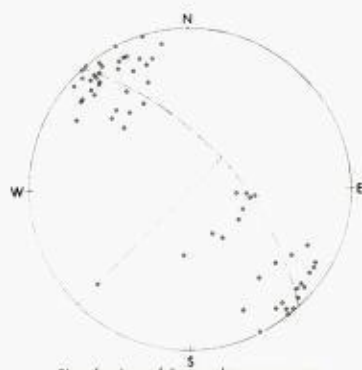
Plot of poles to foliation planes COASTAL FOLD
Bearing 226°, Plunge 20°

Fig. 13.
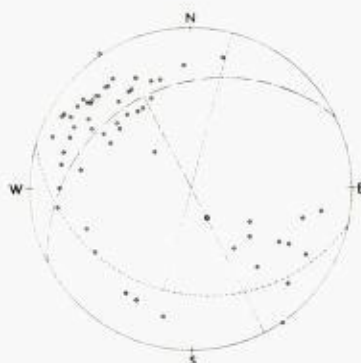
Plot of poles to foliation planes NORTH FOLD
Bearing 153°, Plunge 66°

Fig. 14.

2. Folding within the front of migmatization, which refolded previous structures along N.E. - S.W. axes.

3. Faulting which manifested itself in extensive zones of mylonitization.

Barth (1947) recognized two phases of folding in his work on the Iveland-Evje amphibolite along first N.W. - S.E. axes, and later along N.-S. axes. The present work serves to elaborate upon these earlier interpretations.

Folding

In Eastern Bamble the first recognizable folding took place along N.E. - S.W. axes (c.f. Wegmann, op. cit.). Folds are of similar style, and tend to be open near the coast, becoming strongly isoclinal northwards. In the

cataclastites deformation was of sufficient intensity to shear many folds along their hinges, leaving a series of parallel banded lithologies, often with no visible fold structures.

Axial plane schistosity parallel and sub-parallel to original stratification is frequently observed and suggests that shear folding was the dominant deforming mechanism. β diagrams constructed for the Bamble syncline (see Figure 12) and the Coastal fold (see Figure 13) indicate a fairly shallow plunge of 20° to 30° for the N.E. - S.W. folds.

The lensoid shape of the gabbroic bodies, and their lack of intrusive contacts suggests syntectonic emplacement and distribution during the N.E. - S.W. period of folding. Locally the gabbroic bodies may exert a considerable structural influence on the adjacent lithologies. The apparent S.S.E. plunge of 60° for the Skogen or North fold (see Figure 14) is thought to be possibly due to a tectonic emplacement of the Skogen norite.

In the adjacent area north and west of Ødegaardens verk in Western Bamble, Morton (unpublished data) has found evidence for a second phase of N. - S. similar folding. No direct evidence for this phase was found in Eastern Bamble and it seems likely that the second phase increases in intensity south westwards towards Aust-Agder.

Faulting

Two dominant sets of faults are present in Eastern Bamble (see Figure 15), an early N.E. - S.W. set subparallel to the Porsgrunn-Kristiansand fault and a younger set, which displaces the N.E. - S.W. faults, oriented N.N.W. - S.S.E.

Where observed the N.E. - S.W. faults (see Figure 16) dip steeply southwards and as noted by Wegmann (op. cit.) are frequently associated with zones of brecciation and mylonitization. The similarity of orientation between the N.E. - S.W. faults and the Porsgrunn-Kristiansand fault suggests a genetic relationship. It is probable that they were initiated as transcurrent faults contemporaneous with the formation of the Porsgrunn-Kristiansand fault and the Precambrian initiation of the Oslo Graben. The latest phase of movement along these faults is in a reverse sense and probably relates to a subsequent period of compression.

The N.N.W. - S.S.E. faults (see Figure 15) are vertical to steeply dipping and younger than the N.E. - S.W. faults. Frequently associated horizontal slickensides suggests that some strike slip displacement has occurred. Associated zones of brecciation are normally narrower than those associated with the N.E. - S.W. faults.

ROSE DIAGRAM ILLUSTRATING
FAULT TRENDS IN EASTERN BAMBLE

Fig. 15.

ROSE DIAGRAMS ILLUSTRATING
TRENDS OF HIGH ANGLE REVERSE FAULTS
a.=North, b.=South
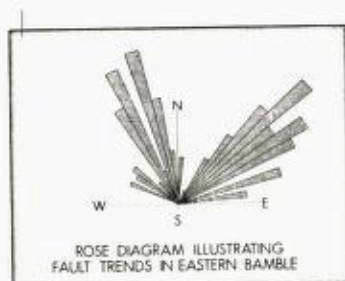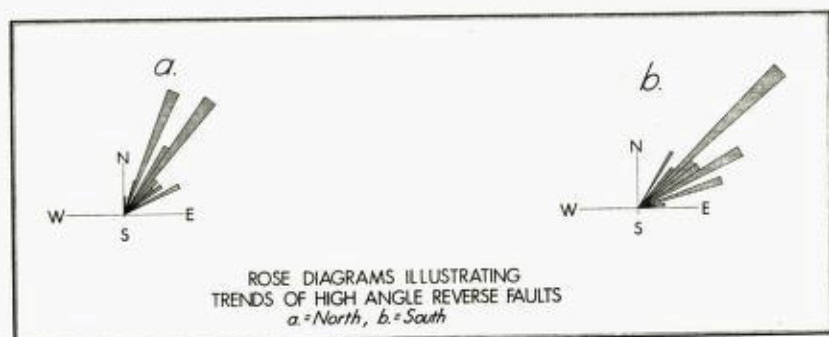
Fig. 16.

The Oslo Graben

The linear contact between Cambro-Silurian rocks and Precambrian metamorphics at the eastern margin of the map area has so often been interpreted as the actual limit of the Oslo Graben; the dominating physiographic feature of the Cambro-Silurian escarpment from Frierfjord to Rognstranda being erroneously interpreted as a fault-line escarpment. Field studies in the Stokkevann area and a study of borehole sections produced by Henningsmoen (1946) do not indicate the presence of any major fault. Similarly Smithson (1964) found no gravimetric evidence to support the presence of a fault. Rather the Porsgrunn-Kristiansand fault is most likely the north-western margin of the Oslo Graben, the S.E. margin being off-shore, demarcated by faults parallel to that which occupies the bathymetrically identified trough passing south-eastwards through the Skagerak between Gumø and Langø.
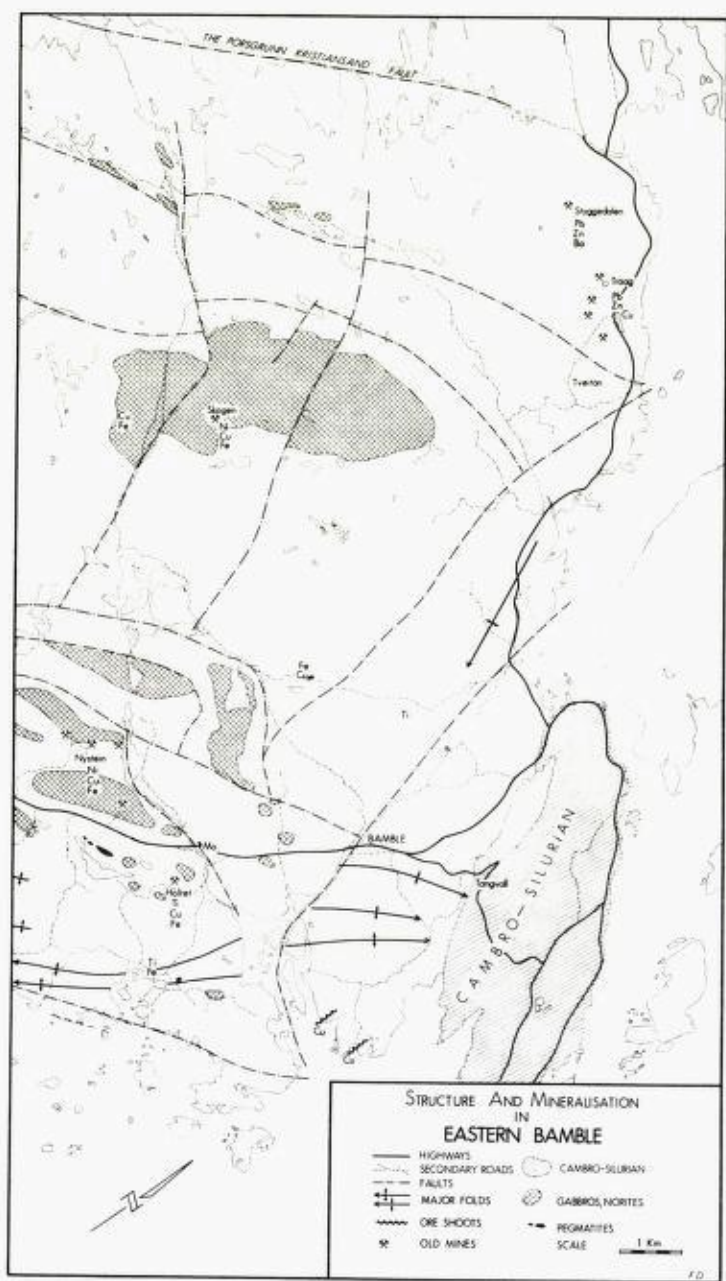
Fig. 17.

METALLIFEROUS ORE DEPOSITS

During the latter part of the 19th century and in the beginning of the 20th century, the Bamble district was the site of a number of small mining and quarrying operations. Scores of abandoned trenches and shallow workings bear witness to a feverish search for metalliferous deposits by the local land-owners of those times. The rewards for their efforts are perhaps meagre in the eyes of today's economic geologist, but the significance of these showings in the light of the present study, is more than encouraging for future systematic exploration.

The distribution of the known mineralization and disused workings of E. Bamble is illustrated in Figure 17. As can be seen from this sketch map, the area has so far yielded minor deposits of Fe, Ni, Cu, Mo, Ti, Pb and Zn ores. In accordance with the metallogenic classification of Norwegian ore deposits proposed by Vokes (1958), the metalliferous deposits of E. Bamble will be briefly described under two separate headings, namely:

1. Ores of the Precambrian metallogenic province.
2. Ores of the Permian igneous province.

Ores of the Precambrian metallogenic province

Two distinct groups of deposits have been recognized within this part of the Precambrian metallogenic province:

(a) Fe, Ni and Cu ores associated with the gabbros, norites and metagabbros.

(b) Fe, Ti, Cu and Mo ores associated with the metamorphic suite.

Precambrian ores associated with
gabbros, norites and metagabbros

The ore deposits of this group have been described and theorized upon in part by Vogt (1886, 1893, 1895, 1907 and 1923), and Holtedahl (1960). However, the most comprehensive (although unfortunately somewhat cursory) descriptions of the Bamble occurrences were given by Bugge (1922, 1965).

Field Relationships:

Three main sectors of Fe, Ni and Cu sulphide mineralization have been located so far. The first is around the S.E. portion of the Skogen norite intrusion and the second and third are associated with the Nystein and Vissestad gabbroic intrusions.

By the S. E. margin of the Skogen norite, approximately 1 km. to the N.E. of Heivatn, small showings of pyrrhotite, pyrite and chalcopyrite are apparently associated with a minor fault zone which cuts the peripheral portion of the norite. A small abandoned working, the Skogen mine, was located within this mineralized sector. Similar disseminated showings of pyrite and chalcopyrite were noted within the norite near the S. E. end of the intrusion approximately 1 km. E.N.E. of the southern end of Krokstjern.

The most intensive mining activity of E. Bamble was associated with vein- and disseminated-deposits of sulphides at Nystein and Vissestad. The Nystein workings were initiated, in 1859, on a 2-3 m. wide, 20-30 m. long sulphide orebody at the contact between the norite and gneiss. This orebody produced a nickeliferous pyrrhotite ore grading 1.15 % Ni and 0.44 % Cu. Below surface, on the 59 m. level, the orebody shortened to a length of only 18 m. The initial phase of operation terminated in 1884. During the second phase of development, in the period 1915-1917, the workings were extended to a depth of 73 m., at which level the orebody had a total length of 35 m. and an average width of 3 m. At the 89 m. level the orebody had similar dimensions of 32 m. x 3 m. Below this latter level, the orebody was proven by a crosscut at 110 m. but was worked only for a few meters. When the Nystein mine closed down in 1917, the vertical shaft had reached a total depth of 130 m. but no crosscuts had been driven below the 110 m. level.

The Vissestad (and Hansaas) mines too were first operated in the 1859-1884 period and later reopened during the Second World War. These mines are situated some 500 m. S.W. of the Nystein workings, almost 1.5 km. from the Vissestad hamlet were located on sulphide offshoots within amphibolites and gneisses adjacent to the Nystein gabbroic intrusion. During the initial period of production, a nickel-rich sulphide orebody, 10-15 m. long and 2-3 m. wide, was opened up to a depth of 49 m. Subsequently a new orebody was worked from the 49 m. level down to a depth of 70 m., where its dimensions were 14 m. x 2-3 m. Diamond boring proved ore to a depth of 84 m. Again, the principal ores, as in the Nystein deposit, were nickeliferous pyrrhotite and chalcopyrite.

Ore paragenesis and textural features:

Remarkably little information is available in the existing literature concerning either the mineral suites present within the nickeliferous ores of Bamble or any textural interrelationships which might throw light upon

their origin. Also, the fact that active mining in the district ceased in 1917, makes access to the partially flooded workings both hazardous and unfruitful. Consequently only a cursory mineralogical examination of specimens from the waste dumps was performed.

The ores of Vissestad and Nystein apparently fall into two distinct types:

(1) Low grade, disseminated, medium-grained pyrrhotite - pentlandite - pyrite $\pm$ chalcopyrite ores in metagabbros and amphibolite. Chalcopyrite-rich patches are often observed.

(2) High grade, massive ores in which amoeboid, ellipsoid or spherical blebs of silicates are set within a matrix of coarse-grained pyrrhotite - pentlandite - pyrite $\pm$ chalcopyrite.

More detailed descriptions of the ores from Vissestad will be presented in a forthcoming paper.

The petrogenesis of the Skogen, Vissestad and Nystein ores:

Both Vogt (op. cit.) and Bugge (op. cit.) have postulated that the ores of these deposits were derived by some process of magmatic segregation. Bugge (1922) compared the sulphide ores of Nystein and Vissestad with those of Copper Cliff, Sudbury, Ontario and concluded that they must have had similar origins, and differed only in dimensions.

It is the authors' opinion that the sulphide ores associated with the gabbroic suite of E. Bamble were derived by differentiation or sulfurization of noritic magmas intruded at a late stage in the Precambrian metamorphic cycle, prior to the formation of the granitic pegmatites. Massive ores exhibiting 'liquid immiscibility' textures between sulphide and silicate phases, identical to those described by Hawley (1962) in the Sudbury deposits, have been observed in numerous specimens from Vissestad and lend support to such an hypothesis.

However, it must also be emphasized that these ores have probably suffered some degree of metamorphism subsequent to their initial separation from the noritic rocks. Consequently future workers should not overlook the possibility that such deposits might well have been partially remobilized during the metamorphic phase and consequently may exhibit some tectonic control.

Precambrian ores associated with
the metamorphic suite

No detailed work was performed on this group of deposits which may
be classified as follows:

(1)   Disseminated ilmenite and rutile associated with albitites, peg-
matites and metagabbros.

(2)   Disseminated molybdenite in pegmatites.

The occurrence of ores of this group is generally confined to the Holtet,
Grostok and coastal sectors. Only one occurrence of molybdenite was noted
in a roadside exposure on the north side of the E-18 highway, west of Åby,
where a small plagioclase-biotite-garnet pegmatite contained approximately
2 % of disseminated molybdenite.

Ores of the Permian Igneous Province

Vein-type occurrences of Pb, Zn, Cu and Fe sulphides, apparently asso-
ciated with younger faults, are common throughout the eastern half of the
present map area. However, as was the case with the Precambrian deposits,
few of the showings have been exploited on a commercial basis. The only
workings of any noteworthy size are those at Tråk (Traag), Styggedalen
and Asdalvann (Trættebæk tjern).

Vogt (1907) described the vein deposits of Tråk, where brecciated
quartz veins contained sphalerite (low in Fe), galena (av. 0.5 % Ag),
chalcopyrite and pyrite. Two sets of fissures, striking N. - S. and E. - W.
were envisaged as forming during the sinking of the Oslo graben in Devo-
nian-Carboniferous times. It was conclusively proven that subsequent to
the initial vein formation, dolerite dikes were intruded into the veins and
the quartz gangue was consequently brecciated.

Foslie (1925) reviewed the ore deposits of S. Norway and pointed out
that the Permian ore deposits were noticeably confined to an area west of
the Permian eruptives. This was thought to be due to a deeper level of
erosion to the west of the supposed N. - S. trending graben.

The most recent study of this group of ore deposits in E. Bamble is that
performed by Røsholt (1963) who has presented a comprehensive and
detailed description of all known showings and workings of such vein
deposits.

The following annotated list provides some brief information concerning
the few major major occurrences of probable Permian ores in E. Bamble.

1. Tråk Mine: Vein deposits of sphalerite, galena, chalcopyrite and

pyrite in a quartz gangue. Veins strike N. 5° - 10° W. (dip. 80-85° W.) and E. - W. (variable, steep dip).

2. Styggedalen Mine: 5' vein of sphalerite and galena in a barite gangue. The dumps now yield perfect idiomorphic crystals of transparent, honeycoloured barite.
3. Asdalsvann Mines: The western working of this group reveals siderite veins, striking 99° E. of N. A central north west shore working shows a vein of galena and sphalerite striking at 90° E. of N. The easternmost working is founded on E. - W. veins.

For a more comprehensive description of mineralization in the Tråk district, which was published subsequent to the completion of this manuscript, the reader is referred to the work of Røsholt (1967).

Petrogenesis and significance of the Permian Ores:

The Permian ores of E. Bamble probably represent low temperature hydrothermal deposits related to underlying Permian intrusives. It would be erroneous to assume that the vein deposits of this district represent a localized concentration of ores adjacent to a well demarcated western limit of the Oslo graben; for similar occurrences have been found to the west and south-west during recent surveys. Therefore, on the basis of the foregoing conclusions, concerning the true position of the Oslo graben, it is suggested that the Permian metallogenic province would trend southwards through Bamble and Aust-Agder, being controlled by the Porsgrunn-Kristiansand fault and associated structures, which together represent the true western-most limits of the graben. The popular concept of a simple N. - S. graben structure should, as was stated earlier, be seriously reviewed in the near future.

GEOPHYSICAL INVESTIGATIONS

Previous Work

An aerial magnetometer survey of E. Bamble was performed, during the spring of 1959, under the auspices of the Norwegian State Ore Survey (Statens Malmundersøkelse). The results of this survey were plotted on a scale of 1 : 25,000 and became available in early 1961.

The most important features of this survey are presented, together with the outlines of the gabbroic intrusives and faults, in Figure 18. The following features of the map are noteworthy:

(1) The south-western 4500 gammas anomaly associated with the marginal sector of the Skogen mass is possibly related to some mineralization peripheral to the norite. It is significant that showings of pyrrhotite, pyrite and chalcopyrite were noted in this region during the geological survey.

(2) The central 4500 gammas anomaly of the Skogen intrusion might be due to the sulphide mineralization around the old Skogen mine.

(3) The north eastern 'high' within the Skogen intrusion is possibly indicative of some mineralization; although no surface showing were observed.

(4) The Bjørkeset and Hønstjern intrusions are characterized by low anomalies.

(5) The Nystein-Vissestad sectors are remarkable in that they exhibit no high anomalies. This is probably due to the fact that the magnetic pyrrhotite ores are worked out near the surface.

Future exploratory programs

To anyone aware of the present intensive exploration activity within analogous regions of the Canadian Shield, the degree of economic interest in the Bamble sector of the Fennoscandian shield is astonishingly minimal. It is unfortunate that the Norwegian economy cannot permit the offering of financial incentives for small companies or foreign investors to indulge in the 'gamble' of mineral exploration. However, it is strongly recommended that this portion of the Fennoscandian shield be subjected to renewed exploration utilizing such surveys as are presented herein as the basis for logical geochemical and geophysical investigations.

As a first step in this direction, it is suggested that one might initiate an exploratory program centred, in the first instance, upon the relatively unexplored Skogen norite and its environs. Such surveys could well reveal new sources of nickeliferous ores and revive the long dormant mining activity. It is also pertinent to reiterate the statement made by Bugge (1922) concerning the ores of Nystein and Vissestad, . . . 'the or deposits can be expected to continue to great depths.' Surely, the closure of such mines at less than 300 ft. should be reviewed in light of present costs and prices?

Finally, it is hoped that the information presented in this paper may encourage further exploration in Bamble both for ores associated with the Precambrian intrusive suite and for those which are probably associated with the numerous later faults cutting both the intrusives and the metamorphic suite.

FAULTS, GABBROIC ROCKS and MAGNETOMETER VALUES
IN
EASTERN BAMBLE

GABBROS, NORITES   1500 MAGNETIC CONTOURS
CAMBRO- SILURIAN   — — FAULTS

SCALE IN KILOMETERS
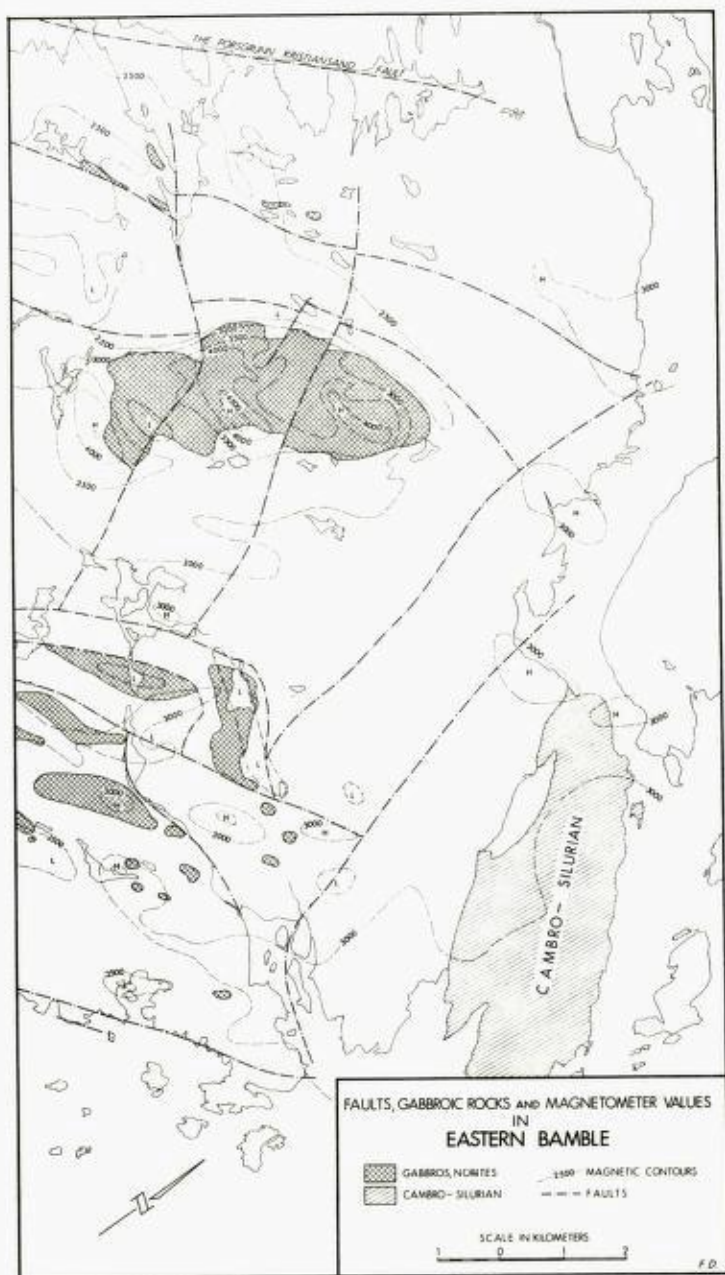
Fig. 18.

APPENDIX 1. MINERALOGICAL NOTES

One sample of biotite taken from a schist in the Grostok area and one garnet from a garnetiferous - quartz - mica schist (Quartz + Plagioclase + Garnet + Biotite) were kindly analysed and examined by Dr. D. C. Burrell. The results of these studies are incorporated in Tables 9 and 10. The results of the garnet study show that it is an almandine - pyrope variety and are consistent with the results published by Burrell (1966) for other garnets taken from other lithologies formed within the almandine - K - feldspar - sillimanite subfacies of the almandine amphibolite facies elsewhere in S. Norway.

APPENDIX 2. ANALYTICAL METHODS

All the analyses cited herein were performed at the University of Nottingham employing a modified version of the rapid silicate analysis scheme proposed by Shapiro and Brannock (1956).

Silica was determined spectrophotometrically by measurement of the absorbance of the blue complex formed by reduction of the yellow silica-molybdate complex.

The method utilized for alumina determination was that of Hill (1956), where a solochrome - cyanine - R - aluminium complex is formed at pH6 (with ammonium acetate buffer) in the presence of Na mercaptoacetate (to supress V, Be, Fe and Zr interference). However, it is noteworthy that in those rocks with high TiO_2, the method was unsuitable.

Total Fe was determined by measuring the absorbance of the orange ferrous orthophenanthroline complex. The method proved unreliable (without dilution) in rocks with > 10 % total Fe.

The volumetric procedure advocated by Wilson (1960) was utilized for FeO determination. This method avoids the atmospheric oxidation of iron during sample decomposition.

The flame photometric procedures of Haywood (1965) were utilized for the determination of alkalies and alkaline earths, subsequent to the precipitation of Fe and Al with ammonium hydroxide.

TiO_2 was determined by measuring the absorbance of yellow titanium peroxide complex according to Shapiro and Brannock (op. cit.).

MnO and P_2O_5 were determined spectrophotometrically by the permanganate method and molybdophosphoric acid complex procedures respectively.

FAULTS, GABBROIC ROCKS & SPECIMEN LOCATIONS
IN
EASTERN BAMBLE

GABBROS/NORITES
CAMBRO–SILURIAN
FAULTS

SCALE IN KILOMETERS
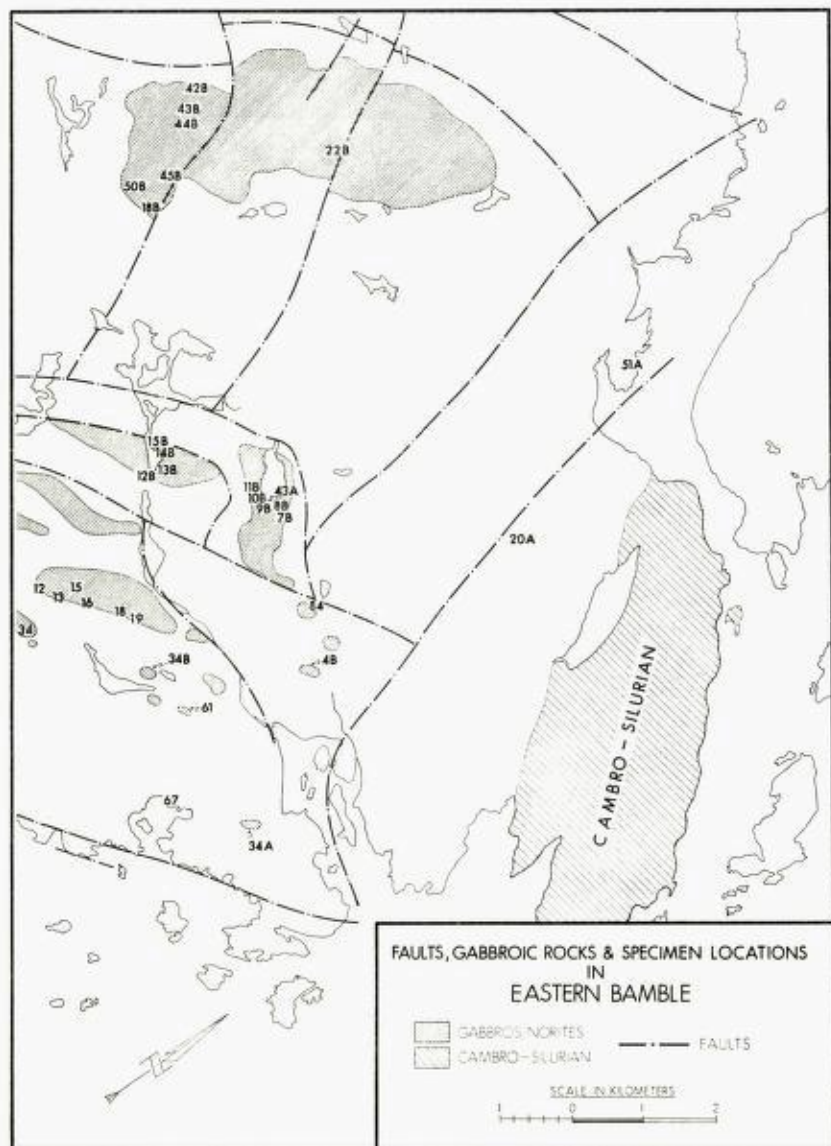
Fig. 19.

STATENS GEOLOGISKE INSTITUTT
BIBLIOTEKET

Table 1: Modal analyses of Quartzites and Quartz-feldspar-biotite gneisses from Eastern Bamble

Spec. No.	10A	11	25	59A	79	37	12A
Quartz	94.8	82.6	93.9	95.2	83.6	41.6	73.4
Microcline	—	—	—	—	—	21.6	7.7
Plagioclase	—	—	—	—	—	0.7	—
Biotite	—	14.9	—	—	0.3	35.2	18.9
Muscovite	5.2	0.2	0.4	4.6	16.1	—	—
Sillimanite	—	1.6	—	—	—	—	—
Tourmaline	—	0.7	5.7	—	—	0.7	—
Apatite	—	—	—	—	—	—	—
Opaques	—	—	—	0.2	—	—	—
Prehnite	—	—	—	—	—	0.2	—

Table 2: Modal analyses of granitic, granodioritic and quartz dioritic gneisses fom E. Bamble

TYPE	GRANITIC GNEISSES							GRANODIORITIC GNEISSES					QUARTZ DIORITIC GNEISSES						
Spec. No.	40A	56A	70	73	76	78	81	27	39	47	82	85	27A	28	38A	42	49	74	77
Mineral																			
Quartz	34.6	30.3	30.7	34.1	41.4	46.0	45.8	15.3	50.0	36.3	52.8	17.3	33.3	39.3	37.3	13.6	11.3	29.2	51.0
K-feldspar	29.7	46.0	31.6	30.9	27.4	21.6	30.2	7.1	16.1	6.9	15.8	16.5	0.4	—	—	—	—	—	—
Plagioclase	20.3	14.7	30.2	22.0	1.4	7.4	11.9	53.9	29.0	36.4	25.2	61.1	61.8	43.4	47.4	42.9	62.5	44.0	45.6
Biotite	7.5	—	3.5	13.0	6.2	20.6	7.5	—	4.9	19.2	4.5	3.2	4.5	11.3	11.0	—	26.0	7.4	3.4
Muscovite	—	7.3	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Hornblende	7.9	—	3.9	—	—	—	—	15.2	—	—	—	—	—	—	4.3	—	—	—	—
Garnet	—	—	—	—	—	—	2.8	—	—	—	1.6	1.8	—	5.9	—	12.7	—	—	—
Sillimanite	—	—	—	—	23.6	4.4	1.8	—	—	—	—	—	—	—	—	—	—	—	—
Opaques	—	1.6	—	—	—	—	—	—	—	0.6	0.1	0.1	—	—	—	1.4	0.2	9.0	—
Apatite	—	0.1	0.1	—	—	—	—	—	—	0.6	—	—	—	0.1	—	0.2	—	0.6	—
Chlorite	—	—	—	—	—	—	—	8.5	—	—	—	—	—	—	—	29.2	—	—	—
Epidote	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	9.9	—

Table 3: *Modal analyses of amphibolites from E. Bamble*

Spec. No.	2A	18A	40	48	52	54A	89	91
Mineral								
Quartz	38.8	3.8	—	4.8	1.8	—	12.8	—
Plagioclase	—	30.9	29.6	23.4	51.7	36.0	25.0	42.3
Pyroxene	—	—	—	—	—	—	—	—
Hornblende	56.8	48.9	57.2	70.5	42.3	61.8	52.2	50.3
Biotite	—	4.4	7.8	—	1.4	—	7.6	0.4
Garnet	—	9.6	—	—	—	—	—	—
Sphene	—	—	2.8	0.2	—	—	—	—
Epidote	3.0	—	—	—	—	—	—	—
Apatite	1.2	0.4	0.3	—	0.3	0.1	0.8	2.0
Opaques	0.2	2.0	2.3	1.1	2.5	2.1	1.6	5.0

Table 4. *Modal analyses of Gabbroic and Metagabbroic rocks from E. Bamble*

INTRUSION	SKOGEN NORITE								VISSESTAD GABBRO							HØNSTJERN NORITE							BJØRKESET NORITE					MINOR GABBROS								
Spec. No.	18B	22B	42B	43B	44B	45B	50B	Av.	12	13	15	16	17	19	Av.	7B	8B	9B	10B	11B	43A	Av.	12B	13B	14B	15B	Av.	4B	20A	34	34A	34B	51A	61	67	84
Mineral																																				
Quartz	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1.9	—	—	—	—	—	—
Plagioclase	69.6	54.0	64.0	65.9	67.2	63.8	22.9	58.2	37.8	28.8	40.9	64.3	40.6	56.9	44.9	44.8	36.7	40.9	29.8	23.5	13.0	31.5	49.1	53.2	18.3	38.6	39.8	45.3	38.1	50.5	43.1	37.2	23.3	8.4	33.4	26.4
Orthopyroxene	26.7	37.1	19.4	14.2	11.5	21.4	64.1	27.8	3.5	—	—	—	—	—	0.6	15.2	—	17.8	7.3	6.9	30.9	13.0	—	14.5	17.8	12.4	11.2	—	—	—	—	—	—	—	—	—
Clinopyroxene	—	—	—	—	—	—	—	—	17.4	20.0	—	4.1	—	8.9	8.4	—	—	—	—	—	—	—	5.0	—	—	—	1.3	6.9	32.5	—	20.5	—	13.8	—	20.4	—
Olivine	—	—	—	3.1	—	—	—	0.5	—	—	—	—	—	—	—	—	19.0	10.9	—	—	10.1	6.7	—	—	—	—	—	—	6.6	—	—	—	—	—	—	—
Hornblende	0.4	7.5	11.3	14.5	15.4	12.0	8.4	9.9	31.7	42.7	49.7	24.0	55.4	20.8	37.4	25.4	25.6	38.6	58.3	40.4	34.1	35.4	29.2	29.0	35.2	43.2	34.2	44.5	20.9	38.2	35.7	59.4	62.0	75.9	7.0	56.0
Biotite	1.6	0.8	1.0	0.3	3.8	0.5	3.4	1.6	—	—	—	—	1.6	4.8	1.1	4.4	0.6	0.9	4.6	8.0	1.9	3.4	2.6	0.9	—	—	0.9	—	1.4	—	1.3	—	—	—	16.7	14.0
Garnet	—	—	—	—	—	—	—	—	—	—	—	—	—	5.2	0.8	10.2	15.3	0.9	—	21.2	10.0	9.6	10.3	—	26.6	4.6	10.4	0.6	—	—	—	—	—	—	—	—
Epidote	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Chlorite	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2.8	—	—	—	—	0.4	—	—	0.3	—	—	—	—	—	—	—	—	—	15.8	—
Sphene	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.2	—	—	—	—	—	—	—	—	2.6	—
Ilmenite/Opaques	1.4	0.5	4.3	1.6	1.4	2.3	1.2	1.8	9.6	8.3	9.0	7.3	0.6	3.0	6.3	—	—	—	—	—	—	—	3.8	0.5	—	1.0	1.3	1.3	1.9	4.2	0.7	1.7	—	12.4	6.7	3.2
Spinel	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Apatite	0.3	0.1	—	0.4	0.7	—	—	0.2	—	0.2	0.4	0.3	1.8	0.4	0.5	—	—	—	—	—	—	—	—	1.9	1.8	—	0.9	1.4	—	3.5	—	0.4	0.9	0.7	—	0.4
Zircon	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.2	—	—	—	0.3	—	—	—	—	—	—

Table 5: Partial chemical analyses and Niggli values of granitic, granodioritic and quartz-dioritic gneiss, E. Bamble.

TYPE	GRANITIC GNEISSES							GRANODIORITIC GNEISSES				QTZ. DIORITIC GNEISSES	
Spec. No.	37	40A	56A	70	73	76	81	27	39	47	82	38A	74
SiO_2	65.05	68.80	75.62	74.07	80.91	75.86	74.23	62.35	72.71	68.67	75.00	54.99	59.81
Al_2O_3	16.01	14.55	12.41	13.07	7.91	13.46	13.11	17.32	13.32	13.92	13.40	16.12	14.01
TiO_2	0.93	0.77	0.30	0.35	0.01	0.18	0.43	0.58	0.29	0.81	0.17	1.21	1.22
Fe_2O_3	0.92	1.02	2.11	0.85	0.63		1.28	1.37	0.34	3.94	0.12	8.97	9.92
FeO	6.89	3.83	0.15	1.68	1.20	1.23	2.79	4.25	0.92	2.34	1.47	7.37	4.40
CaO	2.10	2.80	—	0.40	2.50	0.60	1.00	3.90	1.50	3.50	0.70	3.40	3.20
MgO	4.05	1.15	0.20	0.50	2.70	1.20	1.67	3.85	0.50	2.25	0.55	4.50	2.20
Na_2O	0.41	3.04	3.48	3.51	1.08	3.46	1.29	4.22	3.85	1.79	2.50	2.32	2.91
K_2O	3.37	3.95	4.16	4.13	1.50	4.37	3.64	1.45	2.86	2.71	4.37	2.20	2.06
MnO	0.01	0.09	0.11	0.01	—	tr	0.17	0.12	—	0.01	0.12	—	—
P_2O_5	0.29	0.26	0.09	0.10	0.02	0.08	0.06	0.12	0.10	0.25	0.07	0.03	0.09
TOTAL	100.03	100.26	98.63	98.67	98.46	100.44	99.67	99.53	99.69	100.19	98.47	101.11	99.82
al	35	38	48	45	31	45	42	34	46	35	49	26	27
fm	47	25	14	16	37	16	32	35	11	34	14	54	48
c	8	13	—	3	18	4	6	14	10	16	5	10	11
alk	10	24	38	36	14	35	20	17	33	15	32	10	14

Table 6: Chemical analyses and Niggli values of amphibolites, E. Bamble.

Spec. No.	18A	30	40	48	54	89
SiO_2	46.11	50.19	51.50	47.42	47.59	50.77
Al_2O_3	19.33	18.61	18.49	18.73	16.60	13.90
TiO_2	2.46	1.27	0.85	1.27	2.04	2.32
Fe_2O_3	2.96	11.62	2.62	3.06	3.12	3.33
FeO	11.23	—	7.34	8.71	11.20	11.35
CaO	6.83	6.97	7.38	8.70	10.59	6.91
MgO	5.80	3.40	7.63	7.67	5.96	3.94
Na_2O	2.70	4.16	2.72	2.14	2.60	2.68
K_2O	0.92	1.45	0.64	0.87	0.50	1.61
MnO	0.23	0.18	0.06	0.13	0.01	0.25
P_2O_5	0.20	0.16	0.17	0.12	0.19	0.59
TOTAL	98.77	98.01	99.40	98.82	100.40	97.65
al	27	29	26	25	23	22
fm	48	38	48	48	46	49
c	17	20	19	21	25	20
alk	8	13	7	6	6	9
mg	0.42	0.53	0.59	0.54	0.43	0.33
ti	4.4	2.6	1.6	2.2	3.5	4.7
k	0.19	0.18	0.14	0.21	0.11	0.28
k	0.19	0.18	0.14	0.21	0.11	0.28
na	0.81	0.82	0.86	0.80	0.89	0.72
p	0.0014	0.0016	0.0014	0.0014	0.0013	0.0064

Table 7: Chemical analyses and Niggli values of the Gabbroic Rocks.

	SKOGEN NORITE							HØNSTJERN NORITE						BJØRKESET NORITE				VISSESTAD GABBRO					MINOR GABBROS					
	18B	22B	42B	43B	44B	45B	50B	7B	8B	9B	10B	11B	43A	12B	13B	14B	15B	12	13	15	16	19	4B	20A	34A	51A	67	84
SiO_2	51.72	52.54	50.56	50.07	53.53	52.05	53.68	46.29	45.90	45.37	43.59	41.25	43.98	46.21	47.85	44.55	45.79	43.77	43.69	43.61	43.78	46.08	48.59	49.05	44.41	47.01	44.65	44.33
Al_2O_3	20.33	18.84	19.82	21.52	22.31	21.90	11.39	14.09	19.50	14.32	15.32	14.40	16.00	15.50	20.20	18.42	19.35	14.96	14.82	14.81	16.65	18.04	18.11	19.74	17.42	14.57	16.65	15.44
TiO_2	0.93	0.47	1.42	0.54	0.41	0.83	0.76	1.69	1.03	0.62	3.19	4.02	0.95	2.88	0.93	0.84	1.26	7.08	5.24	5.08	4.41	3.63	1.72	0.54	2.52	0.68	2.42	3.07
Fe_2O_3	1.42	0.95	1.44	1.36	1.03	0.47	2.19	3.12	2.59	3.15	5.60	6.62	3.97	3.98	1.49	2.39	4.22	—	5.26	3.74	3.48	3.50	2.13	1.67	5.76	3.50	5.32	4.14
FeO	6.14	7.87	7.43	7.31	4.40	7.10	10.63	10.39	8.82	10.60	12.35	13.32	11.68	10.56	8.23	9.73	8.89	14.40	12.30	12.70	9.22	11.02	10.93	10.24	11.80	9.60	11.30	14.80
CaO	8.95	5.81	8.95	7.48	8.95	6.96	5.25	8.29	7.28	6.55	7.94	7.60	5.96	7.44	6.55	7.44	6.98	8.69	5.71	10.83	10.47	10.23	5.95	6.88	9.04	10.80	9.76	9.28
MgO	4.97	8.71	5.35	7.33	4.97	4.97	12.52	8.40	9.54	13.75	6.84	5.60	13.26	6.92	8.41	11.82	8.75	5.30	5.50	4.50	4.50	4.30	5.39	8.50	6.10	9.33	6.47	5.80
Na_2O	3.44	2.70	3.17	2.90	3.05	3.54	1.86	2.91	2.71	2.33	2.95	2.43	1.94	3.14	3.00	2.33	2.73	3.70	4.60	3.80	4.30	2.60	3.57	2.53	3.50	2.28	2.30	2.40
K_2O	0.88	0.66	0.78	0.60	0.90	0.94	0.84	0.78	0.65	0.42	0.57	0.57	0.33	0.87	0.45	0.42	0.57	1.00	1.80	0.80	1.40	0.70	1.36	0.34	1.10	1.00	0.40	0.50
Mno	—	tr	0.01	0.16	tr	0.20	0.28	0.18	0.15	0.16	0.13	0.32	0.16	0.21	0.16	0.20	0.16	—	0.02	0.02	0.01	0.09	—	0.16	0.02	0.24	0.96	1.64
P_2O_5	0.34	0.14	0.11	0.15	0.11	0.16	0.42	0.97	0.10	0.06	0.10	1.15	0.18	0.74	0.27	0.16	0.56	2.21	0.72	1.12	0.54	0.76	0.37	0.19	0.31	0.02	0.24	0.38
TOTAL	99.12	98.69	99.04	99.42	99.66	99.12	99.82	97.11	98.27	97.33	98.58	97.28	98.41	98.45	97.54	98.30	99.26	101.11	99.66	101.01	98.76	100.95	98.12	99.84	101.98	99.03	100.47	101.78
al	30	27	29	30	34	34	15	19	25	17	20	19	19	21	28	22	25	21	20	20	22	29	27	26	22	18	21	19
fm	35	50	38	43	31	36	67	53	51	64	54	56	64	52	49	57	52	47	53	46	40	33	46	51	49	52	51	54
c	25	15	24	19	25	19	13	20	17	14	19	19	13	19	16	16	16	22	14	26	26	30	16	17	20	24	23	21
alk	10	8	9	8	10	11	5	8	7	5	7	6	4	8	7	5	7	10	13	9	12	8	11	6	9	6	5	6
mg	0.55	0.64	0.53	0.60	0.63	0.53	0.63	0.53	0.60	0.65	0.41	0.34	0.61	0.46	0.51	0.64	0.55	0.40	0.37	0.34	0.40	0.53	0.43	0.57	0.39	0.56	0.41	0.34
ti	1.8	0.9	2.7	1.0	0.8	1.6	1.4	2.9	1.7	1.0	5.3	6.8	1.2	5.0	1.7	1.3	2.1	12.7	9.23	8.61	7.65	7.40	3.3	1.0	4.1	1.1	3.9	4.8
k	0.14	0.14	0.14	0.11	0.17	0.15	0.23	0.15	0.14	0.11	0.11	0.13	0.11	0.15	0.09	0.11	0.12	0.15	0.20	0.13	0.18	0.16	0.21	0.10	0.17	0.23	0.10	0.11
na	0.86	0.86	0.86	0.89	0.83	0.85	0.77	0.86	0.86	0.88	0.89	0.87	0.89	0.85	0.91	0.88	0.88	0.85	0.80	0.87	0.82	0.84	0.79	0.91	0.83	0.77	0.90	0.89
p	0.0031	—	0.0015	0.0014	0.0016	0.0016	0.0041	0.0095	0.0013	—	0.0013	0.0100	0.0012	0.0070	0.0028	0.0012	0.0053	0.0227	0.0070	0.0108	0.0056	0.0082	0.0065	0.0014	0.0025	—	0.0026	0.0038

Table 8: C.I.P.W. Norms of the Gabbroic Rocks

	SKOGEN NORITE							HØNSTJERN NORITE						BJØRKESET NORITE				VISSESTAD GABBRO					MINOR GABBROS					
	18B	22B	42B	43B	44B	45B	50B	7B	8B	9B	10B	11B	43A	12B	13B	14B	15B	R	14	15	16	19	4B	20A	34A	51A	67	84
Q	—	3.43	—	—	3.11	0.71	3.87	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Or	5.20	3.90	4.61	3.54	5.32	5.55	4.96	4.61	3.84	2.54	3.37	3.37	1.95	5.14	2.66	2.48	3.37	5.91	10.03	4.73	8.27	4.14	8.04	2.01	6.50	5.91	2.36	2.95
Ab	29.09	22.84	26.81	24.53	25.80	29.94	15.73	24.61	22.92	19.71	24.95	20.55	16.41	26.56	25.37	19.71	23.09	30.30	27.03	21.46	15.58	21.99	30.19	21.40	19.67	18.42	19.45	20.30
An	37.44	27.90	37.55	36.12	43.67	33.48	20.25	23.08	35.45	27.35	26.88	26.70	28.39	25.63	30.72	35.86	30.97	21.26	14.48	21.00	22.00	35.49	27.10	32.88	28.58	26.57	33.93	29.88
Ne	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	6.43	5.39	11.26	—	—	—	5.38	0.47	—	—
Co	—	—	—	—	—	—	—	—	—	—	—	—	—	—	3.52	0.99	2.89	—	—	—	—	—	0.84	3.16	—	—	—	—
Di	3.77	—	5.02	—	—	—	2.47	9.57	—	3.83	9.72	2.88	—	5.26	—	—	—	6.17	7.48	21.07	21.50	8.54	—	—	11.71	21.88	10.63	11.47
wo	1.98	—	2.56	—	—	—	1.27	4.89	—	1.98	4.95	1.46	—	2.69	—	—	—	3.10	3.82	10.61	11.03	4.30	—	—	5.94	11.22	5.39	5.71
en	1.12	—	1.40	—	—	—	0.78	2.80	—	1.26	2.70	0.74	—	1.53	—	—	—	1.45	2.15	5.08	6.52	2.04	—	—	3.13	6.64	2.79	2.30
fs	0.77	—	1.06	—	—	—	0.42	1.88	—	0.59	2.07	0.68	—	1.04	—	—	—	1.62	1.51	5.38	3.95	2.20	—	—	2.64	4.02	2.45	3.46
Hy	18.53	34.57	17.36	26.52	18.92	24.02	46.94	11.75	8.62	10.56	2.81	19.50	19.85	13.50	23.06	6.26	19.39	—	3.66	—	—	14.51	13.02	32.44	—	—	10.82	7.29
en	10.95	21.68	9.86	16.16	12.37	12.37	30.69	7.03	5.63	7.18	1.59	10.11	13.13	8.03	14.38	4.16	12.86	—	2.15	—	—	6.99	6.05	18.07	—	—	5.76	2.91
fs	7.58	12.89	7.50	10.36	6.55	11.65	16.55	4.72	2.99	3.38	1.22	9.39	6.72	5.47	8.68	2.10	6.53	—	1.51	—	—	7.52	6.97	14.37	—	—	5.06	4.38
Ol	—	—	—	2.51	—	—	—	13.52	20.14	27.47	16.44	4.39	21.79	9.42	7.66	27.57	9.75	18.37	14.36	9.31	5.47	2.56	11.73	4.06	16.29	19.39	10.41	17.21
fo	—	—	—	1.47	—	—	—	7.77	12.70	18.80	8.92	2.17	13.93	5.38	4.60	17.71	6.25	8.23	8.09	4.29	3.28	1.17	5.17	2.16	8.45	11.63	5.29	6.47
fa	—	—	—	1.04	—	—	—	5.75	7.44	9.39	7.52	2.22	7.86	4.04	3.06	9.86	3.50	10.14	6.27	5.02	2.19	1.39	6.56	1.90	7.84	7.76	5.12	10.74
Mt	2.06	1.36	2.09	1.97	1.49	0.68	3.18	4.72	3.76	4.57	8.12	9.60	5.76	5.77	2.16	3.47	6.12	—	7.63	5.42	5.05	5.07	3.09	2.42	8.35	5.07	7.71	6.00
Il.	1.77	0.89	2.70	1.03	0.78	1.58	1.44	3.21	1.96	1.18	6.06	7.63	1.80	5.47	1.77	1.60	2.39	13.45	9.95	9.65	8.38	6.89	3.27	1.03	4.79	1.29	4.60	5.83
Ap	0.81	0.33	0.26	0.36	0.26	0.38	1.00	2.30	0.24	0.14	0.24	2.73	0.43	1.75	0.64	0.38	1.33	5.24	1.71	2.66	1.28	1.80	0.88	0.45	0.74	0.05	0.57	0.90

Table 9: *Chemical analysis of biotite from schist — Grostok area.*
Anal. D. C. Burrell.

SiO_2	38.49
TiO_2	3.43
Al_2O_3	16.01
Fe_2O_3	2.35
FeO	15.43
MnO	—
MgO	9.54
CaO	0.95
Na_2O	1.67
K_2O	7.14
H_2O+	3.48
H_2O-	1.02
P_2O_5	0.17
Total	99.66
Zn (ppm)	205

Table 10: *Data for garnet from Qtz-Plag-Garnet-Bi schist nr. Grostok.*

SiO_2	38.98
TiO_2	0.12
Al_2O_3	19.18
Fe_2O_3	4.01
FeO	24.82
MnO	0.96
MgO	7.91
CaO	4.02
	100.00

Zn (ppm): 230   Cu (ppm): 2080

Ionic content (24 O) and percentage end-member molecules

Si	6.073			
Al^{4+}	—	6.073	Almandine	56.10
Al^{6+}	3.518		Spessartine	2.08
Ti	0.009	3.995	Pyrope	31.31
Fe^{3+}	0.468		Andradite	10.51
Fe^{2+}	3.200		Grossularite	—
Mn	0.122			
Mg	1.834	5.858		
Ca	0.674			

I.R. Absorption peaks (cm^{-1}) : 695, 805, 880, 900, 965, 1085.
R I. : 1.791 . Cell edge length (a) = 11.56Å.

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PLATE 1

Fig. 1. Well foliated sillimanite-muscovite quartzite illustrating a cluster of prismatic sillimanite crystals partly replaced by muscovite. Spec. RDM 62/11. Plain polarized light. ×25.

Fig. 2. Detail of sillimanite crystals (with well developed [010] cleavage) exhibiting partial replacement by secondary muscovite, within a quartz matrix. Spec. RDM 62/11. Plain polarized light. ×40.

Fig. 3. Well foliated, nodular quartz-sillimanite-biotite-microcline gneiss. Note that in this specimen the sillimanite occurs as fibrolite (as distinct from the more prismatic habit seen in RDM 62/11, figs. 1 & 2). The sillimanite var. fibrolite is predominantly oriented subparallel to the trace of the foliation. However, in the 'nodules', to the right and left of the figure, other orientations are clearly developed. Spec. RDM 62/76. Plain polarized light. ×25.

Fig. 4. Details of a quartz-sillimanite (var. fibrolite) 'nodule' in Spec. RDM 62/76. To the left and in the lower portion of the figure the sillimanite is parallel to the foliation trace, but in the 'nodule' (right portion) a more diverse orientation is noteable. Plain polarized light. ×60.

PLATE 1
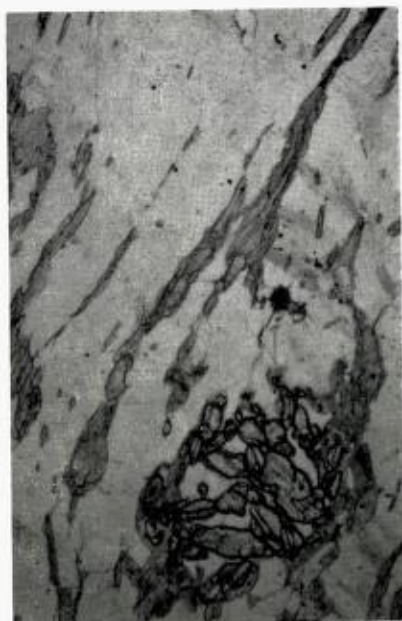
Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

PLATE 2

Fig. 1. Anthophyllite-cordierite schist with minor biotite and rutile. The orthoamphibole exhibits its typical lepidoblastic habit. The cordierite is in part pinitized. specimen RDM 62/9. Plain polarized light. ×60.

Fig. 2. Detail of partly pinnitized cordierite containing anhedral and subhedral inclusions of tourmaline (var. schorl), rutile and apatite. Anthophyllite-cordierite schist, 62/9. Plain polarized light. ×25.

Fig. 3. Typical habit of prehnite within biotite in a hornblende-biotite gneiss. Spec. RB-38A. Plain polarized light. ×40.

Fig. 4. Tourmaline quartzite, with idioblastic tourmaline (var. schorl) within a poorly foliated quartz matrix. Plain polarized light. ×25.
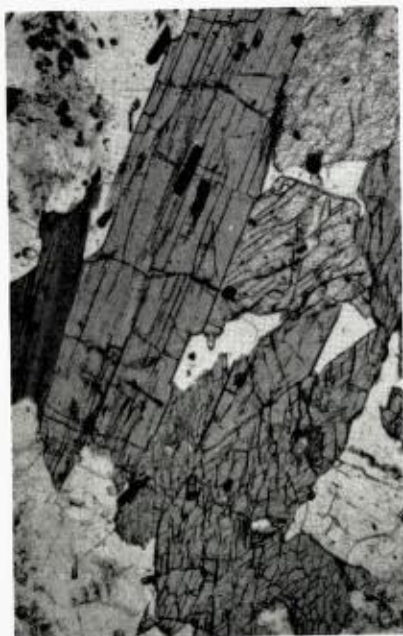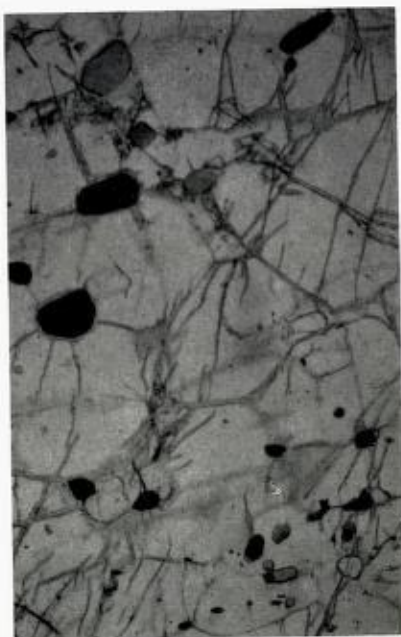
PLATE 2

Fig. 1.

Fig. 2.

Fig. 3.
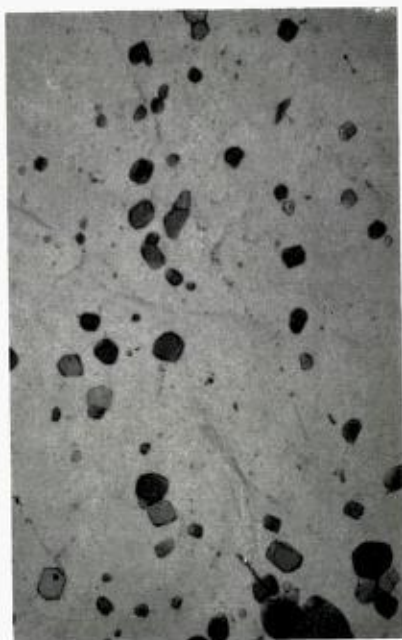
Fig. 4.

PLATE 3

Fig. 1. Secondary rims of hornblende replacing primary hypersthene adjacent to plagioclase crystals in the Skogen norite. Note the abundant opaque inclusions near the centre of the hypersthene crystal. The process of transformation from orthopyroxene→clinoamphibole apparently depletes the inclusions from the peripheral sectors of the pyroxene. Spec. RB-45B. Plain polarized light. ×25.

Fig. 2. As Fig. 1, Skogen norite. Spec. RB-45B. Crossed nicols. ×25.

Fig. 3. Coronite, Hønstjern intrusion. The irregular patches are composed of a central core of fissured olivine successively surrounded by a inner corona of orthopyroxene (radiating fibres), a thin corona of garnet and an outer rim composed of a garnet-clinoamphibole-magnetite(?) intergrowth. Note how the marginal sectors of the plagioclase laths have been depleted of opaque inclusions (indicating a contribution to the post-olivine coronas). Spec. RB-43A). Plain polarized light. ×25.

Fig. 4. Detail of corona structure in the Hønstjern coronite. A polycrystalline olivine aggregate with irregular fractures filled by opaques is seen in the central portion. The olivine is surrounded by an inner corona of radiating fibres of orthopyroxene (Opx), a central rim of isotropic garnet and an outer corona of a garnet-clinoamphibole-magnetite(?) intergrowth. Spec. RB-43A. Crossed nicols. ×60.

PLATE 3

Fig. 1.

Fig. 2.
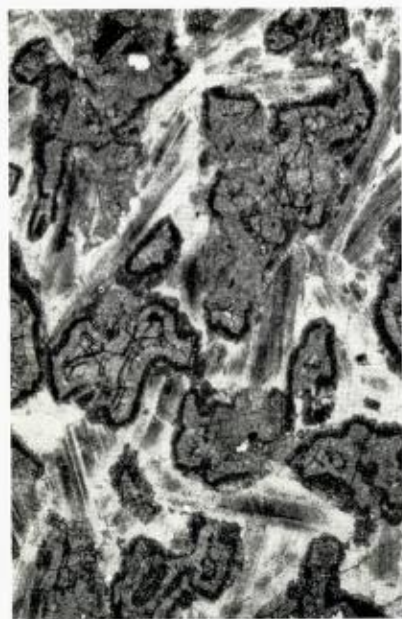
Fig. 3.

Fig. 4.

PLATE 4

Fig. 1. Coronite, Hønstjern intrusion. This advanced stage of reaction between olivine and plagioclase is characterized by an almost total depletion of olivine. A few remnant crystals of olivine can be seen at the lower right. Elsewhere the olivine has totally reacted to form a central granular intergrowth of orthopyroxene, clinoamphibole (+ minor spinel) and an outer rim of granular (in part sub-idioblastic) garnet. Spec. RB-9B. Plain polarized light. × 25.

Fig. 2. As Fig. 1, Hønstjern coronite. Crossed nicols. This indicates the distribution of the isotropic garnet and especially the concentration of this mineral at the periphery of the coronas. Spec. RB-9B. ×25.

Fig. 3. Coronite, Hønstjern intrusion. Olivine has totally reacted to form an inner intergrowth of orthopyroxene and clinoamphibole and an outher rim of subioblastic to idioblastic garnet. Some primary orthopyroxene remains at lower right. The clearing of the opaque inclusions from plagioclase crystal margins is well developed. Spec. RB-7B. Plain polarized light. ×25.

Fig. 4. As Fig. 3, Hønstjern coronite; Spec. RB-7B. Crossed nicols. ×25.
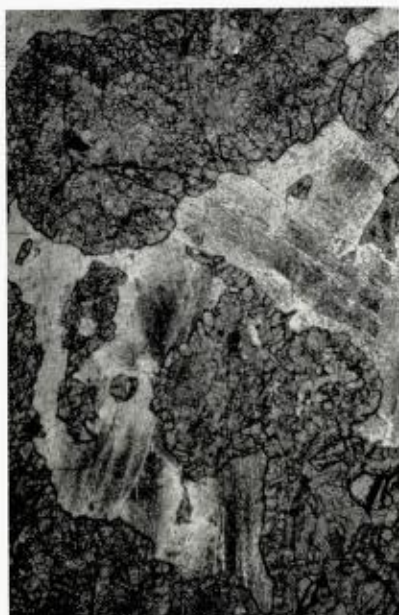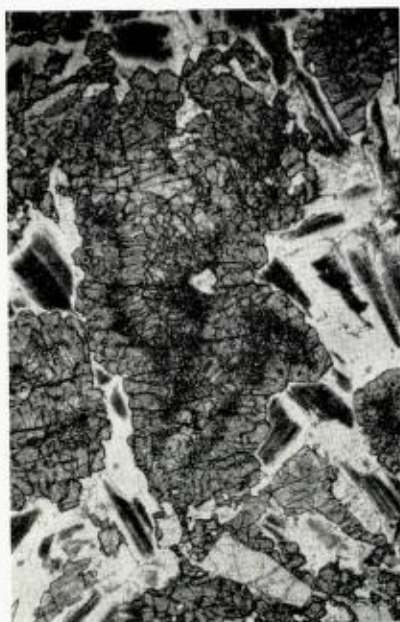
PLATE 4

Fig. 1.

Fig. 2.

Fig. 3.
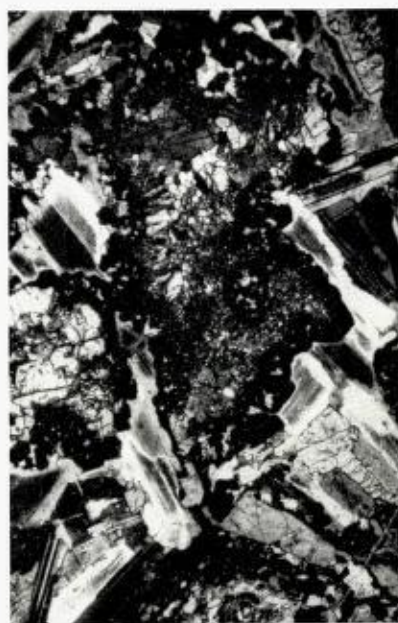
Fig. 4.

PLATE 5

Fig. 1. Hypersthene almost totally replaced by poikiloblastic hornblende i the Skogen norite. Spec. RB.-44B. Plain polarized light. ×25.

Fig. 2. Deformed facies of the Skogen norite. Hypersthene (upper centre) is markedly kink-banded and the original crystal now appears as a lamellar polycrystalline aggregate. The orthopyroxene is also surroundel by a corona of clinoamphibole, biotite and magnetite(?). Plagioclase crystals in the lower portion of the figure are notoceably bent and exhibit undulatory extinction. Spec. RB-42B. Crossed nicols. ×25.

Fig. 3. Well-foliated norite-cataclastite from the Skogen intrusion. Elongate hypersthene crystals with abundant opaque inclusions are in part replaced by minor clinoamphibole-biotite-magnetite (?) intergrowths. The ferromagnesian minerals occur within a matrix of granular, finer-grained plagioclase. Spec. RB-22B. Plain polarized light. ×25.

Fig. 4. As Fig. 3. but with crossed nicols. This emphasizes the granular nature of the plagioclase and clearly demonstrates the total loss of igneous texture during cataclasis. Spec. RB-22B. ×25.

PLATE 5

Fig. 1.

Fig. 2.
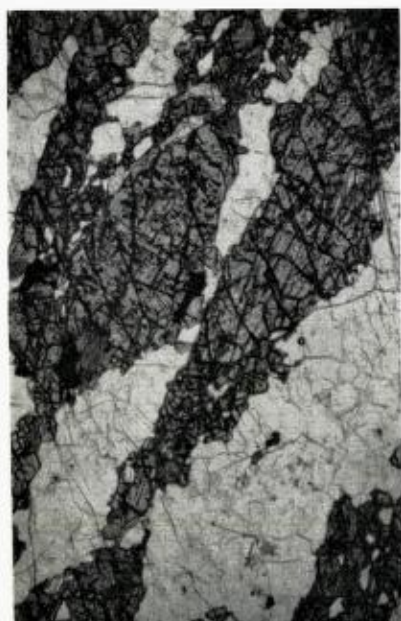
Fig. 3.

Fig. 4.

PLATE 6

Fig. 1. Amphibolitized Hönstjern gabbro (orthoamphibolite). Whilst the original ferro-magnesian minerals are totally replaced by hornblende, magnetite etc., the elongate pellucid plagioclase crystals of the original gabbro are retained. Spec. RB-10B. Plain polarized light. ×25.

Fig. 2. As Fig. 1. Orthoamphibolite, Hønstjern intrusion. Spec. RB-10B. Crossed nicols. ×25.

Fig. 3. Amphibolite illustrating the typical, almost equigranular intergrowth of horn-blende and sericitized plagioclase with minor magnetite, apatite and sphene. Spec. RDM 62/61. Plain polarized light. ×25.

Fig. 4. Garnetiferous amphibolite with an almost equigranular intregrowth of horn-blende and sericitized plagioclase containing larger porphyroblasts of almandine garnet. Abundant idioblastic apatite is seen throughout the specimen. Spec. RB-6B. Plain po-larized light. ×25.
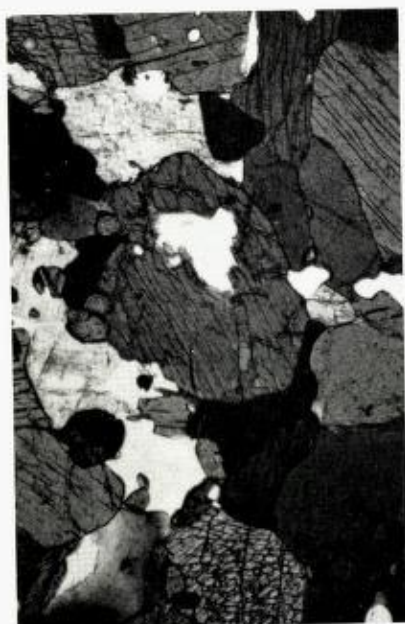
PLATE 6

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

PLATE 7

Fig. 1. Poorly foliated, coarse-grained granite gneiss with large anhedral porphyroblasts of microcline within a groundmass of sericitized plagioclase, quartz, biotite and apatite. Spec. RDM 62/70. Crossed nicols. ×25.

Fig. 2. Granitic cataclastite. A large, rounded porphyroclast of microcline is set in a fine-grained granular matrix of quartz and microcline. Spec. RB-24B. Crossed nicols. ×25.

Fig. 3. Granitic cataclastite with «augen-like» porphyroclasts of microcline within a very fine-grained matrix of quartz and microcline. Spec. RB-47A. Plain polarized light. ×10.

Fig. 4. Quartz-muscovite cataclastite. Spec. RB-10A. Crossed nicols. ×25.
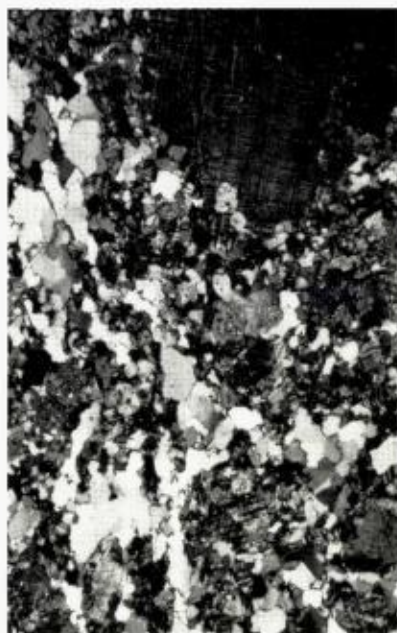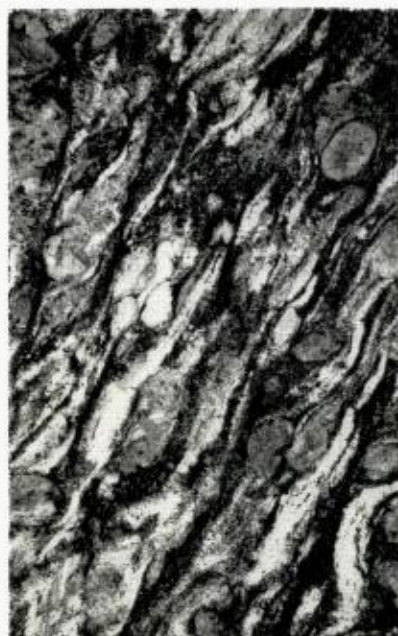
PLATE 7

Fig. 1.

Fig. 2.

Fig. 3.
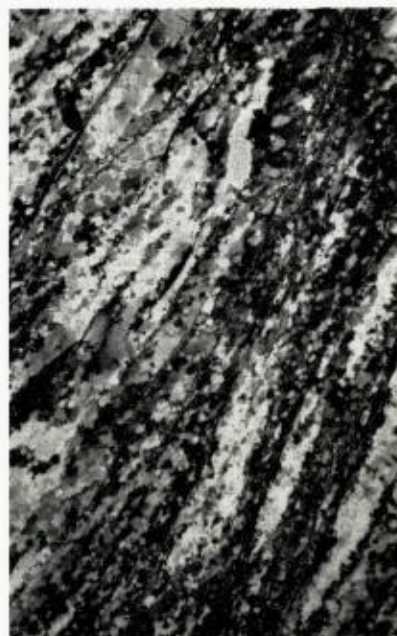
Fig. 4.

PLATE 8

Fig. 1. Well sorted Cambro-Ordovician orthoquartzite with angular grains of quartz exhibiting almost ubiquitous quartz-overgrowths. Spec. RB-11A. Crossed nicols. ×25.

Fig. 2. Post-Cambro-Silurian diabase showing a decussate arrangement of plagioclase crystals and one phenocryst within a groundmass of fine-grained chlorite, epidote, calcite, pyrite and magnetite. Spec. RB-35 A. Plain polarized light. × 25.

Fig. 3. Basal Palaeozoic arkose showing a coarse-grained aggregate of sub-angular to rounded microcline and quartz with some secondary calcite. In the right-centre a well-rounded quartz grain has a thick overgrowth of quartz. Spec. RDM-Ø34. Plain polarized light. ×25.

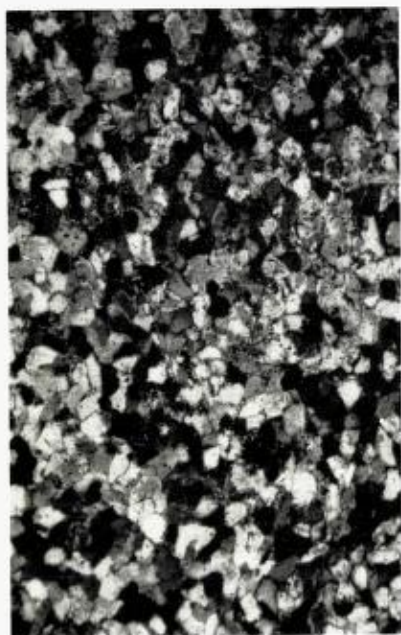Fig. 4. As Fig. 3. Spec. RDM-Ø34. Crossed nicols. ×25.
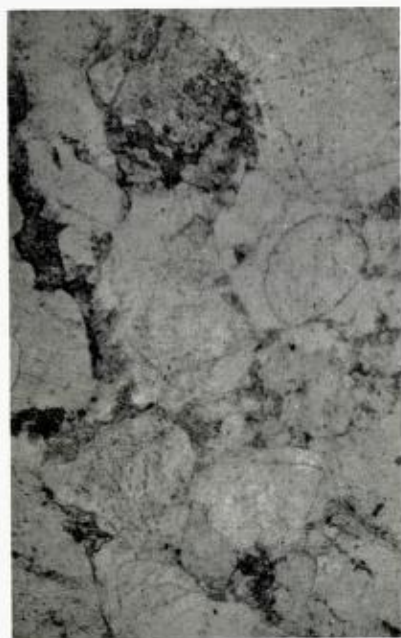
PLATE 8

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

PLATE 9

Fig. 1. View northwards at head of the Rognstranda inlet. The Precambrian banded-gneiss complex is seen in the foreground, recent beach deposits to the centre right, and in the background the scarp-face marking the western limit of the Cambro-Silurian sequence.

Fig. 2. View south-eastwards from Rognstranda. A sequence of banded gneisses occupy the foreground and can be seen to contain lensoid patches of pegmatite. Across the fjord the butress of the sub-horizontal Cambro-Silurian sediments can be seen; the base of which approximately marks the Palaeozoic unconformity.
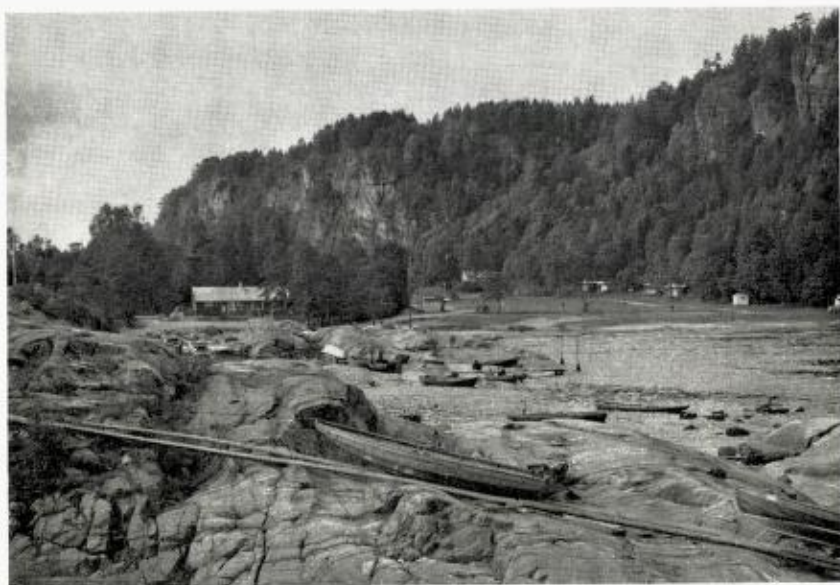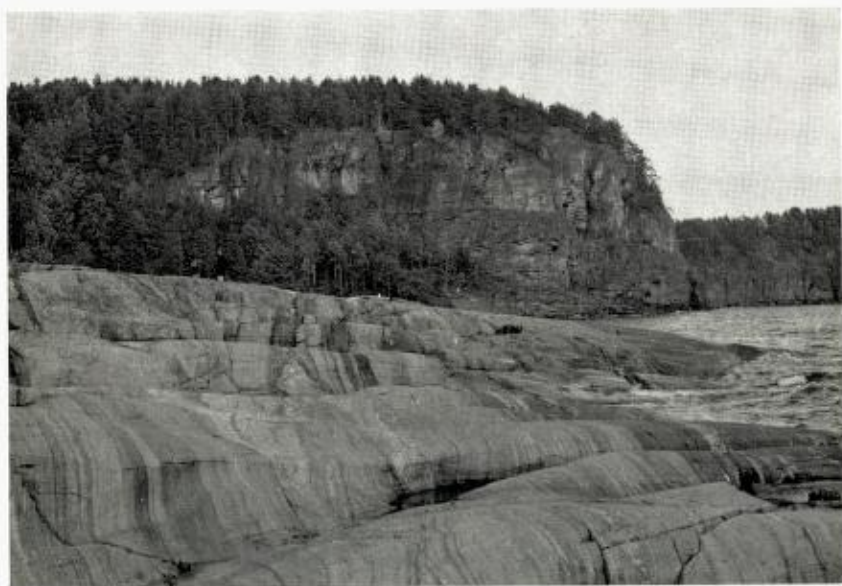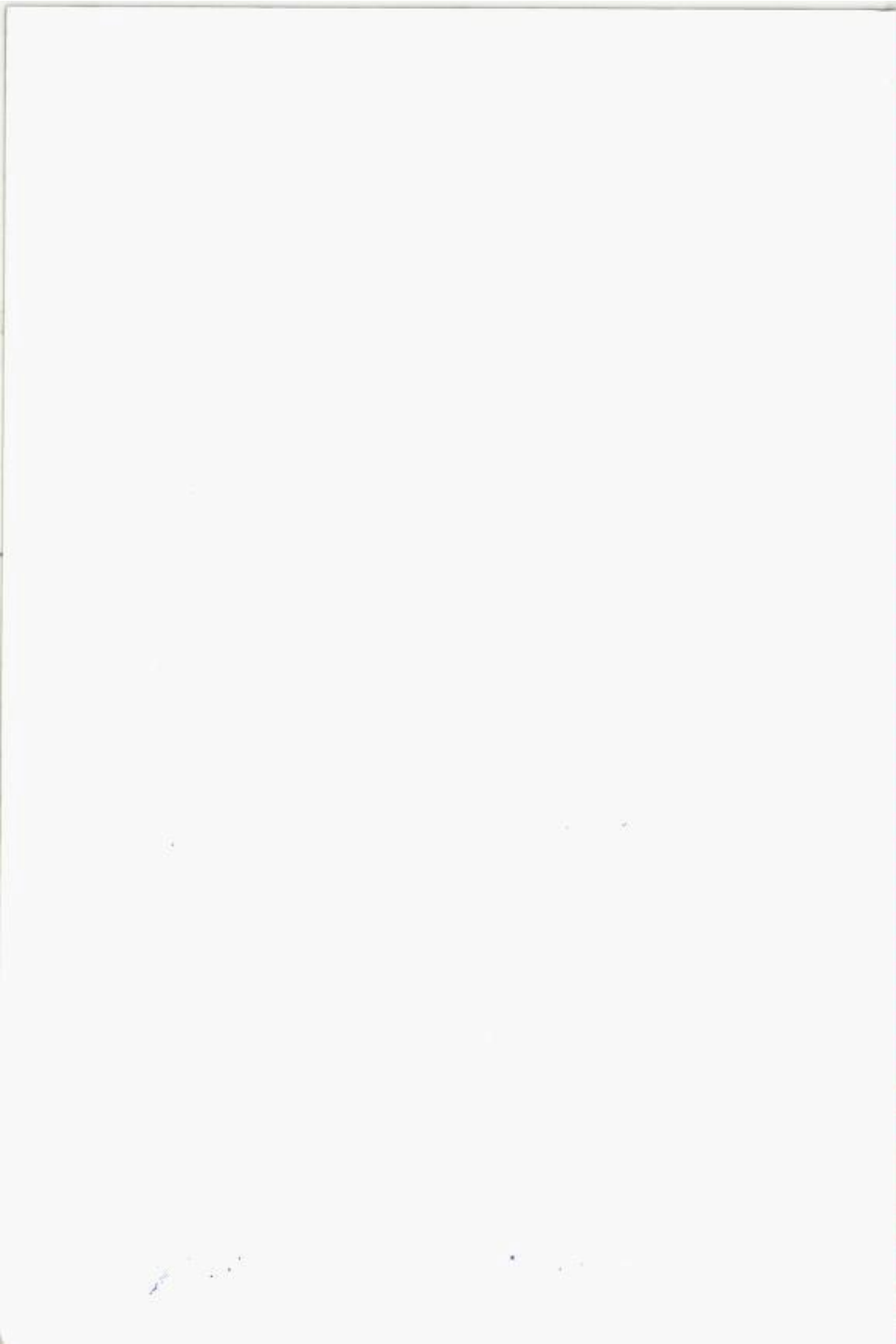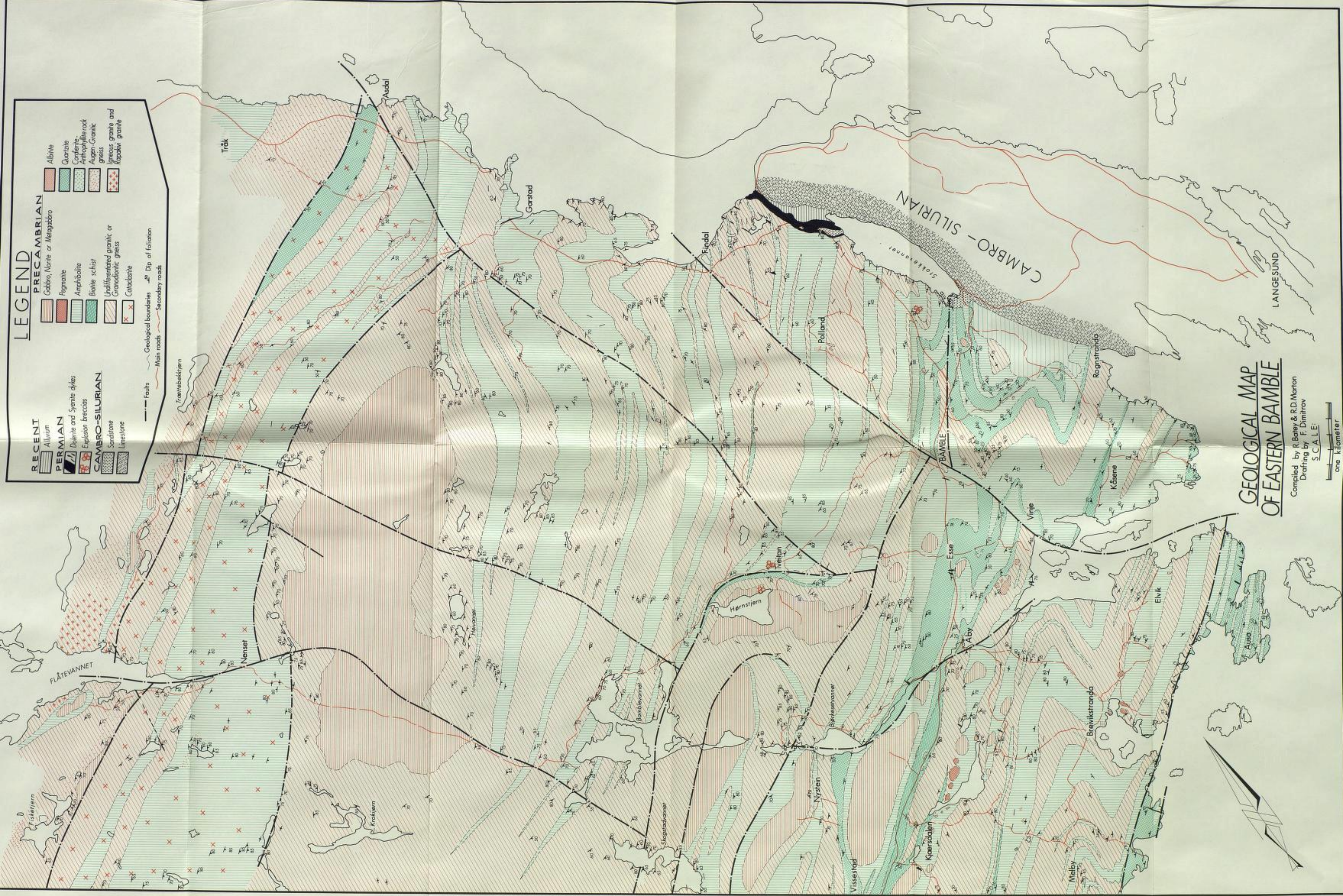
PLATE 9

Fig. 1.

Fig. 2.

GEOLOGICAL MAP OF EASTERN BAMBLE

Compiled by R. Bater & R.D. Morton
Drafting by F. Dimitrov

SCALE:
one kilometer

LEGEND

RECENT
- Alluvium

PERMIAN
- Dolerite and Syenite dykes
- Explosion breccias

CAMBRO-SILURIAN
- Sandstone
- Limestone

PRECAMBRIAN
- Gabbro, Norite or Metagabbro
- Pegmatite
- Amphibolite
- Biotite schist
- Undifferentiated granitic or Granodioritic gneiss
- Cataclasite
- Albite
- Quartzite
- Cordierite-Anthophyllite rock
- Augen-Granitic gneiss
- Igneous granite and Kopalite granite

- Geological boundaries
- Dip of foliation
- Faults
- Main roads
- Secondary roads

CAMBRO-SILURIAN

LANGESUND

Place names: Asdal, Trôk, Garstad, Findal, Polland, Rognstranda, BAMBLE, Vinje, Kåsene, Elvik, Auså, Breivikstranda, Melby, Kjærsdalen, Vissestad, Nystein, Åby, Esso, Bjørkesevannet, Sagerodvannet, Bamblevannet, Nenset, Flåtevannet, Fiskerjern, Kroakjern, Hørnstjern, Tveitan, Stollsundet