Abstract

Geological observations of the Botnneset region, and mineral and chemical compositions of the rock samples collected from the region are presented in this article. The structural and metamorphic history of the region is summarized as follows.

First episode : Development of the foldings, probably of an isoclinal type. Metabasites and paragneisses may have been formed during this episode, probably under granulite facies conditions.

Second episode : Development of the foliation structure. Formation of brown gneissose granodiorite (charnockite) under earlier granulite and later amphibolite facies conditions. E–W asymmetric folding is considered to have occurred late in this episode.

Third episode : Formation of pink gneissose granites and migmatization over wide areas under amphibolite facies conditions. N-S trending open folding is probably the prevailing tectonics.

Fourth episode : Development of greenschist facies or a slightly lower metamorphic conditions over wide areas of the region. This is probably attributed to the effect of the late activity of the pink gneissose granites of the third episode.

1. Introduction

The geology of the four nunataks in the coastal area of the Botnneset region and an island near Botnneset is described in the present article. Botnneset lies on the west coast of Lützow-Holmbukta, East Antarctica. The nunataks around Botnneset were first shown on the map by HANSEN (1946) based on the aerial photographs taken by CHRISTENSEN (in the 1937 expedition) who was the first observer of this region. Only one nunatak, Nt IV*, was once visited by a Japanese party on their way to Botnnuten in 1957** (KIKUCHI and KITAMURA, 1960). The geological survey of the four nunataks of the region was carried out on January 28 and 29 in 1969, by H. ANDO and the present author as a part of the geodetic and geologic program of the Japanese Antarctic Research Expedition (MURAKOSHI, 1969 ; YOSHIDA and ANDO, 1971). The island reported in the present article lies 30 km to the north of the coast of Botnneset, located around 69°25′ S and 37°40′ E. This island was discovered by a Japanese airplane in 1969*** and the first landing on the island was on February 15, 1970, under the geologic and gravimetric program. The geological survey was conducted by the present author. A helicopter was used for the survey of the nunataks and the island.

A geologic sketch on a scale of 1 : 250,000 was previously reported (YOSHIDA and ANDO, 1971). It is presented in this report with some modifications. Geologic sketches and route maps on a scale of 1 : 5,000, a list of samples, and details of field data are presented in this report with supplementary geological considerations. Aerial photographs were utilized to examine the general structure of the region. The samples collected are in the custody of the present author and petrographical investigations will be later carried out.

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* The five areas surveyed are provisionally named in the present article as follows: Nt I (northwestern point of Fletta Bay), Nt II (west of Vesthovde), Nt III (southern part of Austhovde), Nt IV (south of Nesholmen Island), and Nt V (an island located at 69°25′S and 37°40′S). See Figs. 1 and 20. Nt is abbreviation of nunatak.

** Deduced from the simple route map which is the only available data on the route of their visit to this region.

*** The island is only vaguely plotted on the map given in MURAKOSHI, 1969.

2. General Geology and Geomorphology

The Botnneset region is covered extensively by the Antarctic ice sheet, while a few very small nunataks are sporadically scattered along the coast and in the adjacent areas. The nunataks are generally flat or gentle in geomorphology. Some of the nunataks in eastern areas are coastal precipice slopes and those in the western areas are small hills some tens of meters high (Plates 1, 2, 3). Remarkable topographic undulations, several hundreds of meters in wavelength, are characteristic of almost all the nunataks. Small amounts of morainic boulders are scattered on the rock surfaces of all the nunataks except Nt V, and ice striae are sometimes well preserved (Plate 4a), trending north at Nt I, N45°E at Nt IV, and N35°E at Nt V. The smooth but undulating topography may have been caused by glacial denudation which might have once covered these outcrops. Patterned ground (polygonal pattern) or strong mechanical weathering of the rock surface (Plate 4b, c), which may indicate the present periglacial climate, were found at some places in Nt IV.

At several outcrops of the east nunataks of Nt II, small and shallow holes are developed, aggregating on the rock surfaces (Plate 4d). Analogous holes, though smaller and more concentrated, are often observed in the area adjacent to the Ongul Islands (TATSUMI and KIKUCHI, 1959). The morphological difference may in part depend on the difference in lithology of the host rocks. The rock on which the holes are developed is pyroxene gneiss in the Ongul Islands, but is biotite gneiss in Nt II. It is interesting that Nt II lies inland, several kilometers far from the present seashore. The holes were probably formed a considerably long time ago (in geologic time), considering that the aggregates of the holes may have been initiated in relation to the sea water, and the outcrop might have appeared after the latest retreat of the ice sheet from the area, judging from the fact that the holes are free from glacial denudation.

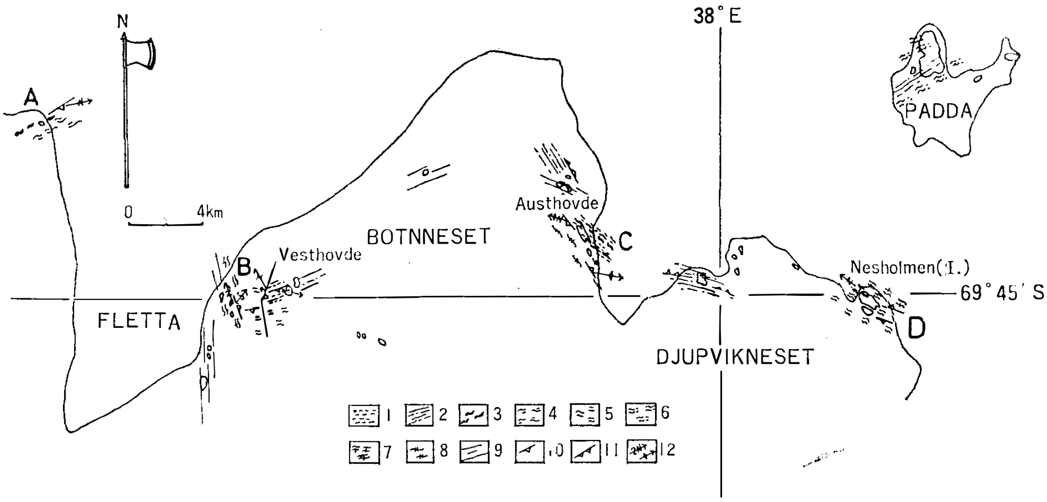

Fig. 1. Geologic sketch of the Botnneset region.
1. Alternation of quartz-feldspathic gneiss and metabasites. 2. Alternation of basic and acid gneisses distinguished in aerial photograph. 3. Metabasites. 4. Acid brown gneisses. 5. Brown gneissose granodiorites. 6. Brown gneissose granodioritic rock distinguished in aerial photograph. 7. White gneissose granodiorites. 8. Pink gneissose granites. 9. Strike of rocks distinguished in aerial photograph. 10. Foliation. 11. Foliation distinguished in aerial photograph. 12. Lineations. A: Nt I, B: Nt II, C: Nt III, D: Nt IV. Nt V is shown in Fig. 20.

The basement rocks of the present region consist largely of paragneisses (alternation of basic and acid gneisses) and brown gneissose granodiorites*, probably of granulite facies, and white gneissose granodiorite and pink genissose granites, probably of amphibolite facies. Small amounts of pegmatites and hornblende-biotite microgranite were also found. The general structure was investigated by field survey and by analysis of the aerial photographs as well. The foliations and zonal distribution of the basement rocks trend WNW–ENE and dip variably. In some western areas, north trending structures (foliations and faults) are developed, and are often associated with the intrusion of the pink gneissose granites. A schematic geologic sketch (on a scale of 1 : 250,000) based on the field survey and aerial photographs is shown in Fig. 1.

* Classification of the igneous rocks is generally based on that of JOHANNSEN (1939). Part of the brown gneissose granodiorite, however, is charnockite (also according to JOHANNSEN) which is characterized by the occurrence of hypersthene with the granitic mineral assemblage.

3. Observations in Each Area

3.1. Nt I (northwestern point of Fletta Bay)

Aerial photographs of the present area are given in Plate 1a. A geologic sketch including a route map (Fig. 2) and a list of field observations and collected samples (Table 1), all of which are taken from H. ANDO's work, are also given.

The area consists of pyroxene metabasite, quartz-feldspathic biotite brown gneiss, and granitic pegmatite. They are zonally arranged, each rock zone

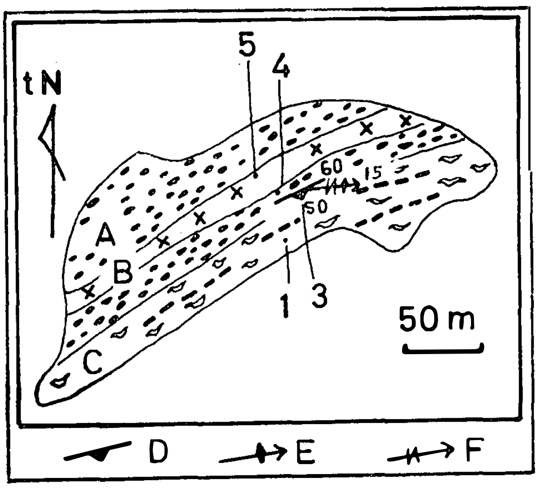

Fig. 2. Geologic sketch of Nt 1.
A. Pyroxene metabasite. B. Granitic pegmatite. C. Quartz-feldspathic biotite brown gneiss. D. Foliation. E. Mafic mineral lineation. F. Crenulation or salic mineral lineation (cf. footnote of the text, p. 12). Symbols 1-5 correspond to JARE A69012901-A69012905 in Table 1.

being tens of meters in width. The general structure is monoclinic, banding structure and rock zonation being parallel trending N60°E and dipping 40°–50° SE with a gentle easterly crenulation lineation.

3.2. Nt II (west of Vesthovde)

Aerial photographs, a geologic sketch including a route map, and a list of field observations and collected samples are shown in Plate 1b, c, Fig. 3, and Table 1.

The survey was carried out at the eastern and western nunataks. The area consists of garnet-bearing potash feldspar porphyroblastic brown gneissose granodiorite and paragneisses composed of the alternation of pyroxene metabasite and quartz-feldspathic garnet gneiss (Plate 5a). Some of the paragneisses

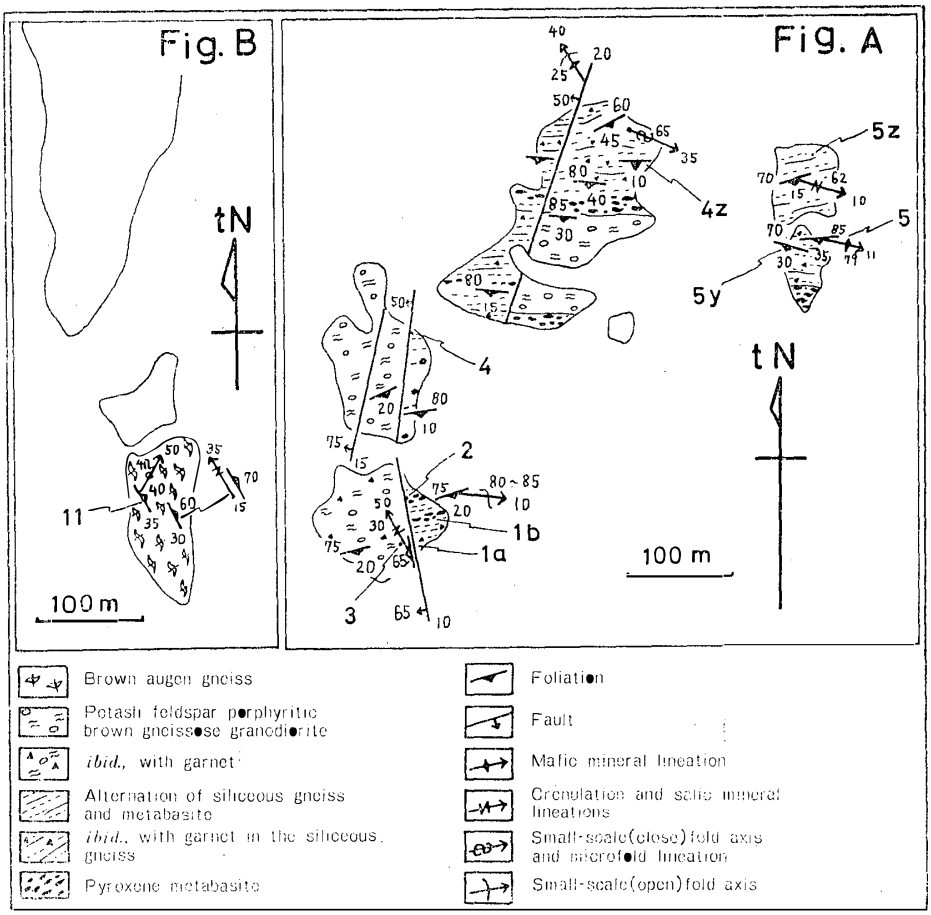

Fig. 3. Geologic sketch of Nt II.
A: Eastern nunataks. B: stern Wenunatak.
Symbols 1-5 and 11 correspond to JARE Y69012931–Y69012935 and JARE Y69012911 in Table 1.

Table 1. List of rock samples and observations in the Botnneset region.

Sample or observation number	Rock types, specimen which is orientated (O) or not (S), Thin section (T), Chemical analysis (C)	Description in field ( ) or for hand specimen in the laboratory [ ]	Constituent minerals detected by naked eye ( ) or under microscope [ ]
Nt I			
JARE A69012901	Bi brown Gn (O, T)	(Siliceous Gn) [Very pale brown felsic gr Gn with very weak lineation due to crenulation and elongation of mafic clot]	[Pl>Qz>Kf≫Ho(→Ch), brownish red Bi, Mus>Apa≫Zeo(?), Opal (?), Zir]
JARE A69012902	Ho Mb (S)	(Basic Gn in siliceous Gn) [Granular Amph with relic banded structure, m, equigranular. Salic: pale brown]	(Ho>Pl)
JARE A69012903	Px Mb (O, T)	(Px Gn) Salic: pale brown, mafic: scattered but somewhat continued to form weakly elongated clot.	[Pl>reddish Bi, rPx, mPx≫Qz(?), Apa≫Zir, Op, Lx, blue Px (?), Mus(?), green Bi]
JARE A69012904	Px Mb (O)	Px Gn [s-m, equigranular, with reddish brown rPx, black mPx, reddish Bi. Weak compositional banding and Bi clot exhibit foliation. Salic: pale brown]	(Pl, rPx, Bi)
JARE A69012905	gr Peg (S)	(Peg) [cm-grained, composed of Qz, Feld, Bi, black unknown mineral. Very leucocratic (color index is less than 3%) massive]	(Qz, Feld, Bi)
Nt II			
JARE Y69012911	brown augen Gn (O, T)	Mylonitic Kf porphyroblastic Gn, veined by pink Kf Gr and folded. Mylonitization (formation of the augen structure) may be synchronous with or later than the Gr, the Gr intruded parallel with the augen foliation and folded. Kf is pale brown, but partly pale reddish (because of hematization(?)) (1cm±), crushed. Bi clot filmed, matrix is s]	[Pl>Qz>reddish brown Bi≫Mir>grass green Ho≫Apa>Hem (?), Op]
JARE Y69012931a	Q-F Ga Gn (O, T, C)	(Leucocratic Ga Gn, alternating with Mb of specimen 2931b) [c-s white rock, s-domain; Bi-Ga Gn, aplitic, equigranular, c-domain: Qz-Feld rich with flattened Qz and Ga]	(s-domain: Bi, Ga, Qz, Feld, c-domain: Qz, Feld, Boundary of s and c: Qz, Feld, Ga) [Pl>pale pink Ga≫Qz>brownish red Bi, Op≫Kf, Apa, Zir]
JARE Y69012931b	Px Mb (O, T, C)	(Basic Gn, alternating with Q-F Gn of specimen 2931a) [Brown, s, equigranular with some porphyroblastic elongated Pl(?)]	[Pl>Qz, reddish brown Bi>mPx, rPx≫Apa, brown Ore(?), Hem-Pyr (?)]

Sample or observation number	Rock types, specimen which is orientated (O) or not (S), Thin section (T), Chemical analysis (C)	Description in field ( ) or for hand specimen in the laboratory [ ]	Constituent minerals detected by naked eye ( ) or under microscope [ ]
JARE Y69012932	pink mig Gn (O, T)	(Ga-bearing Bi Amph in sheared zone associated with pink Kf gn Gr pool) [s-c, banded augen gr Gn-look. Mafic band: s, equigranular with c Ga clot. Salic band: 2–5mm, pink Kf gr Gn, augen-shaped big Kf porphyroblast is white but matrix Kf is pink]	[altered Pl, Qz>Kf, dark brown Bi≫Ga, Mir>Apa, Mus>Zir, Op≫Columdom (?)]
JARE Y69012933a	brown gn Gd (O, T)	(Sheared augen Gn, pink Kf Gr veined and the foliation changed parallel with that near the vein, SK) [Ho-Ga-bearing s weakly mylonitic augen gr Gn. Ga forms clot with Bi. Kf porphyroblastic, (001) of Bi is random. a part changed to 2933b facies]	(Ho, Ga bearing) [Kf, Pl>Qz, reddish brown Bi≫green Ho, Ga, Op ≫Apa, Zir, rPx]
JARE Y69012933b	white gn Gd (O, T)	(No Ga, white colored facies developed along the Gr vein mentioned above) [m ≒1–2mm]	(no Ga) [Qz>Pl>Kf ≫reddish brown Bi> Ga, Mir≫Ap, Op> Zir]
JARE Y69012934	gr Peg (S, T)	(Kf gr Peg intruding parallel with the fault of a left lateral sense bending the pre-existent foliation toward the adjacent of the fault) [Big Kf-Bi, c Qz Peg. Kf is weakly pink due to hematization (?) of Bi]	(Kf≫Bi>Qz) [Qz, altered Pl>Kf]
JARE Y69012934z		(mylonitic banded Ga Gn)	
JARE Y69012935	Q–F Ga Gn (O, T)	(Ga-bearing white-dark gray banded Gn like 2931a, with foliated c Gr cutting the Gn parallel or inclined to the foliation of the Gn as SK) [m=1mm±, white, felsic rock with elongated Qz which is gray. Ga is m=1–5 mm. minor amount of f=0.3mm Ga-Bi Gn band bearing]	(Qz>Feld>Ga, Bi) [Qz, Kf>altered Pl> brownish red Bi>Ga, Mir]
JARE Y69012935z		(mylonitic banded Gn)	
JARE Y69012935y		(Ga-bearing white-dark grayish banded Gn like Y2931, being cut and lit-per-lit injected by weakly foliated c Gr. SK)	
Nt III			
JARE A69012801	Bi brown Gn (O)	(Bi Gn) [m-c, inequigranular, pale brown rock with elongated clear Qz grains. Scattered Bi seams show microfold lineation which is parallel with the Bi clot elongation lineation on the foliation plane.]	(Qz, Feld, Bi)

Sample or observation number	Rock types, specimen which is orientated (O) or not (S), Thin section (T), Chemical analysis (C)	Description in field ( ) or for hand specimen in the laboratory [ ]	Constituent minerals detected by naked eye ( ) or under microscope [ ]
JARE A69012802	Q-F Bi Gn (S, T, C)	(Siliceous Gn with basic Gn) [m, Feld =0.8, Qz=1-2mm, Bi bearing siliceous Gn. Salic minerals are white]	(Qz, Feld≫Bi) [Qz> altered Pl>Op, brownish red Bi≫Zir, Px(?), Ch, Pre, Clay mineral]
JARE A69012803	Q-F Ga Gn (S, T, C)	(Ga-bearing siliceous Gn) [s=0.4mm±, mafic rock band developed, single crystal of Ga (0.5-5mm) with sillimanite(?) well elongated showing lineation]	(Feld, Qz>Bi, Ga, Sill (?)) [Qz, Kf, altered Pl>reddish Bi>Ga≫ Op, Apa]
JARE A69012803z		(Bi Gn with siliceous Gn and basic Gn)	
JARE A69012803y		(Siliceous Gn with intercalations of basic Gn)	
JARE A69012804	Px Mb (S, T)	(Basic Gn) [m-c, inequigranular. Elongated green crystal (Px ?) scattered abundantly assocciated with Pl as ordinary gabbroic Peg vein, with compositional banding structure]	[rPx, mPx>Sc, Pl≫ green Ho]
JARE A69012805	Px Mb (O, T)	(basic Gn) [s=0.6 mm±]	[Pl>Qz, rPx, mPx, green Ho, reddish brown Bi>Op, Apa ≫Zir]
JARE A69012806	pink Kf gn Gr (O, T, C)	(Siliceous Gn with weak foliation) [m= 1mm± pink gr Gn, with elongated Qz. Bi is scattered, its (001) is parallel with the foliation]	[Kf≫Qz, altered Pl> dark brown with reddish tint Bi≫Mir >Mus, Zir, Ch, Apa, Ho, Lx]
Nt IV			
JARE Y69012801	brown Ho-Bi Gn (O)	(gd Gn, with weak enrichment of pink Kf, and pink Kf gr Peg vein developed cutting the foliation) [s=1mm±, pale brownish colored rock, pooled by somewhat c facies with scattered f Bi. Bi of the country Gn is concentrated there] (near this point, SK of Mb/Gn)	(Qz, Feld, Bi)
JARE Y69012802	Ho Mb (O)	(Basic Gn) [s=1mm±, equigranular granoblastic blackish rock. Bi is scattered but its (001) shows good preferred orientation]	(Bi, Ho(?), Pl, Qz)
JARE Y69012802z		(Qz dio Gn)	

Sample or observation number	Rock types, specimen which is orientated (O) or not (S), Thin section (T), Chemical analysis (C)	Description in field ( ) or for hand specimen in the laboratory [ ]	Constituent minerals detected by naked eye ( ) or under microscope [ ]
JARE Y69012802y		(Peg, 40 cm width. Clearly cuts the foliation, thins in basic Gn and thickens in Gn. Occasionally lit-per-lit form. SK)	
JARE Y69012802x		(gn Gr=white gn Gd)	
JARE Y69012802w		(Patterned ground, Photo, SK)	
JARE Y69012803	Ho Mb (S, T)	(Amph band, Photo, SK) [s=1mm±, equigranular. Some Bi are scattered but show preferred orientation]	[Pl, green Ho>brown Bi≫Qz≫Op, Apa≫Zir]
JARE Y69012803z		(Amph band 50 cm wide)	
JARE Y69012804	brown gn Gd with white gn Gd (O, T, C)	(Sheared pale brown dio Gn, partly changed to white gr Gn. Photo, SK) [s=0.5-1 mm, pale brownish rock with m=1-2 mm, white-colored Peg band 1-2cm wide]	[Pl, Kf, Qz, brown with reddish tint Bi, green Ho>Mir≫Apa, Zir, Op, Ch]
JARE Y69012804z		(Glacial striae, N30°W, Photo)	
JARE Y69012804y		(Leucocratic granulitic sheared Gn=brown gn Gd, with many bands of pink gr Gn)	
JARE Y69012811	Px Mb (O, T)	(c-f, alternated basic granulite) [s=0.5 mm±, granoblastic with a few Kf phenocrysts, with weak foliation indicated by mafic lamina]	(Pl, Ho>rPx, Kf) [Pl ≫Qz, green Ho, Kf ≫reddish brown Bi, rPx, brown Ore, Op]
JARE Y69012811z		(Acid granulitic Gn=brown gn Gd, pale pink Kf gr Gn veined)	
JARE Y69012811y		(Bi-Ho Amph)	
JARE Y69012811x		(Intermediate granulite=Px Mb)	
JARE Y69012821	brown gn Gd (O, T, C)	(Kf porphyroblastic Qz dio Gn. Color of the weathered surface is reddish pink but the fresh shuttered plane is greenish gray) [m=1-3 mm rock with Kf porphyroblast (1 cm±). Salic is pale brownish green]	[Pl>Kf, Qz, grass green Ho>dark brown Bi, rPx≫Apa, reddish ore, Zir, Op, Cal]
JARE Y69012822	white gn Gd (S)	(Augen gn porphyroblastic Dio=white gn Gd)	(Feld, Qz>Ho, Bi)

Sample or observation number	Rock types, specimen which is orientated (O) or not (S), Thin section (T), Chemical analysis (C)	Description in field ( ) or for hand specimen in the laboratory [ ]	Constituent minerals detected by naked eye ( ) or under microscope [ ]
JARE Y69012823		(Moss vegetation, Sp)	
JARE Y69012824	Ho-Bi micro-Gr (S, T, C)	(Porphyrite vein cutting dio Gn, the dio Gn changed rather white there) [s=0.7 mm±, equigranular massive rock clearly in contact with the brown gn Gd, the latter is similar to Y2821]	[Kf, Qz, Pl>green Ho, reddish brown Bi>Mir, Apa≫Pyr-Hem, Cal, Op>Zir]
JARE Y69012825	salic vein in the white gn Gd (S, T)	(f salic rock network in white gn Gd. Not found in basic band. This kind of rock is found all over the area) [s=0.8 mm±, equigranular. The country gn Gd is white, same as Y2822]	[Kf>Qz, Pl, Mir>green Ho>reddish brown Bi, Ch>Op, Apa]
Nt V			
JARE Y70021502	brown gn Gd (O)	(Ga-bearing dio Gn, Ho is often concentrated in thin layers showing foliation structure)	(Feld, Qz, Bi, Ho, Ga)
JARE Y70021503		(dio Gn, near by the Peg vein, is coarsened to make the boundary vague, although the vein continues in a straight line)	
JARE Y70021503z		(dio Gn with f mesocratic band=schlieren)	
JARE Y70021504a		(Ga-bearing ap vein, disappears westward)	
JARE Y70021504b		(Ho Peg vein and its surroundings, rather c, Ho dio Gn)	
JARE Y70021504z		(Ho-rich layer=schlieric layer, cut by the new foliation, SK)	
JARE Y70021504y		(Ho-Kf Peg cut by leucocratic band)	
JARE Y70021504x		(Ho-Kf Peg thin vein)	
JARE Y70021505		(Xenolithic black band which is folded, Photo. The country Gn has Kf phenocrysts of about 10 mm diameter, the phenocrytsts show evidence of lotation. SK)	
JARE Y70021506		(Very strong folding shown by basic band of Ho-Px(?)-Qz-Pl-Ga rock and then cut by Ho-Kf Peg. SK)	

The abbreviations are as follows.

Amph: amphibolite, Ap: aplite, Apa: apatite, Bi: biotite, c: coarse-grained, Cal: calcite, Ch: chlorite, Dio: diorite, f: fine-grained, Feld: feldspar, Ga: garnet, Gd: granodiorite, Gn: gneiss, Gr: granite, Hem: hematite, Ho: hornblende, Kf: potash feldspar, Lx: leucoxene, m: medium-grained, Mb: metabasite, Mus: muscovite, Op: opaque mineral, Peg: pegmatite, Photo: photograph was taken, Pl: plagioclase, Px: pyroxene, mPx: monoclinic pyroxene, rPx: rhombic pyroxene, Q-F: quartz-feldspathic, Qz: quartz, s: small-grained, Sc: scapolite, Sill: sillimanite, SK: sketch was made, Zeol: zeolite, Zir: zircon.

(Part of the data is presented by the courtesy of H. Ando.)

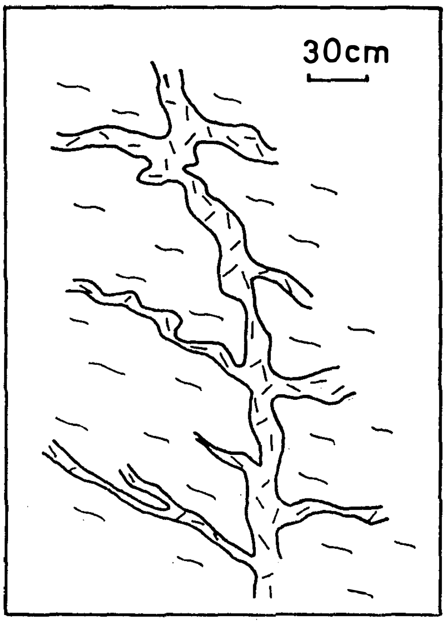

Fig. 4. Arteritic development of leucocratic part in the banded gneiss (SK Y69012935).

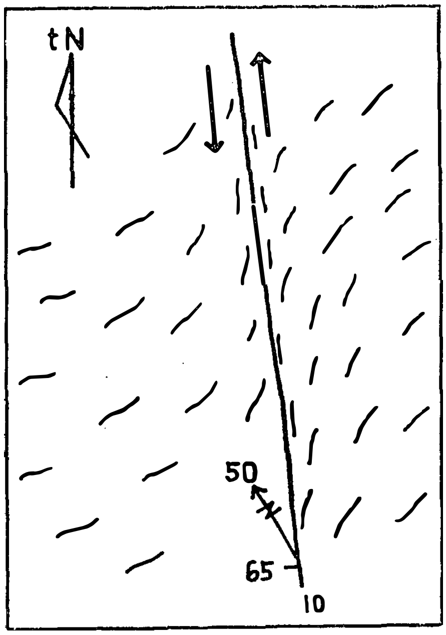

Fig. 5. Left lateral sense fault between the brown gneissose granodiorite and the quartz-feldspathic garnet gneiss (SK Y69012934). The strike of the foliation changes gradually toward the fault plane.

are granitized resulting in an arteritic form (Fig. 4). In the eastern nunataks, some faults of the north trend with left lateral sense are developed (Fig. 5). Pegmatite, hornblende metabasite (amphibolite), and garnet-bearing pink gneissose granite, often intruded along the faults, the latter two rocks are either more or less mylonitized*, or else partly represent pink migmatitic granite facies. The general structure of the eastern nunataks is monoclinic, foliation** trending generally in an east direction, dipping gently southward with gentle easterly mineral and crenulation*** lineations. The general structure of the western nunatak is monoclinic, foliation trending N 30°W and moderately dipping E with two different lineations, that of crenulation and microfolding****.

* Usage after SPRY, 1969.

** The nomenclature of the metamorphic structure of rocks is generally based on that of BILLINGS, 1954.

*** Mineral lineation denotes linear parallelism of mafic minerals. Crenulation lineation means the crenulation-like linear parallelism observed on the foliation plane, some of which is probably due to the elongation of augen-shaped salic minerals.

**** Microfold lineation denotes both an ordinary microfold lineation and an axis of minor fold.

3.3. Nt III (southern part of Austhovde)

Aerial photographs of the area are presented in Plate 1d. A geologic sketch including a route map and a list of field data and collected samples, all of which are taken from H. ANDO's work, are also given (Fig. 6 and Table 1).

The area consists mainly of paragneisses composed of quartz-feldspathic

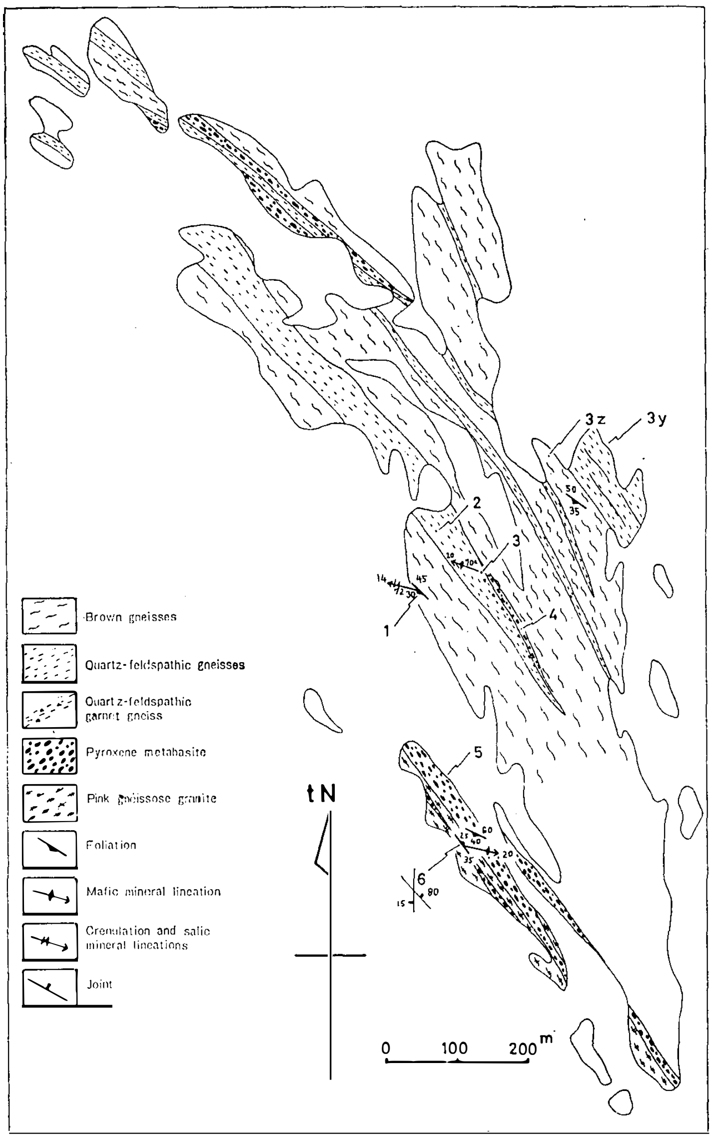

Fig. 6. Geologic sketch of Nt III.
Symbols 1-5 correspond to JARE A69012801-A69012805 in Table 1.

biotite gneiss and pyroxene metabasite, brown gneiss, and pink gneissose granite. All are zonally arranged, each rock zone being from ten to some tens of meters in width. The general structure is monoclinic, foliation and rock zonation being parallel, trending NW and dipping 35° SW with gentle westerly clenulation and mineral lineations. Pink gneissose granite with different foliation and mineral lineation is developed on the southern side of the area, discordantly cutting the gneisses.

3.4. Nt IV (**south of Nesholmen Island**)

Aerial photographs, a geologic sketch including route maps, and a list of field data and collected samples are shown in Plate 2a, b, Fig. 7, and Table 1.

The area consists mainly of white and brown gneissose granodiorites with subordinate metabasites, and pink gneissose granite. Pyroxene metabasite is zonally developed only in the northern part, being about 50 meters in width. Schlieric (schliere-like) bands of hornblende metabasite, on the other

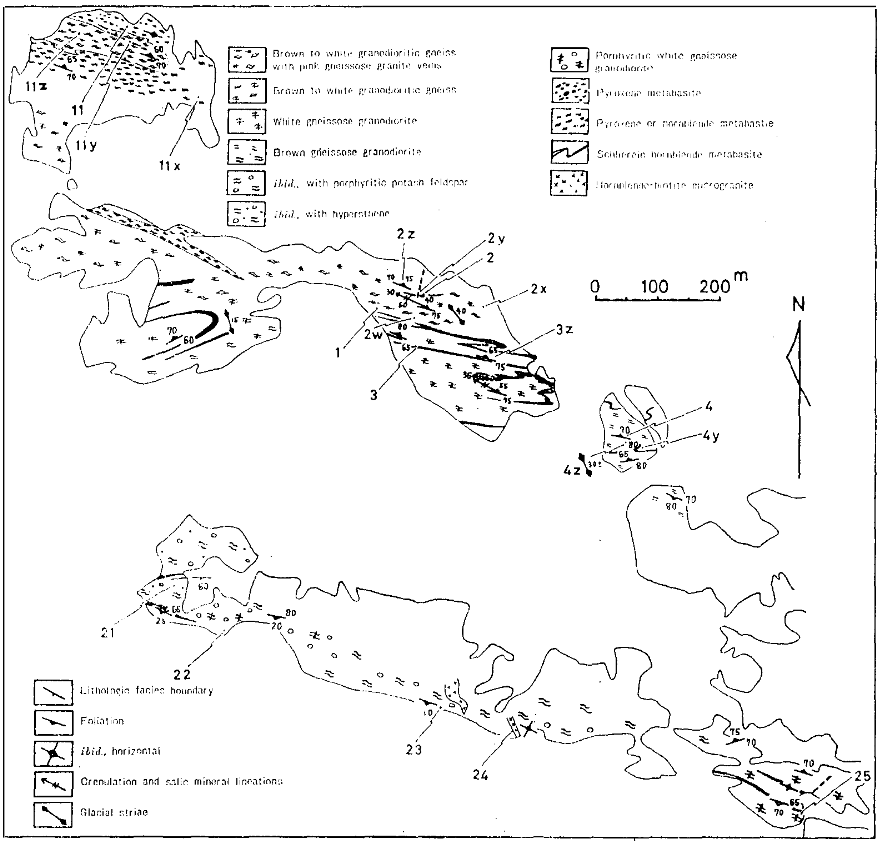

Fig. 7. Geologic sketch of Nt IV.
Symbols 1-25 correspond to JARE Y69012801-Y69012825 in Table 1.

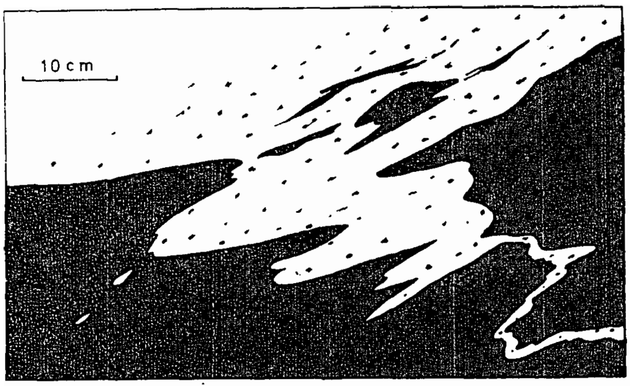

Fig. 8. Boundary phenomenon between the metabasite and the white gneissose tonalite (SK Y69012801). The hornblende metabasite (solid part) diminishes into the white gneissose tonalite in schlieric form. Part of the latter intrudes into the former as leucocratic veins.

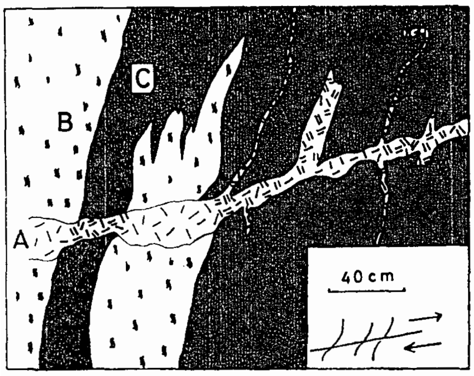

*Fig. 9. Pegmatite vein in the white gneissose granodiorite and metabasite, SK Y69012802.
A : Pegmatite, B: White gneissose granodiorite, C : Metabasite. The pegmatite is pale pinkish colored, composed of potash feldspar, hornblende, and quartz, and thick in width in the white gneissose granodiorite, whereas in the metabasite, it is pinkish-reddish colored, composed of potash feldspar and hornblende, and thin in width.*

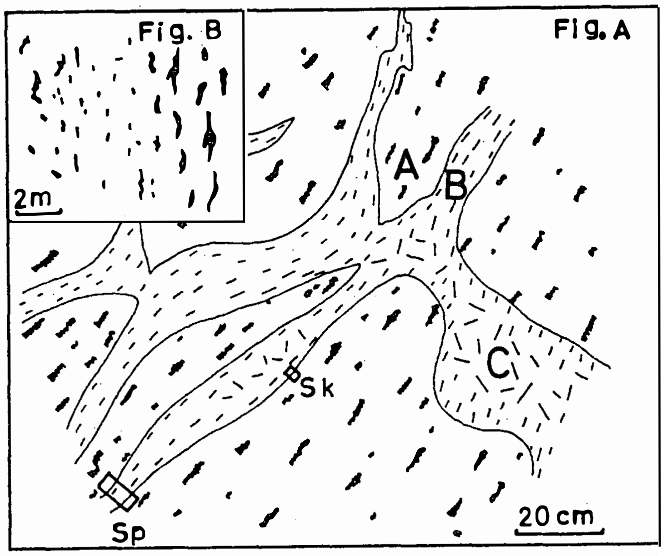

Fig. 10. Occurrence of the white gneissose granodiorite in the brown gneissose granodiorite, SK Y69012804. Fig. A, A: Mylonitic brown gneissose granodiorite. B: White gneissose granodiorite. C: Coarse-grained biotite granite.

*The brown gneissose granodiorite partly changes to white gneissose granodiorite in network form. Sp is the point of the sample collection, JARE Y69012804 (Plate 10b), and SK is the point of Fig. B.
Fig. B, The boundary of A and B facies as pointed in Fig. A as SK. From A to B, the lithologic change is as follows: i) the texture changes from sheared or schistose to recrystalline or gneissic, ii) the mineral composition from hornblende rich to biotite rich, and iii) the color of the salic minerals from brown to pale or white.*

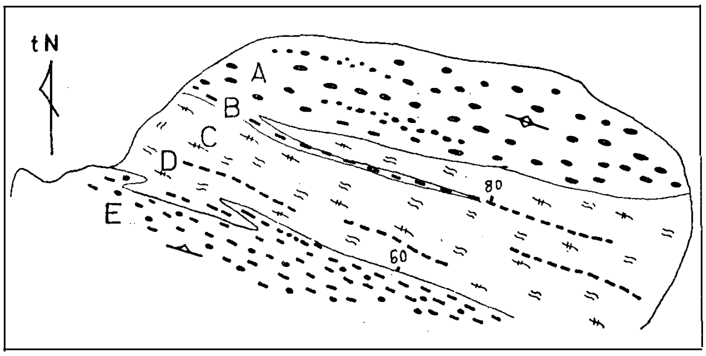

Fig. 11. *Occurrence of metabasite in the white and brown gneissose granodiorites, SK Y69012811.*

The pyroxene metabasite changes to the hornblende metabasite near or in the gneissose granodiorite which is strongly affected by the pink gneissose granite. A: Pyroxene metabasite, B: Hornblende metabasite, C: Brownish to white granodioritic gneiss often veined by the pink gneissose granite. D: Schlieric hornblende metabasite. Other keys are similar to previous figures.

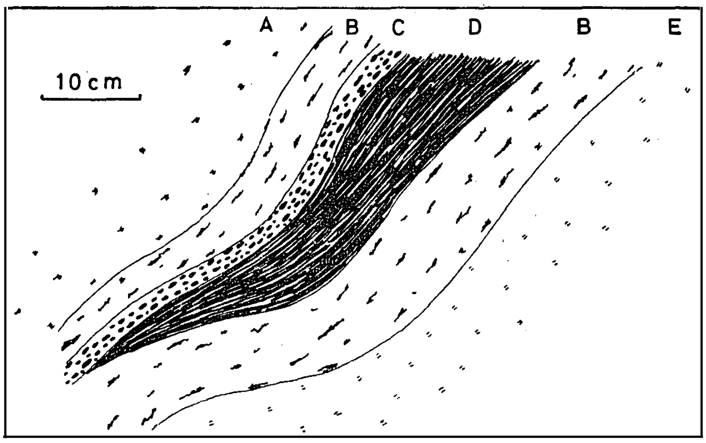

Fig. 12. *Metabasite accompanied by mylonitization, SK Y69012803.*

Two kinds of matabasites occur at the boundary between the white gneissose tonalite and the white gneissose granodiorite. A: Partly tonalitic and partly granodioritic rock. B: Mylonitized facies. C: Pyroxene metabasite. D: Hornblende metabasite. E: White gneissose granodiorite.

The pyroxene metabasite might have existed as a septum between the original rock units of the gneissose tonalite and the gneissose granodiorite. The mylonitization might have accelerated the alteration of the pyroxene metabasite into the hornblende metabasite. It is probable that the mylonitization took place in synchronous with the white granodioritization of the original rock (charnockite?).

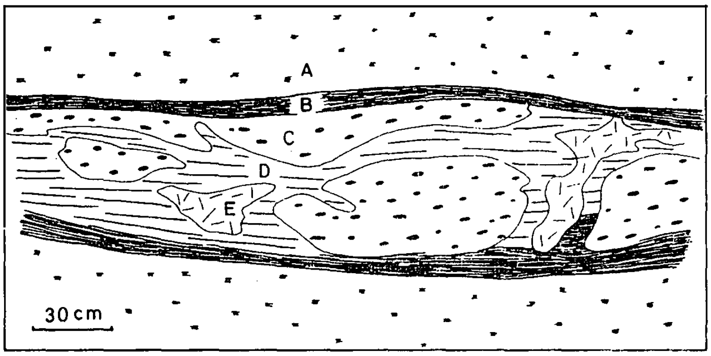

Fig. 13. Boudinaged occurrence of the brown gneissose granodiorite in the white gneissose tonalite.
A: White gneissose tonalite. B: Hornblende metabasite. C: Brown gneissose granodiorite. D: Mesocratic amphibolite or dioritic gneiss. E: Pegmatite.
The brown gneissose granodiorite may be a relic fragment (layer) in the gneissose tonalite probably associated with the pyroxene metabasite layers which changed to the hornblende metabasite (B facies). D and E might have been formed in synchronous with, or a little later than, the formation of the boudinage structure.

hand, are developed everywhere in the gneissose granodiorites (Plate 5b, c, Fig. 8). Small dikes of granitic pegmatite (Fig. 9) and hornblende-biotite microgranite are found discordantly cutting the gneissose granodiorites. Distribution of the white gneissose granodiorites and the brown gneissose granodiorite is rather complex and the boundary between the two rocks is difficult to determine, although the two typical rock facies are easily distinguished in hand specimen. In general, the white gneissose granodiorite is developed altering the brown gneissose granodiorite (Fig. 10 and Plate 5d).

The trend of the foliation is generally WNW, while its dip is variable, generally being steeply northward in the northern part and gently southward in the southern part, showing asymmetric folding. The basic schlieren of the metabasites are generally parallel, but sometimes discordant to the foliation. The crenulation lineations trend commonly WNW 30° and microfold lineations of the basic schlieren were difficult to determine, but appeared to be random. The schlieric metabasites are often well-folded, the foliation of the surrounding gneissose granodiorite being undisturbed by the folding (Plate 5b, c, also cf. Figs. 7, 8). At several outcrops of the white gneissose granodiorite, xenolithic blocks of the acid brown gneiss and pyroxene metabasite were found. Also the pyroxene metabasite was often found to be altered into hornblende metabasite (Figs. 11, 12, 13).

3.5. Nt V (an island located at 69°25′S and 37°40′E)

Aerial photographs, a geologic sketch including a route map, and a list of field data and collected samples are shown in Plate 2c, Fig. 14, and Table 1.

The island consists mainly of garnet-bearing brown gneissose granodiorite with a small amount of schlieric metabasite. Hornblende-potash feldspar pegmatite and garnet-bearing aplitic rock were found sporadically. General

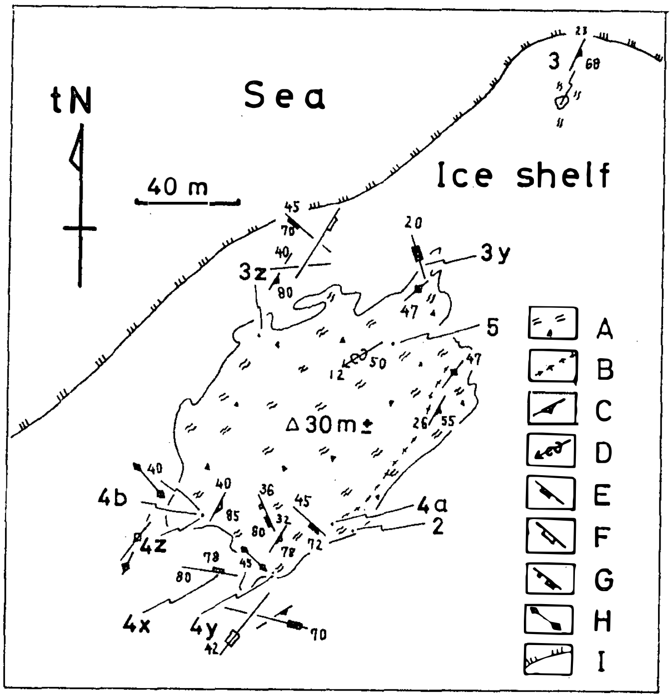

Fig. 14. Geologic sketch of Nt V. A: Brown gneissose granodiorite with garnet. B: garnet bearing aplitic vein. C: Foliation. D: Microfold lineation. E: Hornblende-potash feldspar pegmatite. F: Leucocratic vein. G: Joint along which the hornblende potash feldspar pegmatite intrudes. H: Glacial striae. I: Margin of ice shelf. Symbols 1-6 correspond to JARE Y70021501-Y70021506 in Table 1.

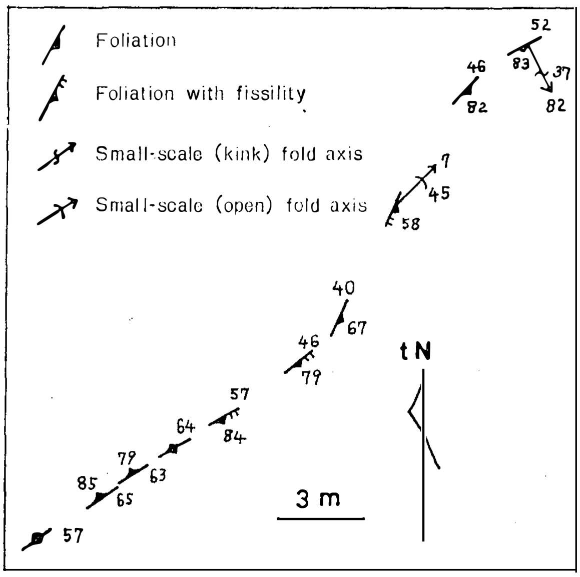

Fig. 15. Change in the trend of the boundary plane of a garnet aplitic vein in the brown gneissose granodiorite, SK Y70021504a.

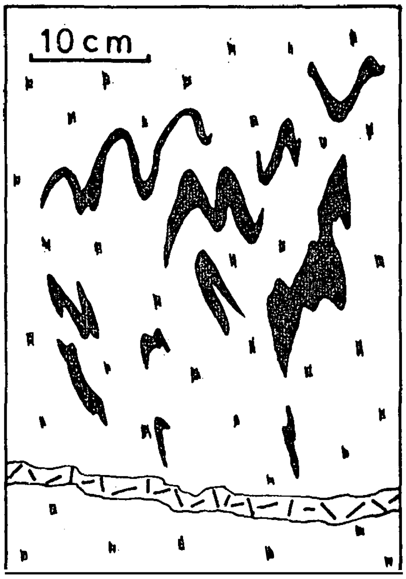

Fig. 16. Occurrence of the folding structure of basic schlieric bands in the brown gneissose granodiorite, SK Y70021506.
The basic schlieric bands are scattered in small blocks whose elongation is discordant to the foliation structure of the surrounding granodiorite. A late stage pegmatite cutting the both structures is seen in the lower part of the figure.

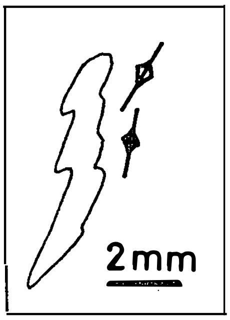

Fig. 17. Superposition of foliation structures, SK Y70021504z.
A clot of hornblende or a very small scaled basic schlieren shows discordance between its elongation (solid mark) and the later stage general foliation (open mark).

structure is steep with a NE trend. The dip is generally 70°–80° SE but somewhat variable (Fig. 15, also cf. Fig. 14). Discordance between the banding structure of the schlieren and the foliation was observed (Figs. 16, 17). A thin (some tens of cm in width) band of garnet-bearing biotite aplitic rock along the foliation of the country rock was found at the eastern part of the island. Inasmuch as the foliation of the brown gneissose granodiorite is indistinct, the strike and dip of this band at many points are variable (cf. Fig. 15). Two different lineations were also discovered on the boundary plane of the band. Thus, three different lineations were noticed on the island, *vis.*, southwesterly microfolding lineation of the basic schlieren, and northeasterly small-scale open folding lineation and southeasterly kink folding lineation of the boundary plane of the aplitic rock in the gneissose granodiorite.

4. Description of Rock Types

The characteristics of rock types of the region, based mainly on the field observations, are briefly summarised in the following paragraphs. Photographs of the rock samples are presented in Plates 6–10, field occurrence and mineral compositions are noted in Table 1, and chemical compositions in Table 2.

4.1. Metabasites

Metabasites occur as alternating layers several centimeters in width, or as zonal masses ten to one hundred meters in width in the paragneisses, or as schlieric bands or pools of about ten centimeters in width in the gneissose granodiorites. They are melanocratic rocks relative to the surrounding rock types. The rocks are generally composed of plagioclase, biotite, quartz, pyroxene, hornblende, and potash feldspar. The latter four minerals are variable in amount and sometimes absent. The rocks are classified into pyroxene metabasite and hornblende metabasite based on the relative amounts of pyroxene and hornblende.

The chemical compositions of two samples of this rock types, *i.e.* the hornblende metabasite and pyroxene metabasite, which occur as alternating layers in the paragneisses, are given in Table 2. Low SiO_2 contents (53.42, 54.59%) and rather high Na_2O (5.12, 2.36%) relative to K_2O contents (1.97, 1.21%) are characteristic. The relative amount of K_2O to that of Na_2O generally coincides with the range of that of metamorphic basic rocks of probably igneous origin in the continental shield (MEHNERT, 1968). The chemical compositions as a whole show similarity with some intermediate to basic rocks such as diorite-syenodiorite (hornblende metabasite) or gabbro-diorite (pyroxene metabasite) described by JOHANNSEN (1939).

The metabasites include the basic granulite and amphibolite described by YOSHIDA and ANDO (1971) and may correspond to the metabasite and part

Table 2. Chemical compositions of the rock samples from the Botnneset region.

Sample No.	A6901 2802	A6901 2803	A6901 2806	Y6901 2931a	Y6901 2931b	Y6901 2934	Y6901 2821	Y6901 2803	Y6901 2824
Rock type	Q-F Bi Gn	Q-F Ga Gn	pk Kf gn Gr	Q-F Ga Gn	Px Mb	gr Peg	bw gn Gd	Ho Mb	Ho-Bi micro Gr
SiO_2	76.09	72.96	73.50	60.03	54.59	67.98	54.04	53.42	63.15
Al_2O_3	13.01	13.95	14.20	19.10	15.54	17.27	22.10	20.58	17.82
Fe_2O_3	0.33	0.48	0.73	1.10	2.06	0.74	0.98	2.83	1.40
FeO	0.25	1.47	0.66	6.79	9.26	1.65	4.07	4.58	1.47
MgO	0.27	0.83	0.33	1.92	6.59	0.89	2.18	2.58	0.97
CaO	0.44	0.95	0.90	3.02	4.82	3.26	5.94	5.84	1.76
Na_2O	1.67	1.70	2.25	4.16	2.36	4.41	5.27	5.12	2.90
K_2O	6.56	6.03	6.02	1.02	1.21	1.58	2.07	1.97	7.29
H_2O^+	0.49	0.66	0.57	0.75	1.17	0.84	1.25	1.07	0.84
H_2O^-	0.24	0.28	0.16	0.22	0.36	0.27	0.30	0.12	0.20
TiO_2	0.11	0.23	0.19	1.22	1.39	0.42	1.01	1.23	1.32
MnO	0.01	0.02	0.01	0.13	0.16	0.01	0.09	0.11	0.04
P_2O_5	0.02	0.05	0.07	0.05	0.13	0.29	0.26	0.21	0.37
	99.49	99.61	99.59	99.51	99.64	99.61	99.56	99.66	99.53

Analytical method is as follows. Na, K: Photometric method; Fe (Σ Fe), Ti, Mn; P: Colorimetric method; Fe^{++}, Ca: titrimetric method; Si, Al, Mg, H_2O^+ and H_2O^-: gravimetric method. (Analyst: J. HIRABAYASHI of the Tokyo Institute of Technology, the data are presented by the courtesy of him and of Prof. J. OSSAKA of the same Institute)

of the pyroxene gneiss described by TATSUMI *et al.* (1964).

4.2. Paragneisses

Paragneisses consist mainly of alternations of basic and acid gneisses, *i. e.* pyroxene metabasite and quartz-feldspathic biotite or garnet gneisses. These rocks are developed in almost every area except Nt IV and Nt V.

The alternation of basic and acid gneisses is on a scale of some tens of centimeters, representing a distinct banding structure of the gneisses. The pyroxene metabasite is mainly composed of plagioclase, quartz, biotite, and monoclinic and rhombic pyroxenes with or without a minor amount of hornblende. It is a small- to medium-grained* (1 mm$\pm$), granular, dark-brownish rock. Only biotite (its basal plane) generally shows preferred orientation, representing foliation structure. Thin salic and mafic rich laminae were often observed to be parallel to the banding structure of the gneiss. The quartz-

* Usage after TEUSCHER (1933).

feldspathic gneiss is mainly composed of quartz, plagioclase, potash feldspar, biotite, and garnet. The latter three minerals are sometimes absent and variable in amount. Quartz-feldspathic garnet gneiss is characterized by the presence of reddish pink garnet. Potash feldspar and biotite are sometimes very small in amount. The rock is medium- to coarse-grained (one to several millimeters), inequigranular and leucocratic. Well elongated coarse-grained (*e.g.*, 0.5×3cm) dark-grayish quartz pools showing typical granulite texture and (001) of biotite arranged in preferred orientation, represent the foliation structure of the rock. The foliation is generally parallel with the banding structure. Mafic minerals are often indistinctly concentrated into thin laminae. Such laminae are parallel to the foliation as well as to the banding structure of the gneiss. Quartz-feldspathic biotite gneiss lacks garnet. It is a small-grained, equigranular foliated rock. The biotite shows dimensional and lattice preferred orientation, is somewhat concentrated in very thin folia, and is arranged in a linear form showing distinct mineral lineation.

The chemical compositions of three samples of the quartz-feldspathic gneisses are given in Table 2. Two of the analysed samples show high SiO_2 (72.96, 76.09%), high K_2O (6.03, 6.56%) and extremely low Na_2O (1.70, 1.67%) and CaO (0.95, 0.44%) contents. But one sample is rather low in SiO_2 (60.03%) and K_2O (1.02%) and rather high in Na_2O (4.16%) contents. The relative amount of Na_2O to that of K_2O of the three samples coincide with the range of metamorphic acid rocks in the continental shield demonstrated by MEHNERT (1968). Ignoring the high alkalis, they are plotted in the field of sandstone and chert, near argillaceous rocks, in the SiO_2–(Al, Fe)$_2$O$_3$–(Ca, Mg)CO_3 diagram presented by MASON (1958). Comparing the chemical compositions as a whole with those of igneous rocks described by JOHANNSEN (1939), the two samples with high SiO_2 resemble rhyolite and the rest resembles to some alkalic acid rocks such as trachyte.

Paragneisses include the gneisses referred to by YOSHIDA and ANDO (1971) and may correspond to the garnet gneiss and part of the metabasite and the pyroxene gneiss described by TATSUMI *et al.* (1964). These investigators recognized this type of rock in many areas around Lützow-Holmbukta. These rocks were probably formed mainly under granulite facies conditions, judging from their mineral assemblages, as pointed out also by KIZAKI (1964), TATSUMI *et al.* (1964), BANNO *et al.* (1964 a, b), and SUWA (1968).

4.3. Brown gneissose granodiorites

These rocks consist mainly of brown gneissose granodiorite developed in all areas except Nt III. Brown augen gneissose granodiorite developed at a western nunatak in Nt II and brown gneisses developed in Nt III also belong to this rock type.

The brown gneissose granodiorite is mainly composed of plagioclase, potash feldspar, quartz, and biotite. Association of hornblende, garnet, or hypersthene is common. The rock is brownish or greenish, medium-grained (one to several mm) and weakly foliated. The dark color of the rock is due to the colored quartz and feldspars. Foliation was easily determined by observing the small folia of mafic clots. Basic schlieren were often observed to be generally arranged parallel with the foliation structure. The basic schlieren, however, sometimes show discordance with the foliation of the country rock. The brown gneissose granodiorite is so homogeneous that its heterogeneity is hardly distinguishable in one outcrop of over hundreds of meters ; however, a minor amount of basic schlieric metabasite was found to be frequently and heterogeneously developed. Comparing the outcrops of the different areas, however, a remarkable difference in lithofacies was found. In the western areas, hypersthene- or garnet-bearing medium- to small-grained facies is developed, whereas in Nt IV, the easternmost area of the region, the rock is coarse-grained and often potash feldspar porphyritic ; garnet or hypersthene is rare in amount or absent.

The brown augen gneissose granodiorite is developed at a western nunatak in Nt II in a 500 m^2 outcrop isolated in the ice field. The rock is mainly composed of plagioclase, potash feldspar, quartz, and biotite. It is a small-grained (0.8 mm$\pm$) rather pale colored rock with abundant coarse-grained (5 mm) potash feldspar augens. Films of clots of biotite exhibit the foliation structure of the rock. Numerous thin veins of pink gneissose granite are frequently developed along the foliation of the country augen gneissose granodiorite.

The brown gneisses are composed of a zonal alternation of acid brown gneisses and metabasite, some tens to one hundred of meters in width. The acid brown gneisses range from biotite-bearing quartz-feldspathic brown gneiss to biotite brown gneiss. A small amount of garnet is sometimes included in these rocks. They are medium-grained rocks, light brownish in color due to the colored nature of the salic minerals. The biotite shows a preferred orientation, giving the rock a distinct foliation structure parallel with the rock zonation. The elongation of quartz, which was wrongly identified as sillimanite needles in the field, shows a distinct lineation structure.

Metabasites associated with the brown gneissose granodiorite are pyroxene metabasite and hornblende metabasite. They are small- to medium-grained, mesocratic to melanocratic and often thinly laminated. Their mineral constitution changes in relation to that of the country granodiorite, *i. e.* poor in pyroxene and predominant in hornblende when the country rock is poor in or lacks hypersthene. They occur as small sized lenticular or banded bodies, often showing a palimpsestic minorfolding structure. Metabasites occurring as part of the brown gneisses are pyroxene metabasite. Hornblende occurs in minor amounts or is absent; scapolite was found in one specimen. Lamination structure is not developed, but the scapolite-bearing variety is heterogeneous in grain size, varying from small-grained to medium-grained in the hand specimen. They occur as distinct rock zones alternating with the acid brown gneisses.

The chemical composition of one sample of the brown gneissose granodiorite is given in Table 2. In contrast to its modal composition, the rock is low in SiO_2 content (54.04%). The relative amount of K_2O to Na_2O coincides with the range of metamorphic acid rocks in the continental shield as demonstrated by MEHNERT (1968). Very high Al_2O_3 (22.10%), rather high Na_2O (5.27%) and relatively low K_2O (2.07%) may be comparable with the chemical characteristics of such alkalic igneous rocks as syenodiorite, described by JOHANNSEN (1939). It is worth noting that such chemical characteristics as alkalic igneous rocks are more or less common to some specimens of metabasites and of quartz-feldspathic gneisses.

The brown gneissose granodiorite includes the gneissose granodiorite referred to by YOSHIDA and ANDO (1971). It may correspond to the variety of the pyroxene gneiss described by TATSUMI *et al.* (1964) and KIZAKI (1964). The hypersthene-bearing variety of this rock is referred to as the charnockite (JOHANNSEN, 1939) as already pointed out by TATSUMI and KIKUCHI (1959). Brown gneisses have never been described elsewhere around Lützow-Holmbukta. These rocks were considered as one variety of the gneisses described by YOSHIDA and ANDO (1971). The brown gneissose granodiorites are probably formed mainly under granulite facies conditions, judging from the mineral assemblages as was already suggested by KIZAKI (1964) and other authors, although the gneissic variety and some of the coarse-grained facies (in which hypersthene and garnet are absent or rare) were probably formed under amphibolite facies conditions.

4.4. Hornblende-biotite microgranite

This rock is only found in Nt IV in clear-cut dike form, several meters in width, intruding into the potash feldspar porphyritic brown gneissose granodiorite. The boundary of the dike and the country rock is sharp because of the distinct difference in the grain size between the two rocks, but no smooth contact plane is recognized. The country brown gneissose granodiorite is rather pale colored in comparison to the ordinary brown gneissose granodiorite widely distributed in the same area.

The rock is composed of quartz, potash feldspar, plagioclase, biotite, and hornblende. It is a medium-grained (1–2 mm) brownish rock with foliation structure due to biotite flakes, the brownish color being due to the colored salic minerals. All the constituent minerals are distributed homogeneously.

The chemical composition of one sample of this rock type is given in Table 2. High Al_2O_3 (17.82%), high K_2O (7.29%), low CaO (1.76%), and low Na_2O (2.90%) contents relative to SiO_2 content (63.15%) are the characteristic that closely resembles some kind of alkali-granite (*e. g.* sodaclase syenite) described by JOHANNSEN (1939).

Hornblende-biotite microgranite includes the micro biotite granite referred to by YOSHIDA and ANDO (1971). It was probably formed under amphibolite facies conditions, judging from the mineral assemblage.

4.5. White gneissose granodiorites

These rocks consist of white gneissose granodiorite and white gneissose tonalite. Both are generally associated with the pink gneissose granite. White gneissose granodiorite is distributed in a small amount in Nt II and Nt IV occurring in the brown gneissose granodiorite. It is distributed along small faults some decimeters in width cutting the brown gneissose granodiorite in Nt II. In Nt IV, however, it is widely developed in the northern part of the area and only partly in the southern part. Pink gneissose granites are well developed, being associated with the white gneissose granodiorite in the northern part. Leucocratic aplitic network veins or hornblende-biotite microgranite veins are developed in the brown gneissose granodiorite in the southern part, associated with the white gneissose granodiorite. White gneissose tonalite only occurs in Nt IV associated with the white gneissose granodiorite.

The white gneissose granodiorite is mainly composed of quartz, plagioclase, and potash feldspar, with hornblende and/or biotite. The rock is medium-grained (1–2 mm). The salic minerals of this rock are not colored, and accordingly the rock appears distinctly white colored when it is distributed in the brown gneissose granodiorite. Elongated clots of hornblende and/or biotite exhibit the foliation structure of the rock.

Metabasite occurring in the white gneissose granodiorite is hornblende metabasite devoid of pyroxene; *i. e.* it may generally be assigned to amphibolite. It is small-grained equigranular foliated rock. It occurs as schlieric lenticular bodies often showing a palimpsestic minorfolding structure (cf. Plate 5b, c).

The white gneissose granodiorites may correspond to the hornblende gneiss referred to by TATSUMI *et al.* (1964) and KIZAKI (1964). The rocks were probably formed under amphibolite facies conditions judging from the mineral assemblages, as pointed out by KIZAKI (1964).

4.6. Pink gneissose granites

These rocks consist of pink gneissose granite and pink migmatitic gneiss which are characterized by the predominance of pink-colored potash feldspar. Among these rocks, pink gneissose granite is predominant.

Pink gneissose granite is developed in Nt III with dimensions of 40×600 meters, discordantly cutting the gneisses. The rock is medium-grained (1 mm+), composed of potash feldspar, quartz, plagioclase, and biotite. Feldspars of this rock are pink or white and accordingly the rock presents a somewhat pinkish color. Elongated clots of biotite give the foliation structure to the rock. The pink gneissose granite is also well developed in the form of lit-per-lit injection into the brown gneissose granodiorites in Nt IV and in the west nunatak of Nt II.

Pink migmatitic gneiss is developed in Nt II and Nt IV. In Nt II, it is located within a sheared zone cutting the paragneisses and the brown gneissose granodiorite. It is rather heterogeneous, being composed of garnet-bearing pink gneissose granite, acid gneissic rocks, and amphibolite. The latter two rocks are distributed as blocks in the pink gneissose granite. Some parts of the pink gneissose granite has a pegmatitic appearance as will be mentioned later.

The chemical composition of one specimen of this rock type is given in Table 2. High SiO_2 (73.50%), high K_2O (6.02%), and low CaO (0.90%) contents are its characteristic that closely resembles ordinary granitic rocks described by JOHANNSEN (1939).

The pink granites include the pink potash feldspar gneissose granite referred to by YOSHIDA and ANDO (1971) and probably correspond to the granite described by TATSUMI *et al.* (1964), the granite by KIZAKI (1965), and the pink granite by OHTA and KIZAKI (1966). These rocks were probably formed under amphibolite facies conditions, judging from the mineral assemblages, as was also pointed out by KIZAKI (1964, 1965) and OHTA and KIZAKI (1966).

4.7. Pegmatites

These rocks comprise pink granitic pegmatite, hornblende granitic pegmatite, and biotite granitic pegmatite. Pink granitic pegmatite is found in Nt II, intruding along the fault developed on the boundary between the brown gneissose granodiorite and the paragneisses. Pink gneissose granite is also found in association with a similar fault in this area. Potash feldspar of the pegmatite is pale pinkish to white.

Hornblende granitic pegmatite and biotite granitic pegmatite occur mainly in Nt IV. They are exclusively distributed in the white gneissose granodiorites, cutting and lit-per-lit injecting into the latter (cf. Figs. 9, 10, 13). They are centimeter-grained, equigranular, leucocratic, being either foliated, or massive rock. Quartz is present in the pegmatite when the country rock is granodiorite, but is absent when the country rock is metabasite (cf. Fig. 9). Biotite granitic pegmatite is also developed zonally as a mass, 15 meters wide, at Nt I.

Hornblende granitic pegmatite is also found in Nt V. Here numerous veins of hornblende potash feldspar pegmatite, some centimeters in width, are developed crosscutting the foliation of the garnet-bearing brown gneissose granodiorite.

The chemical composition of one specimen of the biotite granitic pegmatite is given in Table 2. High Al_2O_3 (17.27%), CaO (3.26%) and Na_2O (4.41%) contents relative to SiO_2 content (67.98%) are characteristic that resembles some sodaclase adamellites cited by JOHANNSEN (1939).

5. Sequence of Rock Formation

The paragneisses are probably the earliest among the rocks of the present region. These rocks are cut by the pink gneissose granites. No direct time relationship between the paragneisses and the brown gneissose granodiorites was observed in the field. The brown gneiss (granitic biotite brown gneiss) of Nt III may possibly have originated from some of the paragneisses, since its banding structure as well as rock association indicate that it originated from a rock rather similar to paragneisses, although the alternation structure is somewhat wider in the brown gneisses than in the paragneisses (Figs. 2, 3, 6, and the descriptions in Table 1). Randomly folded basic schlieren in the brown gneissose granodiorites may also be palimpsestic rocks of the basic gneiss bands of the original gneisses, although the mode of the alternation of the original gneisses might have been somewhat different from that of the paragneisses and brown gneisses. Thus it is possible that the brown gneissose granodiorites are the advanced products of the granitization of the alternating gneisses of some kind. This granitization, the nature of which is uncertain, may be distinguished from the ordinary granitization and the resultant product is not granite but garnet or hypersthene granodiorite, the latter being identified as charnockite defined by JOHANNSEN (1939), as already mentioned.

Still unclear is the time of the charnockite formation. It may have either occurred distinctly after the formation of the granulite facies paragneisses or represented a culmination of the paragneiss epock, although the folding structure of the paragneisses might have predated the charnockite. This will be discussed in a later chapter supplemented by data on tectonics. Potash feldspar porphyritic coarse-grained facies of the brown gneissose granodiorite, a part of which may belong to the amphibolite facies, is distinguished from the other rocks by its lithofacies. The time relationship between the granulite facies brown gneissose granodiorite and that of the amphibolite facies will be discussed later. The hornblende-biotite microgranite is probably intimately related to the brown gneissose granodiorite, especially to its lower grade facies. The brown nature of the salic minerals of the rock, as well as the parallelism of the schistosity with the country rock, may suggest the simultaneous association of this rock with the country brown gneissose granodiorite.

The white gneissose granodiorites and the pink gneissose granites clearly postdate the brown gneissose granodiorites. The pink gneissose granites are associated with the fault which cuts the brown gneissose granodiorite in Nt II. In Nt III, the same rocks are distributed discordant to the metabasite associated with the brown gneiss, suggesting an intrusive relationship. At Nt IV, part of the brown gneissose granodiorite is heterogeneously veined by this rock type and the schlieren of the pyroxene metabasite are there altered to hornblende metabasite (cf. Fig. 11). Thus the pink gneissose granites clearly postdate the brown gneissose granodiorites. Some of the pegmatites are associated with the pink gneissose granite as revealed in Nt II.

White gneissose granodiorites also cut the brown gneissose granodiorite in Nt II and Nt IV. These rock types are developed along small faults, the brown gneissose granodiorite grading into white gneissose granodiorite some decimeters from the faults. The foliation of the parent brown gneissose granodiorite in this case is changed becoming parallel with the fault as if it were bent by (slip of the) fault tectonics (cf. Plate 5d). The alteration of the pyroxene metabasite to hornblende metabasite is often found in Nt IV where the white gneissose granodiorite is well developed (cf. Figs. 11, 12, 13 and the descriptions of Nt IV in Table 1). This also supports the above-mentioned time relationship of the white gneissose granodiorites and the brown gneissose granodiorite. A network of leucocratic vein (point 25 in Fig. 7) developed in the white gneissose granodiorite at the southern part of Nt IV may belong to this stage.

The time relationship between the white gneissose granodiorites and the pink gneissose granites is too ambiguous. They must, however, be intimately related in their petrogenesis, the two rock types being distributed in nearly similar manner and areas. The fact that the relationship between the brown gneissose granodiorites and the white gneissose granodiorites is closer than that of the brown gneissose granodiorites and the pink gneissose granites suggests the possibility that the white gneissose granodiorites are transformed from the brown gneissose granodiorite by some action of the pink gneissose granites.

6. Tectonic Sequence

The succession of the tectonic events will be discussed in the following paragraphs, supplemented with descriptions in the previous chapters.

Stage 1: The earliest structure distinguished in the present region is some of the minorfold structures of the paragneisses and those of the basic schlieric bands (metabasite) in the plutonic rocks predating the foliation structure of the plutonic rocks.

The microfold lineations (axes of minorfolds) observed in Nt II are discordant from the other lineations and are apart from the probable β of the foliation planes of the same area (cf. Fig. 3). The style of the macroscopic tectonics of this stage is unclear. The author believes, however, that linear foldings such as isoclinal type might have prevailed during this stage, such a folding having been well observed in Skallen Hills which lie only 30 km east of the present region, resulting in the development of a gentle homoclinal structure.

It is probable that some kinds of foliations were formed during this episode. The thin banding structures observed in most of the metabasites, and also probably in most of the quartz-feldspathic gneisses are considered to be of metamorphic origin. They were probably formed during this stage, although most of the medium to thick banding structures of the paragneisses are considered to be directly derived from the structures of the original rocks.

Stage 2: The foliations and associated lineations of the brown gneissose granodiorite belong to this stage. Basic schlieren in the brown gneissose granodiorite probably subjected a shear folding by this tectonics, judging from their occurrence (cf. Figs. 8, 16, 17, and plates 5b, c).

The foliations of the brown gneissose granodiorite are generally parallel

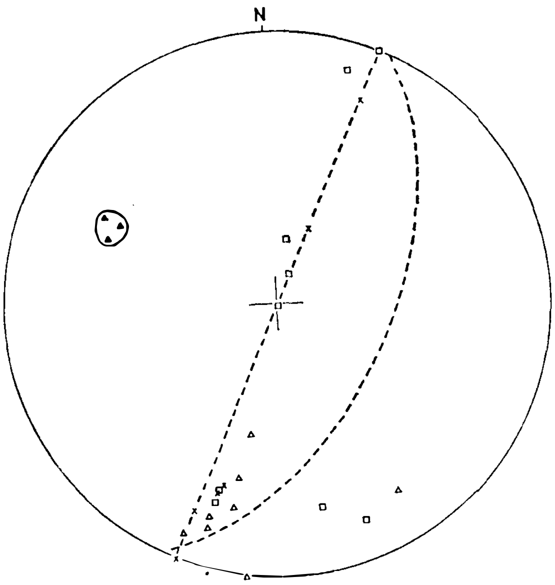

Fig. 18. *Equal area stereographic projection of mesoscopic structures of Nt IV (lower hemisphere).*
Square: Brown gneissose granodiorites, Triangle (open): White gneissose granodiorite and pink gneissose granite, Cross: Lithologic facies boundary of basic schlieren, Solid triangle: Lineation obtained from the white gneissose granodiorite and pink gneissose granite. The vertical great circle indicates the tendency of deviation of the planer structures, and the inclined one denotes the plane perpendicular to the lineations. See text.

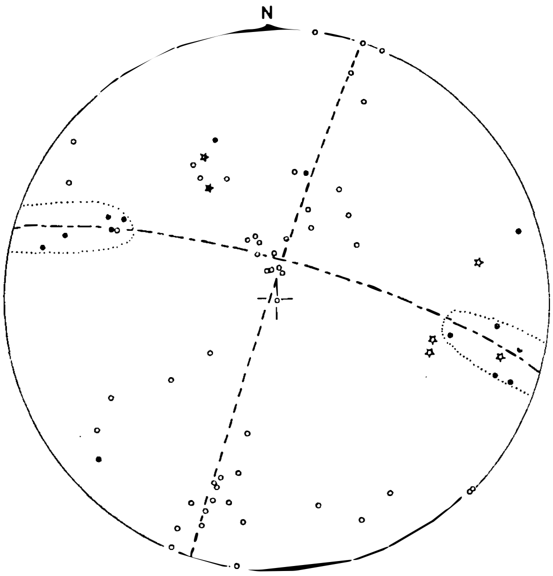

Fig. 19. *Equal area stereographic projection of mesoscopic structures of the Botnneset region (lower hemisphere). Solid keys are lineations and the open ones are planer structures. Circle: Foliation and banding structure, Star: Fault. The NNE great circle is perpendicular to the mean lineation and that with WNW trend indicates the tendency of deviation of lineation structures by N-S foldings. The group of northerly lineations is related to fault or mylonitic rocks. See text.*

or subparallel to the banding structure of the paragneisses or schlieric metabasites; but the planer structure of the original banding structure of the schlieric metabasites is considered to be somewhat inclined from the foliation, the schlieren often being folded, becoming discordant to the foliation nearer to the hinge (cf. Figs. 7, 8, 16, 17). The poles of the foliations and the banding structures present a great circle girdle (π circle) in Nt IV (Fig. 18). The lineations measured on the foliations, however, are discordant with the estimated β obtained from the foliations and banding structures. This inconsistency is found in some extent in other areas where detailed field surveys were made

(Nt II and Nt V). This characteristic relation of foliation and lineation may be explained as follows : the foliation of the second stage tectonics developed either parallel or discordant to the pre-existing foliation or banding structure of the gneisses, *i. e.*, the former is more or less mimetic of the latter. The crenulation and mineral lineations are easily observed on the newly formed foliations but the banding structure of the earlier stage is also clearly discernible and discrimination of a mimetic foliation and new one was impossible in the field; the inconsistency thus results.

An equal-area stereographic projection of all the measured planer and linear structures of the present region is shown in Fig. 19. It will be found that the great circle perpendicular to the lineations shows clear divergence from the distribution of the π poles. This indicates the absence of the direct relationship between the lineations and the planer structures and thus does not contradict the above-mentioned considerations. The schematic structural map (Fig. 20) shows the existance of east (ESE–ENE) trending asymmetric open foldings with a half wavelength of 1–1.5 km in the eastern areas. This is attributed to the divergence of the plots of the planer structures in the indistinct great circle girdle of Fig. 18 as demonstrated in the case of Nt IV. Figs. 19 and 20 show to some extent that these east trending asymmetric foldings develop over all the areas of the region. The asymmetric folding were probably formed by the reconstruction of the older planer structures by the late tectonics of this stage*. A distinct divergence of the π poles from the great circle in Fig. 19 may be explained in part by the above-mentioned reason (*i. e.*, the planer structures are polygenetic), and in part by the later stage (stage 3) disturbance. This disturbance may also have resulted in the divergence of the lineations in an great circle girdle as will be mentioned later.

Stage 3: The north (NNE) trending faultings and probably also the plunging open foldings of the similar trend are the third tectonics. Mylonitization of various intensities occurred during this stage. The east trend asymmetric foldings of the earlier stages are disturbed by the north trending faults or the open foldings with an aperture or half wavelength of about 4 km as shown in Fig. 20. The northwesterly moderately dipping lineations recognized at the fault zones, which are distinctly developed in Nt II, belong to this tectonics. A plunging synform which is developed near Vesthovde, may also belong to the tectonics of this stage. The divergence of crenulation and mineral lineations from the great circle girdle (Fig. 19) may show the effect of the disturbance caused by the faults and the plunging open foldings, and

* It is still possible that the asymmetric folding occurred in the third stage.

the great circle girdle itself is attributed to the plunging symform structure. Foldings predominate in the eastern areas, and faults in the western. Mylonites, hornblende metabasite, and pink gneissose granites are associated with the faults of the western areas. In Nt III, which is the westernmost area of the eastern areas, the pink gneissose granite with foliation trending northwest and dipping gently to the north, intrudes obliquely into the brown gneiss.

The faults associated with the intrusion of the pink gneissose granites or the white gneissose granodiorite in Nt II show a distinct lateral sense judging from the change in the trend of foliations near the faults (cf. Fig. 5). The vertical sense of the faults is also estimated from the moderately inclined

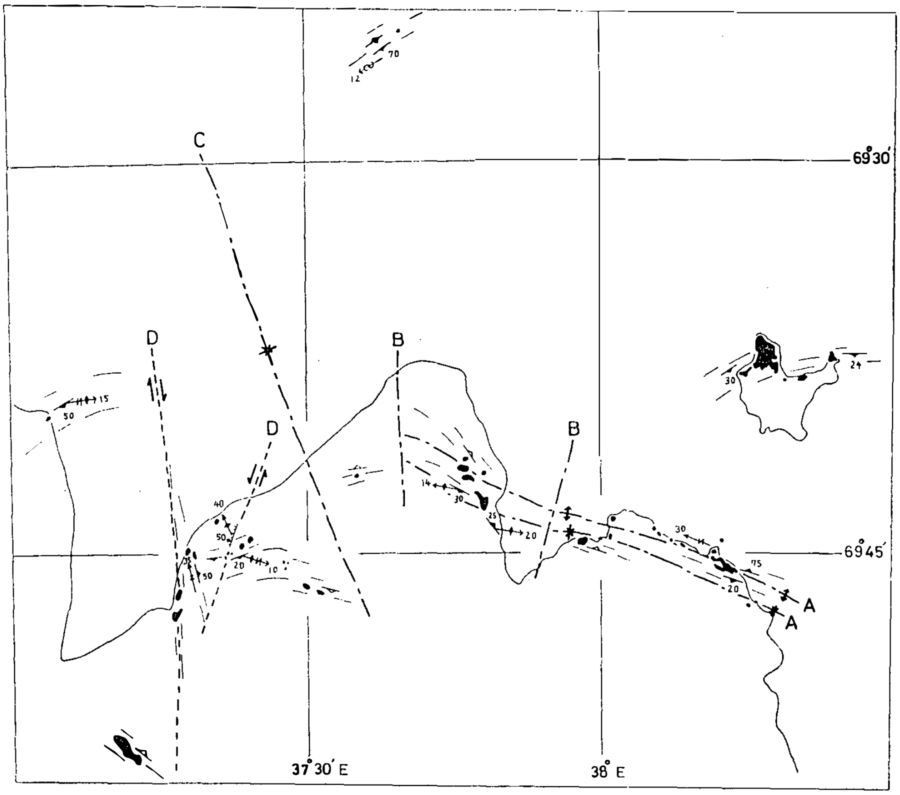

Fig. 20. Structural outline of the Botnneset region.
The data were obtained from field surveys, aerial photographs, and partly (Padda Island) presented by Mr. T. ISHIKAWA through the courtesy of him. The solid areas are outcrops. The tectonic symbols are the same as in the previous figures. The foliation symbols with open triangle are estimated from aerial photographs. The large scale structure is shown by chains (for folds) and broken lines (for faults). The succession of this large scale tectonics is (A)-(B, C, D). See text. Nt V is shown at the northern margin of this figure.

nature of the lineations associated with these faults or with the associated mylonite. The faults may have been able to develope in a compressional stress field of north (NNE) direction with some vertical sense. A similar stress field is also suggested, when some of the faults in the western areas are regarded as a conjugate set. The plunging open foldings might have been able to be formed synchronously with the faulting tectonics due to the subsidiary stress. The synform near Vesthovde may have been formed by the same stress as were the faults. Such a kind of tectonics would have been possible by the block movement of the continent with lateral (with a NNE-NE trend) and vertical sense*. The northwest trending foliation of the pink gneissose granite intruded in Nt III also supports this argument, when the foliation is considered to have been developed perpendicular to the maximum compressional stress direction. The later stage disturbances of the foliation structure of the brown gneissose granodiorite by two different lineations observed in Nt V may correspond to the tectonics of this stage.

The superposition of open folding over isoclinal folding was mentioned by the present author (YOSHIDA, 1970; YOSHIDA and ANDO, 1971) in Skallen Hills on the eastern coast of Lützow-Holmbukta, and the development of crossed lineations was found in East Ongul Island or at some outcrops of southern part of the same coast by KIZAKI (1964) or YOSHIDA and ANDO (1971), although the meaning of the crossed lineations was left uncertain. The correlation of the tectonics of the Botnneset region to those of the other regions in East Antarctica will be tried in the next chapter in considering metamorphic history.

* It is still possible that the north trending faults and foldings are distinguished from each other in both time and genesis. The foldings, especially the synform, may be related to an E-W compression and may predate the faulting tectonics of the third stage and postdate the E-W asymmetric folding of the second stage. The discussion on this possibility is left for future studies.

7. Discussion on the Metamorphic History

The succession of the formation of rock types, *i.e.*, paragneisses and metabasites, brown gneissose granodiorites and hornblende-biotite microgranite, and pink gneissose granites and white gneissose granodiorite, was discussed in the foregoing pages. The metamorphic conditions of the paragneisses and the brown gneissose granodiorites are mostly of the granulite facies but partly of the amphibolite facies, while the other rocks are of the amphibolite facies as mentioned in the foregoing chapters. Table 3 shows a schematic geologic history of the present region deduced from the evidence and interpretations previously mentioned. It is also supplemented by the following discussions.

Although the succession of the formation of the six rock types is rather distinct, the time interval and genetic relationships among them were not so easily defined. The evidence of the first episode (the oldest metamorphism of the present region) is the minorfolding structure of the paragneisses and schlieric metabasites. The granulite facies mineral assemblages especially well represented by most of the paragneisses and some of the metabasites are considered to have been attained during this metamorphic episode. The time relationship, however, between the formation of the granulite facies mineral assemblages and the folding structures is ambiguous*.

The second episode is the formation of the brown gneissose granodiorites (charnockitization) and the development of the foliation structures often cross-cutting the banding structure and resulting in the formation of the shear folding structures of the schlieric metabasites, which are considered to be palaeozomic bodies of the folded metabasites intercalated in such original rocks as the paragneisses.

The brown gneissose granodiorites may have been mostly formed under granulite facies conditions of a probably earlier stage and partly under amphibolite facies conditions of a probably later stage. In general, garnet-free

* The possibility of dividing these two events into two different stage still remains.

Table 3. Schematic metamorphic and tectonic sequence of the Botnneset region.

	First episode	Second episode	Third episode	Fourth episode
Rock or mineral formation	Original gneisses and metabasites of the brown gneissose grandiorites. (Paragneisses).	Brown gneissose granodiorites. (Hornblende-biotite microgranite).	Pink gneissose granites. White gneissose granodiorites. Pegmatites.	Chlorite, epidote, sericite in many of the rocks.
Metamorphic conditions	(Granulite facies).	Earlier granulite facies and later amphibolite facies.	Amphibolite facies	Greenschist facies or slightly lower temperature conditions.
Mesoscopic tectonics	Minorfold structure of paragneisses and that of schlieric bands of metabasites in the gneissose granodiorites. (Metamorphic banding structures of the metabasites and the paragneisses).	E-W trend foliation structure of the brown gneissose granodiorites, often mimetic of the first stage tectonics. Mineral lineation of the brown gneissose granodiorites and the paragneisses. (Part of the minorfold of schlieric metabasites in the gneissose granodiorites).	Faults with both lateral and vertical senses associated with mylonitization. E-W trend foliation of the pink gneissose granites.	Not distinguished.
Macroscopic tectonics	Some foldings, the style of which is unclear (E-W? isoclinal type).	(E-W open folding of asymmetric type with wave-length of 1-1.5 km) (under the N-S compressional stress field).	N-S trending faultings and plunging open foldings with aperture or half wave-length of about 4 km (under the N-S compressional stress field accompanied by the longitudinal block movement tectonics).	Not distinguished.

In parentheses are indistinct phenomena.

and hypersthene-rare facies of the brown gneissose granodiorite and the hornblende-biotite microgranite may belong to the latest or postdating stage of the charnockitization and may have been formed under amphibolite facies conditions. It is noticeable that the hornblende-biotite microgranite is cross-cutting the general trend of the foliation structure of the country brown gneissose granodiorite but bearing schistosity made of scattered biotite flakes parallel with the foliation of the country rock.

Here the three possibilities of the sequence of metamorphism in the earlier episodes can be considered as follows : (a) the brown gneissose granodiorite (charnockite) clearly postdating the paragneisses, (b) the long-continued granulite facies metamorphism which produced the paragneisses ceased to form brown gneissose granodiorites (charnockite), and the latest stage of this metamorphism might have decreased its metamorphic grade to attain amphibolite facies conditions, and (c) the amphibolite facies metamorphism occurred, clearly postdating the granulite facies metamorphism.

A similar view to the last assumption (c) has been raised by some authors, among whom RAVICH (1972) and some Russian geologists in order to explain the wide distribution of the polymetamorphic rocks of Archaean granulite facies and early Proterozoic amphibolite facies in the East Antarctica. It is probable, however, that possibility (a) above mentioned, *i.e.*, the charnockitization clearly postdated the formation of the paragneisses, is preferable, judging from the tectonic considerations that most of the foliation-lineation structures of the brown gneissose granodiorites probably superposed upon the folding and banding structures of the schlieric metabasite and probably of the paragneisses*. A similar metamorphic sequence of the earlier episodes is expected to have prevailed in the wide areas around Lützow-Holmbukta, judging from the similar features in the tectonics and petrology (TATSUMI *et al.*, 1964; KIZAKI, 1964, 1965; OHTA and KIZAKI, 1966; YOSHIDA, 1970; YOSHIDA and ANDO, 1971). BANNO *et al.* (1964 a, b), SUWA (1966, 1968), and SUWA and TATSUMI (1969) discussed the granulite facies metamorphism of the region around Lützow-Holmbukta. Further examinations of the mineral genesis concerning such complicated geologic events, as revealed in the present survey, will contribute valuable data to their discussions.

The third episode, the intrusion of the pink gneissose granites under amphibolite facies conditions associated with the alteration of the brown gneissose granodiorites into the white gneissose granodiorites, clearly postdates the earlier two episodes above mentioned. This is sometimes associated with migmatization and in places is accompanied by mylonitization. The north trending faultings, and probably the plunging open foldings, are considered to be synchronous with this metamorphism.

The amphibolite facies or a little lower grade of metamorphism associated with the pink gneissose granites overlapping granulite facies metamorphism has already been reported in some regions around Lützow-Holmbukta and the Yamato Mountains (TATSUMI and KIKUCHI, 1959; TATSUMI *et al.*, 1964; KIZAKI, 1964, 1965; OHTA and KIZAKI, 1966; YOSHIDA and ANDO, 1971) and in some nunataks of central Enderby Land (SHIRAISHI *et al.*, 1972). In East Ongul Island, KIZAKI (1964) reported that the granite (corresponding to

* The possibility (b) is not yet invalid. Further detailed study on this point is needed.

the pink gneissose granites of the present classification) intrudes at the frontal zone of an isoclinal fold as well as along some sheared zones, and therefore may be synchronous with the folding. KIZAKI's conclusion may generally conform with, but in some part contradict this paper's observations on the present region: the N-S faults or open folds which cut the east trending asymmetric folds of the present region would possibly be different from an isoclinal type folding, although the correlation of the folding styles between the two distant regions should be carefully examined*.

The intrusion of granitic rocks of probably early Palaeozoic is widespread in the East Antarctic Platform (cf. RAVICH, 1972; YANAI, 1973). In Mac-Robertson Land and Kemp Land coast of central Enderby Land, McCARTHY and TRAILL (1964) obtained a metamorphic sequence similar to the first, second, and third episodes of the present region. In the SØr Rondane Mountains of eastern Dronning Maud Land, granitic rocks with the similar field features to the present region are well developed along some tectonic zones (AUTENBOER and LOY, 1972). GRIKUROV *et al.* (1972) also pointed out the association of intrusive rocks along with fractured zones of a late stage (early Palaeozoic) block upheaval in wide areas of the East Antarctic platform. The evidence that the pink gneissose granites of the present region are often associated with fault zones is rather conformable with the views of these authors.

The fourth episode is the wide development of the lower grade metamorphic environment (probably greenschist facies or slightly lower metamorphic conditions) without any distinct mesoscopic structure. This is recognized by observing scanty development of chlorite, sericite, epidote, and some other minerals partly altering primary constituent minerals such as biotite, hornblende, and feldspars. The alteration is rather distinct in the third stage rocks or in some other rocks examined in the areas where the third stage rocks are predominant.

The development of the greenschist facies rocks has been reported in some regions in East Antarctica around Lützow-Holmbukta, *e.g.*, eastern Enderby Land (McLEOD, 1964; SOLOVIEV, 1972; TRAIL, 1964). The development of similar conditions in the higher grade rocks from some other regions of East Antarctica has also been pointed out by such authors as OHTA and KIZAKI (1966), RAVICH and SOLOVIEV (1966), AUTENBOER and LOY (1972), and BREDELL (1973). The lower grade conditions of the present region may have taken place in a later period of granite intrusion of the third stage metamorphism, as deduced from the manner of distribution characteristics of

* The possibility of correlation of the asymmetric folding of the present region to the isoclinal folding of the East Ongul Island still remains.

the alteration*. In this respect this may be comparable with the development of sericite and chlorite described in the pink granite and pegmatite by OHTA and KIZAKI (1966).

The radiometric age determinations of the rocks of the region around Lützow-Holmbukta and the Yamato Mountains showed pronounced distribution of about 500 m.y. (NICOLAYSEN *et al.*, 1961; SAITO *et al.*, 1961; SAITO and SATO, 1964; PICCIOTTO and COPPEZ, 1964; KANEOKA *et al.*, 1968; YANAI and UEDA, 1974) but some other scattered values were found to be as old as 1100 m.y. (MAEGOYA *et al.*, 1968). This generally suggests the existence of an overlapping of at least two geologic events taking place over a very long period. Judging from the data obtained so far in the geological investigations of the regions around Lützow-Holmbukta, these different ages may be a reflection of the combination of the earlier and the later metamorphic events.

The two metamorphic events may be referred to the third and the earlier metamorphic episodes of the present region. The third episode is characterized by the discordant intrusion of the pink gneissose granite; a similar event is widely observed throughout the region around Lützow-Holmbukta. The exclusively wide distribution of the younger ages in the same region may suggest a possibility of the correlation between the two. This possibility is supported by the general tectonic characteristics of the Ross stage tectogenesis in the surrounding regions of Lützow-Holmbukta in East Antarctica where granitic rocks discordantly intrude into the older gneisses along the tectonic zones, as mentioned previously (cf. GRIKUROV *et al.*, 1972; AUTENBOER and LOY, 1972). The similar opinion (correlation of the pink granite with 500 m.y. age) has also been presented by some of the Japanese geologists (MAEGOYA *et al.*, 1968; KIZAKI, 1973; YANAI and UEDA, 1974).

GRIKUROV *et al.* (1972) and RAVICH (1972) summarized the metamorphic history of the Antarctic platform as follows: granulite facies metamorphism of late Archaean, amphibolite facies metamorphism of early Proterozoic, greenschist facies metamorphism of early to middle Proterozoic, and block movement associated with granitic intrusions of early Palaeozoic. If their views are accepted, the first and second metamorphic episodes of the present region may be referred to as late Archaean and early Proterozoic.

* A burial metamorphic origin of this alteration is still possible because there is as yet no evidence to deny the existence, in the preglacial denudation period, of some considerable amount of overlying materials such as the metamorphic-plutonic complex of the present rock species, sedimentary formation of late Proterozoic, early Palaeozoic, and/or late Palaeozoic to Mesozoic, which are reported in the area east of Enderby Land (MCLEOD, 1964; SOLOVIEV, 1972) or in western Dronning Maud Land (AUCAMP *et al.*, 1972; NEETHLING, 1972; BREDELL, 1973).

KIZAKI (1972) described that the granulite facies metamorphism overlaped the early stage amphibolite facies in the Mawson charnockite, whereas McCARTHY and TRAIL (1964) clearly described the superposition of the later stage amphibolite facies metamorphism upon the granulite facies metamorphism in the same region. AUTENBOER and LOY (1972) pointed out that the grade of the metamorphism of about 600–950 m.y., which is lower granulite to amphibolite facies, gradually decreases its metamorphic grade toward the west in Dronning Maud Land. The evidence obtained in the present study does not contradict their views. The metamorphic history of the East Antarctic platform (cf. RAVICH, 1972) will be further studied from the viewpoints given in the works of these authors, *i.e.*, paying attention to the distinction of multiple metamorphic episodes as well as their spatial distributions.

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