Abstract

The Lützow-Holm Bay region (latitude 69°S; longitude 38°E to 40°E) is located in the Prince Olav Coast of Enderby Land of East Antarctica, where crystalline basement rocks extensively occur under the glacial cover. These basement metamorphic rocks in the Ongul Islands, Langhovde, Breidvågnipa, Skarvsnes, Kjuka and Skallen areas, entirely of Precambrian age, are geologically investigated, and the geologic maps of these areas are presented. In the metamorphic rocks of the Lützow-Holm Bay region are recognized many phases of deformation during late Precambrian to Paleozoic time; three major folding events, designated as F_1, F_2, F_3, and fracturing after F_3 are clearly recorded in them. The first folding event, F_1, under the granulite facies metamorphism is characterized by an isoclinal recumbent fold with N-S axial trace. The second folding event, F_2, occurred under the amphibolite facies metamorphism, showing a concentric fold with E-W axial trace. The third event denoted as F_3 took place under a metamorphic condition lower than the amphibolite facies, forming a concentric fold with N-S axial trace. Fracturing associated with an upheaval of the basement after the last phase of folding occurred over the whole region. Discussion is extended to the geological history of this region and the Ross orogeny that had been widespread in the East Antarctic shield.

1. Introduction

In the Lützow-Holm Bay region of East Antarctica (Fig. 1), metamorphic rocks of the granulite facies occur widely and they are considered to be of Precambrian in age.

Preliminary surveys in this region were done and the outline of geology was reported by TATSUMI and KIKUCHI (1959a, b), members of the first

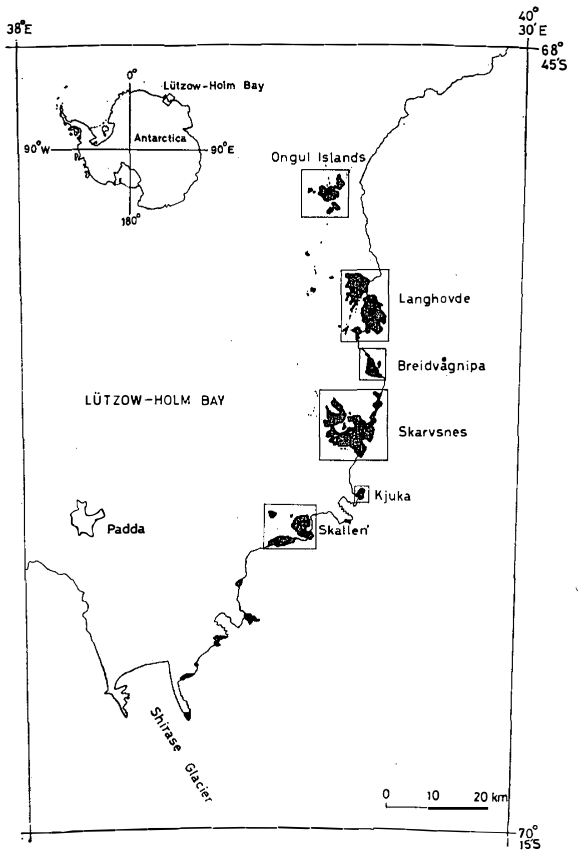

Fig. 1. Locality map of the Lützow-Holm Bay region, East Antarctica.

wintering party of the Japanese Antarctic Research Expedition (JARE). After that, geological reconnaissances of this region were carried out during 1960 (by K. KIZAKI), 1968 (by K. YANAI) and 1969 (by M. YOSHIDA and H. ANDO). The present author was a member of the 13th wintering party in 1971–73, and explored the Lützow-Holm Bay region, Padda Island and Hinode Point (Fig. 1). He further tried to study in more detail a geological structure of the Lützow-Holm Bay region bounded by latitude 68°30′–70°S and longitude 38°–40°E, and a part of his result was already published (ISHIKAWA, 1974).

Maps available at the time of the survey were the 1 : 25,000 series for Langhovde and Skallen and the 1 : 5,000 series for East Ongul Island, West Ongul Island, Ongulkalven Island and Teøya compiled by the Geographical Survey Institute, Japan, and the preliminary map about 1 : 25,500 in scale for Breidvågnipa, Byvågåsane and Skarvsnes. The aerial photographs of approximately 1 : 25,500 scale produced by the 6th JARE in January 1962, were also available for the field work.

2. Geology of the Lützow-Holm Bay Region

The Lützow-Holm Bay region occupies a marginal part of the Antarctic shield (latitude 69°S, longitude 38°E to 40°E). The geological map of this region (TATSUMI and KIZAKI, 1969), drawn originally to the scale of 1 : 500,000, illustrates briefly the result of geological investigations of JARE carried out till 1969. According to these works, the region is composed mainly of metamorphic and plutonic rocks, and they are classified on the basis of petrography and mode of occurrence as follows: (1) pyroxene gneiss, (2) pyroxene syenite, (3) marble and quartzite, (4) metabasite, (5) biotite gneiss, (6) garnet gneiss, (7) hornblende gneiss, (8) migmatite gneiss, (9) granitic gneiss, (10) biotite or microcline granite (11) pegmatite, (12) fossil-bearing beach sands and gravels, and (13) glacial moraines. Except for the sedimentary covers, most of these are metamorphic rocks of the granulite facies (BANNO *et al.*, 1964a, b).

Along the eastern coast of the bay, the foliation and banding of these metamorphic rocks generally strike N-S and dip eastward at 30° to 60°, but local fluctuations and gentle folds are found in some places. A geological survey of the south of Lützow-Holm Bay region was carried out in detail by YOSHIDA and ANDO (YOSHIDA and ANDO, 1971; YOSHIDA, 1975). According to them, the geological structure of the Skallen area in the Lützow-Holm Bay region is characterized by the recumbent fold, the foliation generally striking N-S to WNW-ESE and dipping southward at 30° to 40°. The geological structure of Botnneset is represented by foliation with strike of NW-SE and southward dip.

Previously, metamorphic rocks in this region were correlated with the basement complex of East Antarctica purely on the petrographical ground and they have been considered to be Precambrian in age. However, recent radiometric age measurements on the metamorphic minerals suggest that the regional metamorphism in this region occurred in the late Cambrian (NICOLAYSEN *et al.*, 1961; Saito *et al.*, 1961; Maegoya *et al.*, 1968; Yanai and Ueda, 1974). Radiometric age determinations made on biotite, euxenite and phlogopite show good agreement, yielding about 500 m. y. Potassium feldspar, however, gives generally older age than that of the other minerals and yields 700 to 1,100 m.y. (Maegoya *et al.*, 1968). The younger age probably comes from rejuvenation of the crystalline basement rock (Yanai, 1973). It is very likely that basement rocks of the Lützow-Holm Bay region were polymetamorphosed.

2.1. Ongul Islands area (Fig. 2)

The Ongul Islands consist mainly of East Ongul Island, West Ongul Island, Ongulkalven Island and Teøya. They are situated in the northeast

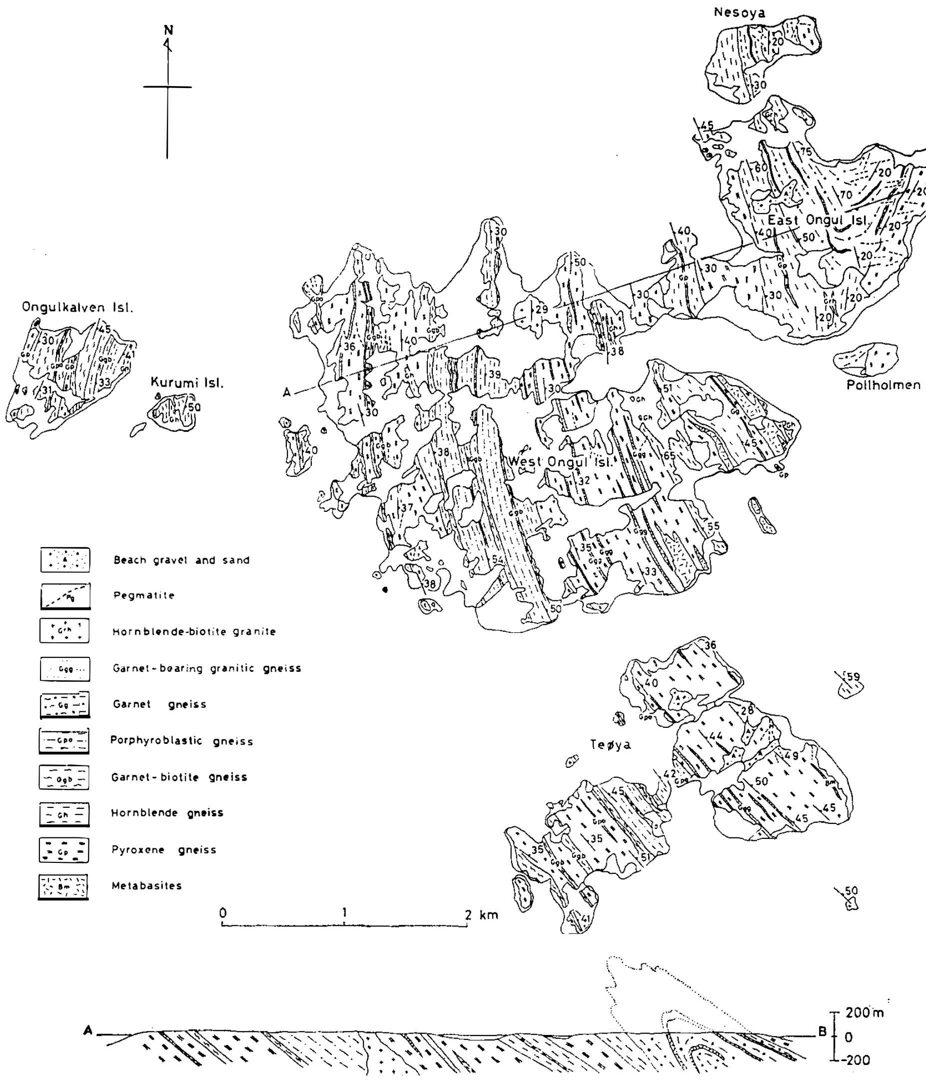

Fig. 2. Geological map of the Ongul Islands area.

of the Lützow-Holm Bay region and are separated from the Prince Olav Coast of the Antarctic Continent by the Ongul Strait of 5 km wide. The Syowa Station of JARE is located on the northern coast of East Ongul Island.

Geological investigations of this area were carried out by TATSUMI and KIKUCHI (1959a, b), KIZAKI (1962, 1964), and YANAI *et al.* (1974a, b, 1975a, b); KIZAKI (1962, 1964) extended his tectonic and petrological discussion on East Ongul Island. Radiometric age data are reported from gneisses, granite and ultrabasic rocks cropping out in the ice-free area of the Ongul Islands. The K-Ar and Rb-Sr ages for biotite in the gneisses are approximately 500 m.y. (NICOLAYSEN *et al.*, 1961 ; MAEGOYA *et al.*, 1968; KANEKO *et al.*, 1968; YANAI and UEDA, 1974). The K-Ar ages of phlogopite in the ultrabasic rocks are approximately 500 m.y., too (YANAI and UEDA,

Table 1. Radiometric ages of rock from the Ongul Islands.

Sample No.	Locality	Rock	Mineral	Method	Age (m.y.)	Ref.
JARE 57122307	West Ongul Island 69°1.5′S, 39°34′E	Charnockite lens in granodioritic gneiss	Biotite	Rb-Sr	500±30	1
A-02	East Ongul Island	Biotite-hornblende gneiss	Whole rock	K-Ar	387	2
〃	〃	〃	Biotite+ hornblende	K-Ar	421	2
〃	〃	〃	Feldspar+ quartz	K-Ar	350	2
A-02	West Ongul Island	Gneissic rock	Biotite	Rb-Sr	508	3
〃	〃	〃	K-feldspar	Rb-Sr	726	3
A-05	West Ongul Island	Gneissic rock	Biotite	Rb-Sr	465	3
A-2 68032704	East Ongul Island 69°00′S, 39°35′E	Pyroxenite	Phlogopite	K-Ar	517	4
A-3 68091201-2	East Ongul Island 69°00′S, 39°35′E	Hornblendite	Phlogopite	K-Ar	533	4
A-4 68090706	Kurumi Island 69°1.5′S, 39°28′E	Garnet-biotite-plagioclase rock	Biotite	K-Ar	539	4
〃	〃	〃	〃	〃	515	4
A-7 68091201-1	East Ongul Island 69°00′S, 39°30′E	Eclogite	Phlogopite	K-Ar	467	4
A-8 68022002	West Ongul Island 69°01′S, 39°30′E	Biotite gneiss	Biotite	K-Ar	560	4
A-9 68022014	West Ongul Island 69°01′S, 39°32.5′E	Microcline-biotite granite	Biotite	K-Ar	399	4
A-11 68022609	West Ongul Island 69°1.5′S, 39°33.5′E	Hornblende gneiss	Biotite	K-Ar	485	4

(1) NICOLAYSEN *et al.*, 1961
(2) KANEOKA *et al.*, 1968
(3) MAEGOYA *et al.*, 1968
(4) YANAI and UEDA, 1974

1974). On the other hand, the Rb-Sr age of potassium feldspar in the gneissic rock is 726 m.y. (MAEGOYA *et al.*, 1968). These results of age determination are summarized in Table 1.

Metamorphic complex of this area is composed mainly of garnet gneiss, porphyroblastic gneiss, hornblende gneiss and pyroxene gneiss. Pegmatite, hornblende-biotite granite, garnet-bearing granitic gneiss and garnet-biotite gneiss also occur, though sparsely.

Garnet gneiss exposed on East Ongul Island is medium- to fine-grained and is usually white to gray in colour. It has a granoblastic equigranular texture and is made up of potassium feldspar, quartz, plagioclase, garnet and biotite. The garnet gneiss formation in East Ongul Island is characterized structurally by an isoclinal fold plunging to the south (Fig. 2).

Porphyroblastic gneiss is mainly distributed in West Ongul Island and Teøya. This coarse-grained well-foliated gneiss is characterized by containing large potassium feldspar porphyroblasts approximately 4 cm in size. It is composed of quartz, plagioclase, potassium feldspar, garnet and biotite.

Garnet-bearing granitic gneiss also occurs in West Ongul Island and Teøya as concordant lenticular bodies of ten to several tens of meters thick and several hundred meters long. It is composed of potassium feldspar, plagioclase, quartz, biotite and garnet.

Garnet-biotite gneiss occurs as thin beds in West Ongul Island, Ongulkalven Island, Kurumi Island and Teøya. It is often found within porphyroblastic gneiss and pyroxene gneiss in West Ongul Island, and has a mineral assemblage similar to the porphyroblastic gneiss. The rock with a marked gneissose structure is fine- to medium-grained, and is characteristically reddish brown in colour owing to the presence of abundant garnet and biotite.

Hornblende gneiss occupies mainly the western half of East Ongul Island and the eastern margin of West Ongul Island. The rock is intercalated within thin layers of pyroxene gneiss. The hornblende gneiss is also found in the pyroxene gneiss along the boundary of pink microcline pegmatite (KIZAKI, 1964), and alternates with the pyroxene gneiss. It seems likely that the hornblende gneiss represents the granitized equivalent of the pyroxene gneiss. That rock is medium-grained and brownish gray to pinkish gray in appearance, showing weak gneissosity and granular texture. It is composed of hornblende, biotite, potassium feldspar, plagioclase and quartz, being free from garnet.

Pyroxene gneiss widely distributed in the Ongul Islands is weakly gneissose and is brown to blue-gray owing to the coloured quartz and feldspars included in this rock. It is medium- to fine-grained and granoblastic in texture. The banded structure displayed with the layered concentration of mafic minerals is partly developed. The rock is composed of clinopyroxene, orthopyroxene, hornblende, plagioclase, potassium feldspar and quartz.

Metabasites occur as thin beds, lenses or irregular-shaped inclusions of various sizes within all varieties of gneisses. They are generally massive, sometimes showing a gneissose structure, fine- to medium-grained, and black or dark-bluish black in colour. They always carry pyroxene.

As is distinctly visible on the geological map, a garnet gneiss formation occurring in East Ongul Island assumes a horse-shoe shape convex to the south. Formations of the outward flanks of this garnet gneiss dip easterly, forming an isoclinal fold plunging to the south. A general trend of the gneiss formations in West Ongul Island strikes N-S and dips 40°E, while that of Teøya, south of West Ongul Island, strikes NW-SE and dips 35°NE. Ongulkalven Island west of West Ongul Island strikes NNE-SSW and dips 30°E. As shown in Fig. 2, the gneiss formations are structurally bent from N-S to NW-SE, and form, as a whole, a homoclinal structure dipping to the east.

2.2. **Langhovde area** (Fig. 3a and 3b)

The Langhovde area is an ice-free area located at 20 km southward from the Syowa Station of JARE. The area belongs to a part of the Prince Olave Coast of Lützow-Holm Bay, and is 14 km long longitudinally and 8 km wide latitudinally along the marginal part of glaciated lands. The basement rocks are covered with the Langhovde Glacier and great ice sheets on the east, and are bounded by a fjord shoreline on the west. This area has been studied geologically and petrographically by the present writer, and the geological map has been published (ISHIKAWA, 1974), by compiling a preliminary survey made by TATSUMI and KIKUCHI (1959a, b) and YOSHIDA and ANDO (1971) especially along the Lützow-Holm Bay region including the Langhovde area. Geological formations exposed in this area are gneissose rocks with a subordinate amount of microcline granite and metabasite. The gneisses consist mainly of garnet-biotite gneiss, garnet-bearing granitic gneiss, garnet gneiss, porphyroblastic gneiss, hornblende gneiss and pyroxene gneiss. Rocks denoted

Table 2. Radiometric ages of rocks from the Langhovde area.

Sample No.	Locality	Rock	Mineral	Method	Age (m.y.)	Ref.
JARE 57112001	69°13′S, 39°38′E	Granitic pegmatite in granitic gneiss	Biotite	Rb-Sr	525±40	1
A-09		Gneissic rock	Biotite	Rb-Sr	526	2
A-1 68013113	69°13′S, 39°45′E	Pyroxenite	Biotite	K-Ar	463	3

(1) NICOLAYSEN *et al.*, 1961.
(2) MAEGOYA *et al.*, 1968.
(3) YANAI and UEDA, 1974.

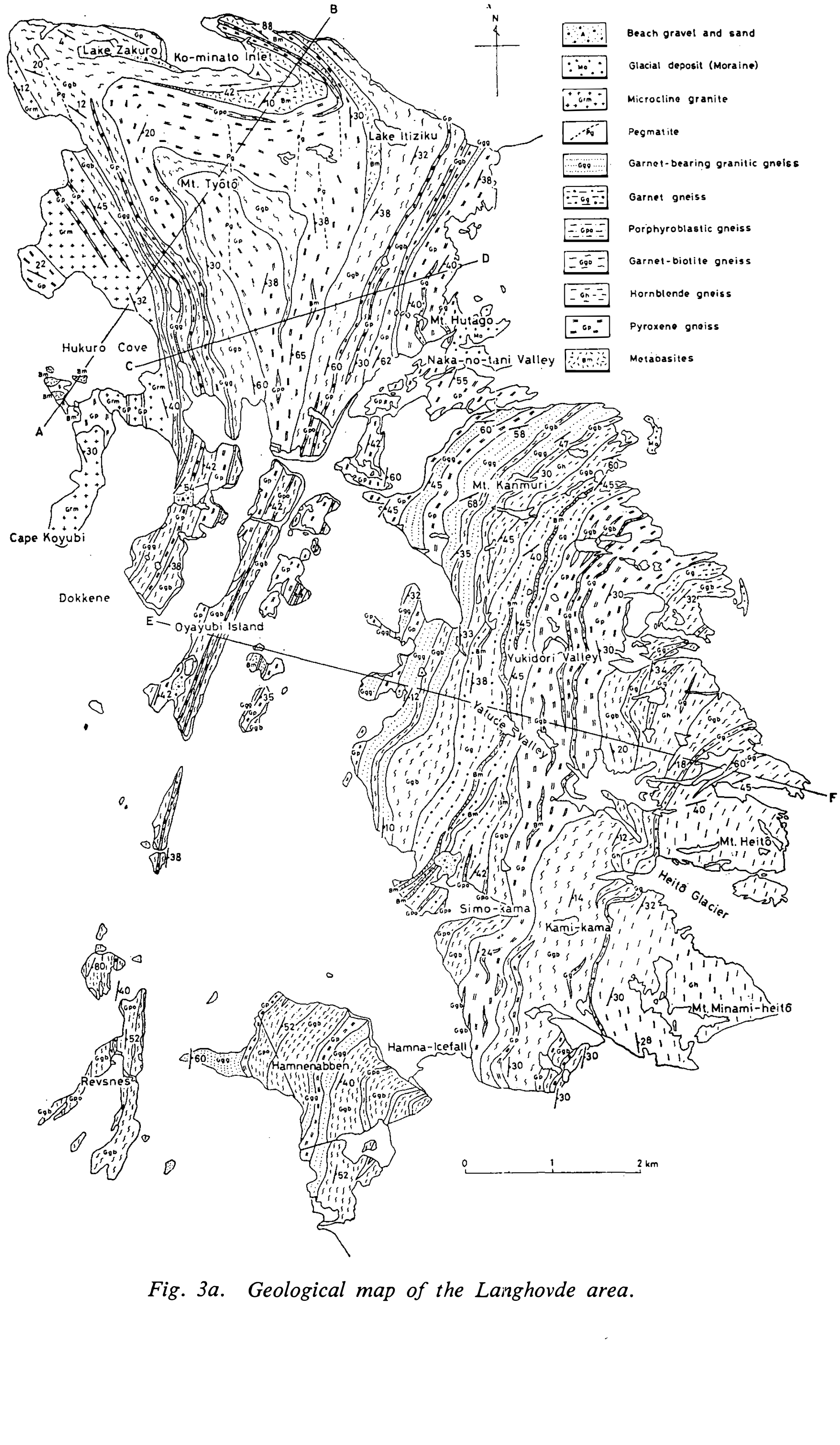

Fig. 3a. Geological map of the Langhovde area.

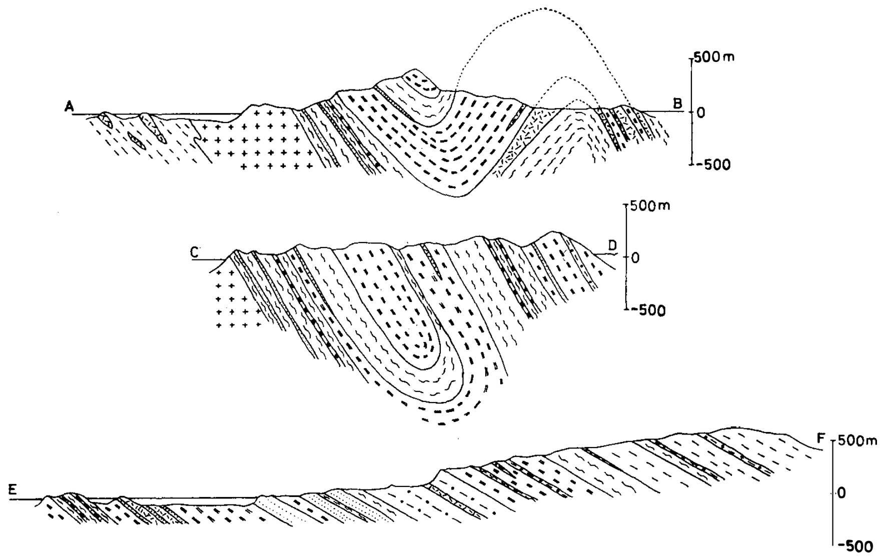

Fig. 3b. Geological section of the Langhovde area.

as metabasites in the map include amphibolite and pyroxenite. Radiometric ages were measured on biotite in granitic pegmatite within granite at the Hukuro Cove and in a small lense of pyroxenite at Naka-no-tani Valley by Rb-Sr and K-Ar methods. They are 525±40 m.y. (NICOLAYSEN *et al.*, 1961) and 463 m.y. (YANAI and UEDA, 1974), respectively (Table 2).

Garnet-biotite gneiss is widely distributed together with lesser amounts of porphyroblastic gneiss in the Langhovde area, and is characterized by containing a large quantity of garnet and biotite and by the absence of hornblende. Reddish brown colouration of this rock due to the presence of garnet is remarkable in the field. Potassium feldspar is often contained in the rock as a porphyritic crystal. Foliation in this rock bodies is represented by the parallel arrangement of garnet and biotite. This foliated structure is exaggerated by alternation of melanocratic layer consisting of biotite and garnet and leucocratic one consisting of quartz and feldspar (Fig. 24). Because these layers possess different strength for erosion, the metamorphic formation shows a rough and bumpy feature on the northern part of the Langhovde area. The rock is composed of biotite, garnet, quartz, potassium feldspar and plagioclase. Plagioclase shows twinning after the albite law and is antiperthitic. Potassium feldspar is commonly perthitic and myrmekite is not uncommon. Most of the feldspars are sericitized. Biotite shows reddish brown to pale yellow in pleochroism ; inclusions of zircon surrounded by small yellow pleochroic haloes are common. Garnet is present in large amounts in the rock throughout the area and often includes a minute crystal of zircon. Accessories are sphene, zircon and apatite ; the last is rare, though.

Porphyroblastic gneiss is found to occur in Hamnenaven, and is characterized by carrying porphyritic potassium feldspar. The mineral, elongated in form about 3 cm in length (Fig. 27), shows microcline texture and perthite. The remaining fine-grained part of this rock is composed of garnet, biotite and quartz. Biotite is arranged linearly, whereas garnet is scattered in the groundmass. The rock consists of potassium feldspar, quartz, plagioclase, biotite and garnet. Myrmekite is commonly observed at a contact of plagioclase with potassium feldspar. Biotite, minute in size and scattered in occurrence, has a strong pleochroic nature and is brown to colourless under the microscope. Garnet is about 1 mm in size. Accessories are zircon, apatite and sphene. Secondary minerals such as sericite and chlorite are found sparsely in the rock to replace the felsic minerals as well as mafic ones.

Thin layers of garnet-bearing granitic gneiss are distributed at the south to Naka-no-tani Valley and the west to Mt. Tyôtô. This bears pink-coloured potassium feldspar and a minor amount of garnet. It is easy to differentiate this from the other rock, because this rock is characterized by its pink colour due to the potassium feldspar. A weak foliation is present and a linear arrangement of minute grains of biotite is recognized. This rock consists of potassium feldspar, quartz, biotite, and garnet, but is barren of hornblende. Potassium feldspar is mostly perthitic microcline. Plagioclase forms myrmekite where it contacts potassium feldspar. Biotite, brown to pale yellow in pleochroism, is mostly chloritized. Accessory minerals are zircon and apatite.

Garnet gneiss occurs in the southern part of the Langhovde area, and forms a thick layer in Yukidori Valley, traceable as a marker formation. It alternates with garnet-biotite gneiss. Generally the garnet gneiss has a weak foliation, and is leucocratic in composition, always including spot-like garnet (Fig. 32). It serves as a key bed in the field investigation because of its continuous nature in distribution. In the southern part of the Langhovde area there are lenticular bodies and boudinages of metabasite in the garnet gneiss. The rock designated as metabasite in the map is composed of quartz, potassium feldspar, plagioclase, garnet and biotite. The quartz content ranges from 30 to 40 percent. Perthitic potassium feldspar is generally more aboundant than plagioclase. Plagioclase is generally oligoclase and, less commonly, andesine. Plagioclase grains often shows an antiperthitic texture. Garnet, pale red in colour, is scattered in the rock. Biotite occurs rarely and shows brown to pale yellow in pleochroism. Accessories are zircon and apatite.

Pyroxene gneiss occurs extensively in the Langhovde area, especially at Mt. Tyôtô, Naka-no-tani Valley and Yukidori Vally. The gneiss is medium-grained and usually dark brown and gray in colour, showing a faint gneissose structure (Fig. 22). The rock mass is rather homogeneous and occupies a wide area, characterized by the presence of pyroxene and by the absence of garnet. There are a small quantity of coloured minerals and a large quantity of plagioclase in the rock. Hornblende occurs in a part as a clot-like assemblage. Constituent minerals of the rock are quartz, plagioclase, hornblende, orthopyroxene, clinopyroxene and biotite. Perthite and/or antiperthite are present in addition to plagioclase. Plagioclase in the pyroxene gneiss from Mt. Futago is composed of labradorite (An 52.6), twinned according to the albite and pericline laws and of a low-temperature type (SUWA, 1966). Hornblende is bluish green hastingsite (SUWA, 1966). Pyroxene grains are usually associated with brown to green hornblende. They are hypersthene and clinopyroxene. Biotite occurs in some rocks and shows brown to yellow in pleochroism. Garnet occurs rarely ; its composition is rich in Mg and Fe, and is poor in Ca ($Mg : Fe^{2+} : Mn : Ca = 45.6 : 43.1 : 1.0 : 10.3$) (SUWA, 1966). Accessory minerals are zircon and apatite.

Hornblende gneiss is distributed at Mt. Heitô and Mt. Minami Heitô. It is gray in colour and quartz-feldsparthic in composition, and is characterized by the presence of hornblende and by the absence of garnet and pyroxene. The gneiss is medium- to coarse-grained (Fig. 23). Coloured minerals are small in amount, but plagioclase and quartz are commonly included. The rock is generally composed of hornblende, biotite, potassium feldspar, plagioclase and quartz. Garnet is generally absent but exceptionally present. Many of potassium feldspar are perthitic. Plagioclase exsoluted from potassium feldspar shows a clear albite-law twin, and antiperthite is often seen. Plagioclase, when being in an immediate contact with potassium feldspar, replaces potassium feldspar and forms myrmekite. Hornblende shows green to pale green in pleochroism. Biotite occurs in a small quantity and shows brown to pale yellow in pleochroism. Accessory minerals are zircon and apatite. Basic xenolith, lenticular and sometimes irregular in form, is often found in the rock.

Metabasite occurs frequently as a thin layer, lens and irregular-shaped body in hornblende gneiss, pyroxene gneiss, garnet gneiss and garnet-biotite gneiss (Fig. 34). On the northern part of Mt. Tyôtô, Yukidori Valley and Naka-no-tani Valley, the thin layers of metabasite extend along their strike for a considerable distance. They are medium- to coarse-grained and usually black in colour. Metabasite is composed of hypersthene, diopside, hornblende, biotite and plagioclase. Plagioclase is unstained and its clear crystal sometimes shows twin lamella. Hornblende is greenish brown to pale yellow in pleochroism. Strongly pleochroic hypersthene is, though rarely, rimmed with biotite. It occurs as anhedral grains. Biotite is small in amount as compared with the other minerals. The following three types of occurrence of biotite are recognized : (1) biotite is found to occur independent of the other minerals, (2) a part of hornblende transforms into biotite, (3) a part of pyroxene transforms into biotite. Biotite shows a strong pleochroism of reddish brown to golden yellow in all of three cases.

Microcline granite is widely distributed in the vicinity of the Hukuro Cove. The rock always has pink-coloured potassium feldspar as the most characteristic constituent. It is fine- to coarse-grained and composed mainly of biotite, plagioclase, perthite, quartz and garnet, with or without a small grain of antiperthite. A gneissose structure is usually weak and is developed parallel to the contact plane. The granite includes in some places many irregularly shaped blocks of basic metamorphic rocks of various sizes. Most of potassium feldspar show perthitic texture, and are suffered from sericitization. Plagioclase is rare ; when found, it often forms a myrmekitic contact to potassium feldspar, and also is sericitized in part. Biotite occurs in a small amount and is chloritized, showing brown to pale yellow green in pleochroism. Garnet is rare. Accessories are apatite and zircon. Sericite and chlorite are secondary minerals.

Many lenticular bodies, clear-cut veins and dikes of pegmatite occur in the vicinity of Mt. Tyôtô. Straight dikes of pegmatite are about 30 cm in width and 1.5 km in length in average, and these trend in an N-S direction crossing discordantly the geological structure. Pegmatite stands out in relief about 40 cm high against the country rock all around. Irregularly shaped pegmatite also occurs in garnet-biotite gneiss. It is observed that the garnet content in the country rock increases, as it nears to the pegmatite.

Glacial deposits are distributed throughout ice-free areas and around a marginal part of the ice sheet. A large amount of glacial deposits has been accumulated around continental glaciers as a moraine. They are very poorly sorted mixture of gravel, sand and silt. In Naka-no-tani Valley the glacial deposits are accumulated at the termination of continental glacier, dam thawing water of glacier and form a dammed lake. Most of boulder in the moraine are angular in shape, but some of them have facets joining each other along smoothed or rounded edges. Judging from the striation observed on some of the facet, it is likely that they are formed by grinding. As pebbles turn and change their attitude in the matrix of ice, new facets are made. Most of the boulder and pebble in till are the same kind of rocks as the bedrocks on which the till was deposited, but some of them are of the other kinds, having been brought from a greater distance. They are garnet-tourmaline hornfels, tourmaline-biotite hornfels, quartzose sandstone and basalt. The hornfels and sandstone, and perhaps also basalt, were probably derived form the Beacon formation which is supposed to crop out in an inland area.

Near the present shoreline and the low land areas of the Kominato Inlet, Yatsude Valley, Yukidori Valley and the Lake Oyayubi, there are some fossil-

Table 3. ^{14}C *ages of fossils from raised beach deposits of Langhovde area.*

Locality	Elevation above sea level (m)	Sample	Age B.P. (years before 1950)	Ref.
Kominato Inlet, Langhovde 03	5-6	*Laternula elliptica*	23,830±910	1
Kominato Inlet, Langhovde 04	1.5	*Adamussium colbecki*	4,290± 90	1
Kominato Inlet, Langhovde 07	6	*Adamussium colbecki*	10,250±210	1
Kominato Inlet, Langhovde 08	6	*Laternula elliptica*	over 33,400	1
Oyayubi Island	2		2,000±220	1
Simo-kama	1.5	*Laternula elliptica*	3,840± 90	2

(1) MORIWAKI, 1974.
(2) ISHIKAWA, 1974.

bearing sand and gravel deposits. These deposits are composed mainly of fragments of rocks exposed in the region, although there are also some erratic boulders. Sorting of the deposits is notably poor. The distribution of the deposits is restricted exclusively to low areas in the inlet, their highest locality being 20 m above sea level in the middle of the Langhovde area (YOSHIKAWA and TOYA, 1957). The deposits about 1.5–2 to 6 m above sea level contain fossils such as *Adamussium colbecki* and *Laternula elliptica* (MORIWAKI, 1974; ISHIKAWA, 1974). Main localities of the fossils are the Kominato Inlet, the Lake Oyayubi and Shimo-kama. Age determinations made on these fossils by the ^{14}C method give the result as listed in Table 3.

As is distinct on the geological map, gneiss formation occurring in Mt. Tyôtô of the Langhovde area shows a horseshoe shape convex to the northwest. Formations north of this garnet-biotite gneiss dip southerly, and those south of this northeasterly, forming a synform plunging to the southeast. This synform fold shows an isoclinal fold in the south of Mt. Tyôtô. On the other hand, metabasites show a horseshoe shape convex to the west in the Kominato Inlet, forming an antiform plunging to the east. The synform and antiform are of a type of similar fold (Fig. 3b), and have a wave length of about 2 km in the vicinity of Mt. Tyôtô. The axial trace of this antiform through the Kominato Inlet strikes WNW-ESE. But the axial trace of the synform through Mt. Tyôtô is bent from NW-SE to NNE-SSW (Fig. 3a). Garnet-biotite gneiss occurring in the Lake Itiziku is distributed as an arch shape with a varying trend from NW-SE to NE-SW. Pyroxene gneiss occurring in the vicinity of Mt. Tyôtô shows a crescent shape distribution. These represent a horizontal section of the deformed structure which involves two types of folding. The one is the first fold of a similar type with a wave length of about 2 km, and the other is a younger one by which the older fold was refolded together with gneiss formations of the northern part of the Langhovde area. The fold-

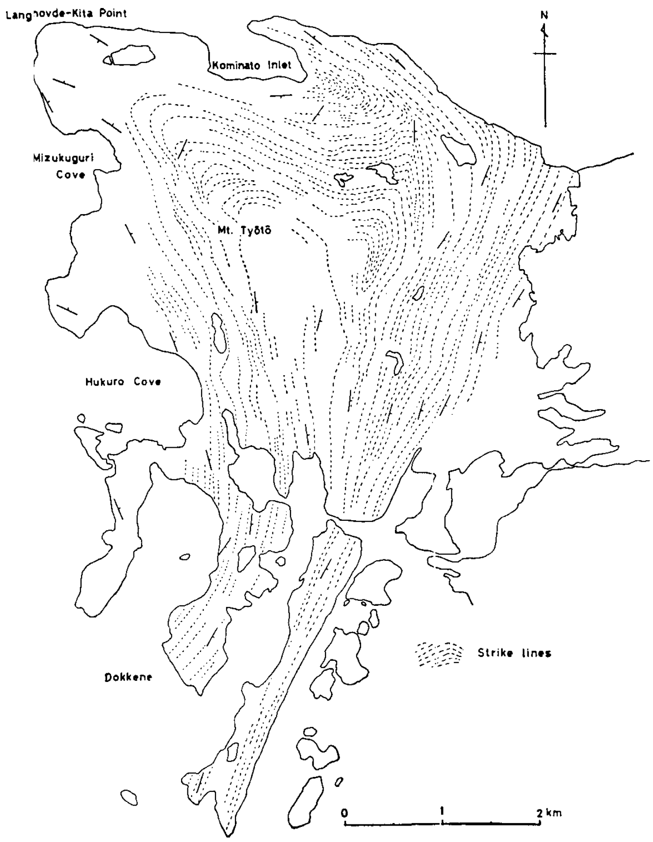

Fig. 4. Tectonic map of the northern part of the Langhovde area.

ing structures formed by the older and the younger movement mentioned above is designated as F_1 and F_2, respectively. The first fold is probably of a flow type as shown on the geologic map. In a marked contrast with this first fold, the second fold has an axial trace trending approximately ENE-WSW and is a flexure fold, because the thicknesses of the gneiss formations are approximately constant throughout the fold. Apparently, the F_1 fold was refolded by the F_2 fold. At about 1 km east of Mt. Tyôtô, a refolded minor fold is observed in the tectonic map of the northern part of the Langhovde area (Fig. 4). On the other hand, the southern part of the Langhovde area show a homoclinal structure striking N10°E and dipping to the east (Fig. 37). In the east of Naka-no-tani Valley, the east of Yukidori Valley and Mt. Heitô, however, gneissose structure is bent to N60°E (Fig. 3a).

2.3. **Breidvågnipa area** (Fig. 5)

The Breidvågnipa area, about 30 km south of the Ongul Islands, is entirely an ice-free area and located at the coastal range area of the western end of Enderby Land, East Antarctica : the highest altitude is 312 m above the sea level. In the south of the Langhovde area, gneissose rocks are also well

Table 4. Radiometric ages of rocks from the Breidvågnipa area.

Sample No.	Rock	Mineral	Method	Age (m.y.)
A-01	Gneissic rock	Biotite	Rb-Sr	508
A-01	Gneissic rock	K-feldspar	Rb-Sr	971
A-03	Gneissic rock	Biotite	Rb-Sr	471
A-24	Gneissic rock	Biotite	Rb-Sr	442
A-24	Gneissic rock	K-feldspar	Rb-Sr	1,116

After MAEGOYA *et al.*, 1968.

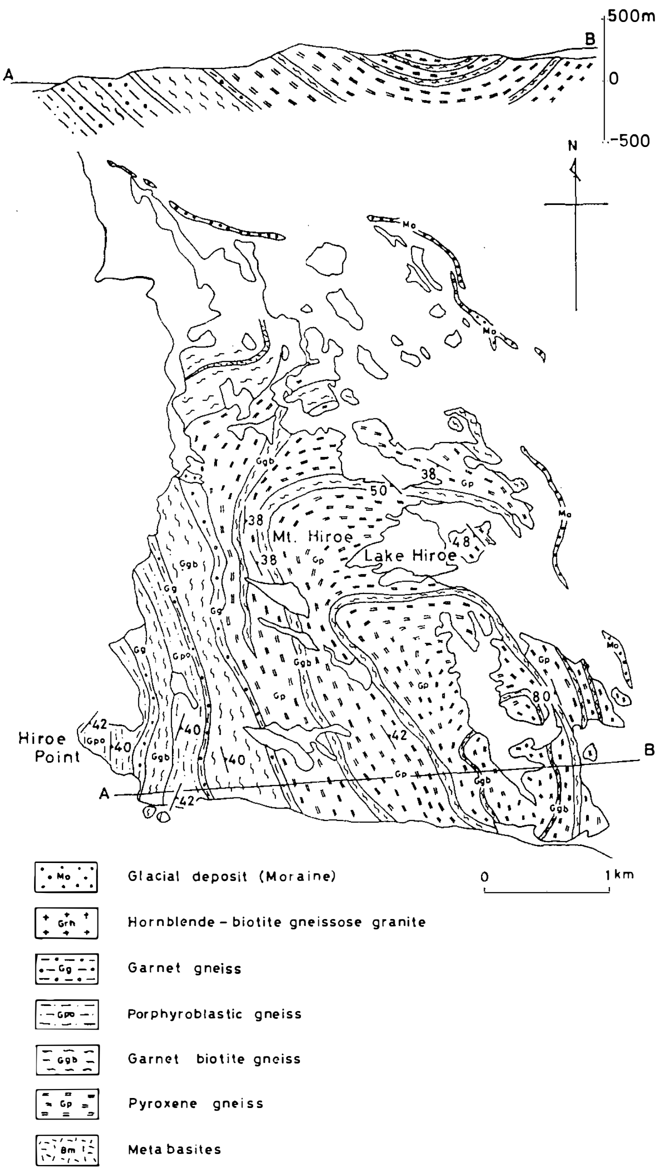

Fig. 5. Geological map of the Breidvågnipa area.

exposed. This area has not been surveyed untill the present writer carried out a field investigation in 1972, although MAEGOYA, a member of the 7th JARE, collected rock samples from here for the purpose of radiometric dating. He has done Rb-Sr age determinations on biotite and potassium feldspar of rock samples (MAEGOYA *et al.*, 1968). Two different age groups of 500 m.y. and 1,100 m.y. have been obtained from biotite and potassium feldspar, respectively (Table 4).

Metamorphic rocks in the Breidvågnipa area consist mainly of garnet-biotite gneiss and pyroxene gneiss, and of subordinate amounts of garnet gneiss, porphyroblastic gneiss, hornblende-biotite gneissose granite and metabasites.

Pyroxene gneiss, generally grayish blue and massive, is widely distributed in the Breidvågnipa area. Gneissose structure is sometimes distinct. The rock intercalates thin layers of garnet-biotite gneiss. Porphyroblast of pyroxene is often found in the pyroxene gneiss, and pyroxene crystals occur also as a vein mineral. Generally, garnet is not included in pyroxene gneiss. Main constituent minerals are hornblende, pyroxene, plagioclase and quartz.

Garnet-biotite gneiss occurs generally as thin layers in the pyroxene gneiss, and it is traceable as a key bed. The rock is white in colour and include a large amount of garnet. The gneissose structure is displayed by alingnment of garnet and biotite (Fig. 31).

Garnet gneiss is found to occur as a thin layer along the boundary between garnet-biotite gneiss and the other rocks in the neighbourhood of Hiroe Point. The rock is fine- to medium-grained, carrying spotted garnet crystals of reddish brown in white matrix. The foliation is not conspicuous. Constituent minerals are quartz, garnet and potassium feldspar, with a minor amount of plagioclase. Mafic minerals are scarce.

Porphyroblastic gneiss occurs as a layer at Hiroe Point. This rock is similar to the garnet-biotite gneiss in appearance, and is characterized by including porphyroblast of potassium feldspar. Matrix of porphyroblastic gneiss is fine-grained and reddish brown in colour. Constituent minerals are garnet, biotite, potassium feldspar, plagioclase and quartz.

Metabasites occur as thin layer or lens in garnet-biotite gneiss north of Mt. Hiroe.

In the geological map the pyroxene gneiss and garnet-biotite gneiss are arranged, forming a horseshoe shape convex to the north. Each formation in the gneissic rock dips convergently to the symmetrical axis of this horseshoe shape, and the strike varies almost parallel to the trace of the horseshoe. The horseshoe-shaped zonal distribution convex to the north represents a southerly plunging synform. This synform is displayed on the geological section (Fig. 5) and on the tectonic map (Fig. 6) by drawing a strike line

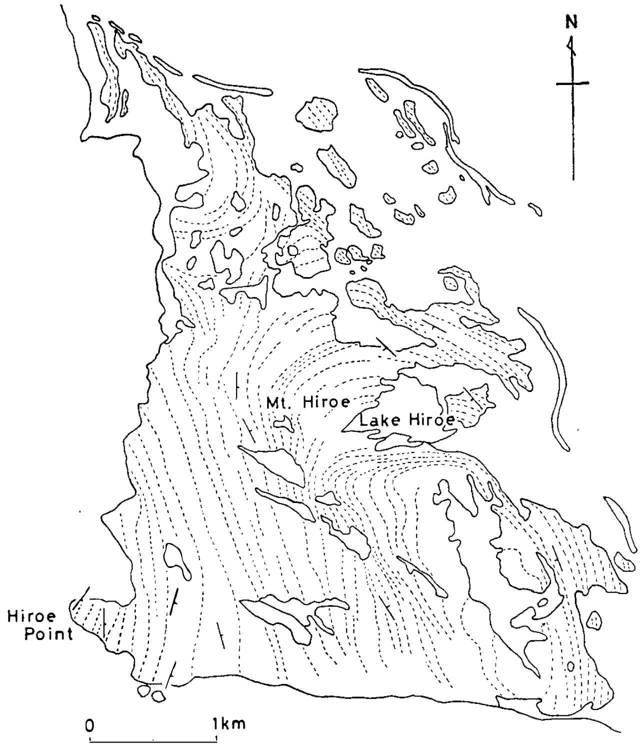

Fig. 6. Tectonic map of the Breidvågnipa area.

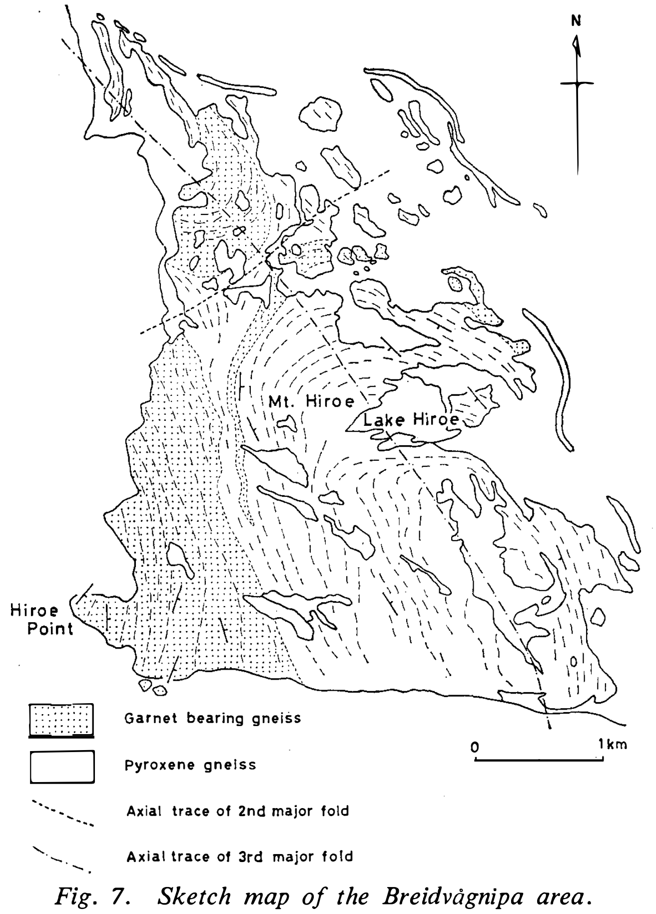

Fig. 7. Sketch map of the Breidvågnipa area.

observed on the aerial photograph. Corresponding to this horseshoe shape convex to the north, the other horseshoe with the common symmetrical axis is found in the northern part of the surveyed area, and it assumes a shape convex to the south. As shown on the tectonic sketch map (Fig. 7) summarized from Fig. 5 and Fig. 6 and from the aerial photograph (Figs. 42 and 43), it seems very likely that the synform originally trending N-S was deformed again to form a gentle bend with the fold axis of E-W trend. Thus, the synform of N-S trend was superimposed by the antiform of E-W trend. The N-S fold is a concentric flexure fold as shown in the geological section (Fig. 5), and the E-W fold is considered to be a concentric flexure fold, too.

2.4. **Skarvsnes area** (Figs. 8a and 8b)

The Skarvsnes area situated about 40 km south of the Syowa Station, East Ongul Island, is an ice-free area along the Lützow-Holm Bay coast, and gneissic rock is well exposed there and in its vicinity. This area is covered by a continental ice on the east; the highest altitude is 361.8 m above the sea level. This area had not been surveyed in detail, until the present writer studied in 1972. Age determination on the basement rocks of the Skarvsnes area has been carried out by NICOLAYSEN *et al.* (1961), KANEOKA *et al.* (1968) and MAEGOYA *et al.* (1968), and the results are listed in Table 5.

Table 5. Radiometric ages of rocks from the Skarvsnes area.

Sample No.	Locality	Rock	Mineral	Method	Age (m.y.)	Ref.
JARE 57110704	69°26′S, 39°34′E	Granitic pegmatite in dioritic gneiss	Biotite	Rb-Sr	510±30	1
As		Garnet biotite gneiss	Whole rock	K-Ar	363	2
A-04		Gneissic rock	K-feldspar	Rb-Sr	745	3

(1) NICOLAYSEN *et al.*, 1961.
(2) KANEOKA *et al.*, 1968.
(3) MAEGOYA *et al.*, 1968.

Geology of the Skarvsnes area is characterized by porphyroblastic gneiss, garnet-biotite gneiss and pyroxene gneiss, and by subordinate amounts of garnet-bearing granitic gneiss, garnet gneiss and metabasites.

Pyroxene gneiss is the most widespread especially in the medial part of this area. Typically, it is a uniformly fine- to medium-grained granulitic-textured rock with the dark colouration in a hand specimen. It contains hypersthene, quartz, potassium feldspar, plagioclase, hornblende and biotite, and rarely garnet. A poorly defined foliation is imported to the rock by the

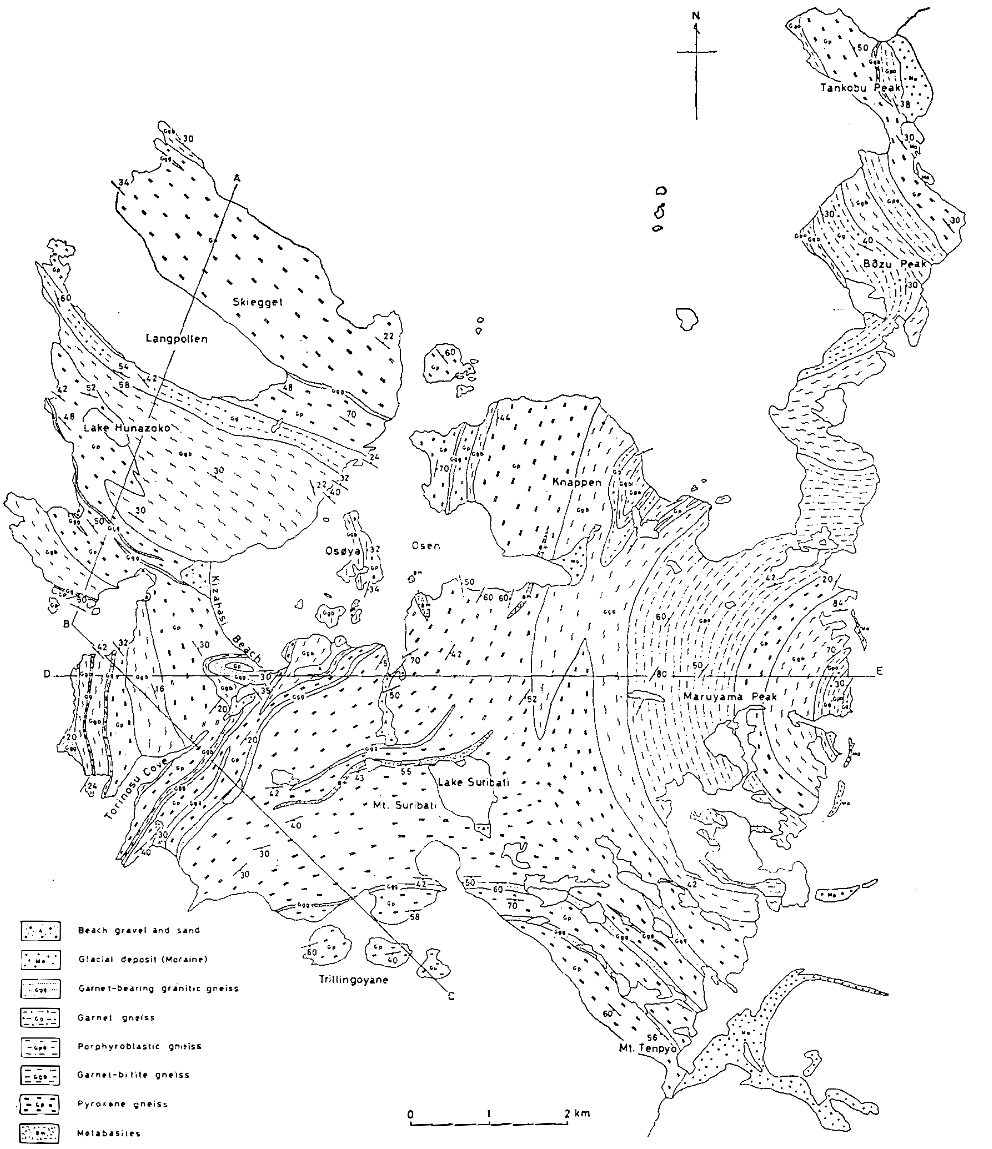

Fig. 8a. Geological map of the Skarvsenes area.

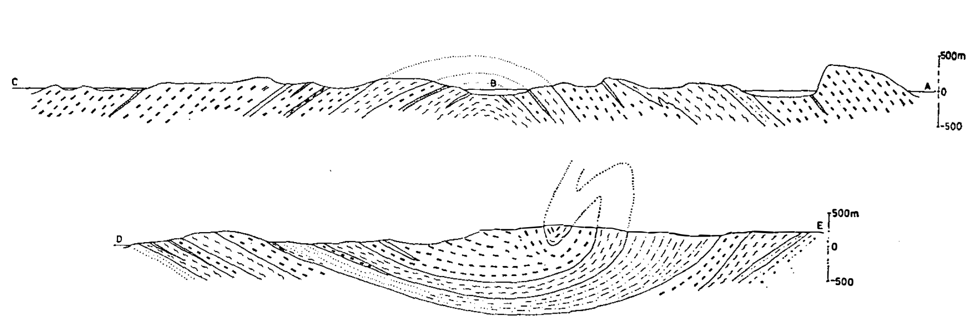

Fig. 8b. Geological section of the Skarvsnes area.

parallel orientation of mafic minerals and the elongated inclusion.

Garnet-biotite gneiss occurs on the western and eastern part of the Skarvsnes area (Fig. 28). The rock is light-coloured, but slightly reddish, fine- to medium-grained, and commonly has a granitoid texture. It contains predominantly quartz and feldspar ; biotite and garnet is commonly present. The rock possesses a well-defined large-scale banding due to concentration of biotite and garnet. It sometimes contains bands of pyroxene gneiss up to 2 or 3 m in thickness.

Garnet-bearing granitic gneiss is generally medium-grained, roughly equigranular, and consists essentially of pink or white feldspar, quartz and biotite, with garnet in minor amounts. Both potassium feldspar and plagioclase occur and either may be predominant ; perthitic structure is common in them. Biotite ranges from common to rare. A gneissose structure is usually distinct but some rocks are quite massive. The rock occurs as a thin layer and is employed as a key bed in the vicinity of the Torinosu Cove and Mt. Tenpyô.

Porphyroblastic gneiss occurs mainly in the vicinity of Maruyama Peak (Fig. 26). The rock is characterized by relatively large crystals of potassium feldspar, approximately 4 cm in diameter. It is fine-grained and has a distinct gneissose structure displayed with concentration of biotite flakes. Major constituent minerals are quartz, potassium feldspar, plagioclase, biotite and garnet. The rock is very similar to the garnet-biotite gneiss in appearance, and these two rocks are probably closely related in their genetical process.

Garnet gneiss occurs at Langpollen, Knappen and the eastern part of this area. The rock has white-coloured potassium feldspar as the most characteristic constituent. It is medium- to rather coarse-grained, and composed mainly of quartz, plagioclase, perthite and garnet, with a small amount of garnet and rare biotite. The rock is quite massive and a gneissose structure is not distinct.

Metabasites occur at Osen within garnet-biotite gneiss as many ovoid-shaped bodies (Fig. 35) They are usually black or dark green in colour.

As is distinctly shown on the geological map, gneiss formations occurring at and around Maruyama Peak show a semicircle distribution convex to the west (Fig. 40), and those of the Kizahasi Beach and Osøya convex to the east. The former is an antiform plunging to the east. Gneiss formations in the vicinity of Trillingoyane and Mt. Tenpyô also show a semicircle shape convex to the north. Formations east of this gneiss dip southwesterly, whereas those west of this do southeasterly, forming a synform plunging to the south. Axial trace of this synform passes through Osen. As is illustrated in a sketch map (Fig. 9), the E-W trending antiform is superimposed by N-S trending synform. The sketch map shows an interference pattern that antiform and synform were superimposed one another at right angles.

In Knappen, isoclinal minor folds are observed. These folds in a garnet-

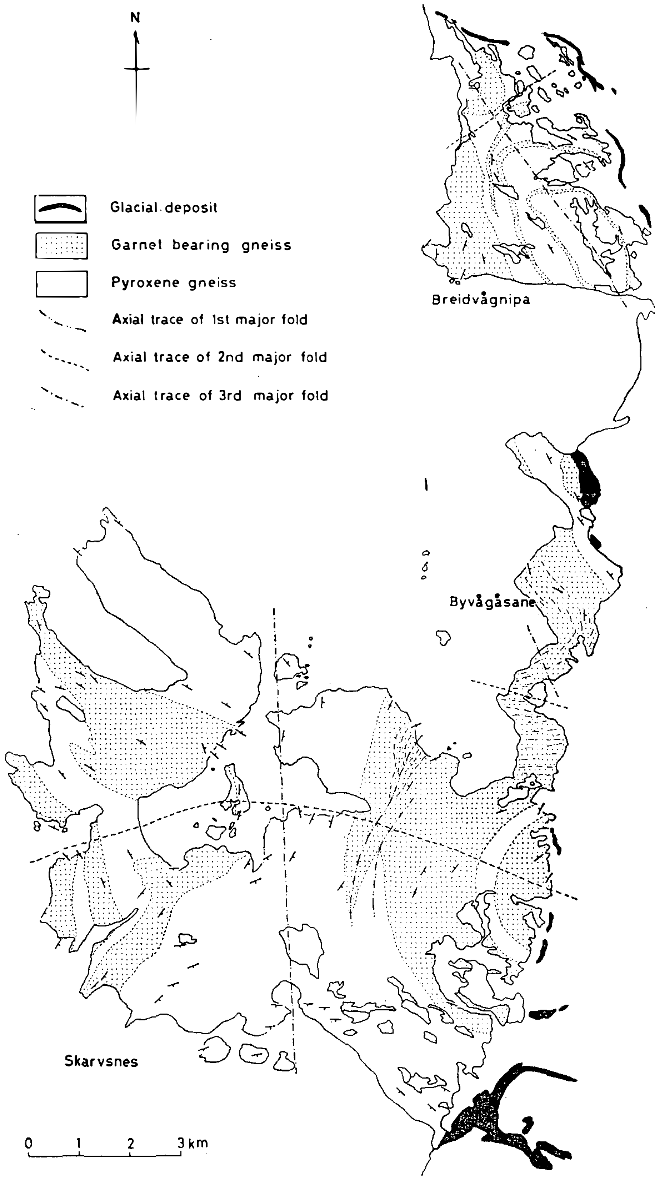

Fig. 9. Sketch map of the Skarvsnes area.

biotite gneiss formation are involved in the E-W trending antiformal fold plunging to the west mentioned above. They show, as a whole, a synformal structure and are flow fold. This synform structure itself is a superimposed fold which was developed in the rocks previously folded.

In the Byvågåsane area and northeast of Skarvsnes, the trend of gneissic rock strikes N30°W and dips 50° to the east. As shown on the sketch map (Fig. 9), this structure is interpreted as an evidence of the superimposed fold established by E-W synform and N-S antiform.

The axial plane of the E-W trending fold is slightly deformed, wheras that of the N-S trending large-scaled fold is planar. This fact suggests that these fold sets were formed separately. The N-S trending small-scaled fold of the Knappen area had been refolded by a later movement with the E-W axial trace of fold, which in turn was refolded again by another movement forming the N-S trending large-scaled fold, thus making it possible to discriminate three phases of folding in this Skarvsnes area. If the N-S trending small-scaled folds are referable to the first fold designated before as F_1, the E-W fold and the N-S trending large-scaled fold are assigned to the second fold (F_2) and the third fold (F_3), respectively.

2.5. **Kjuka area** (Fig. 10)

The Kjuka area is approximately 8.7 square km wide and situated about 65 km south of the Syowa Station, East Ongul Island. No geological investigation has been carried out, untill the present writer studied this area in 1973. Only one map of 1 : 250,000 series, "Lützow-Holm Bay", was available at the time of the survey. The area was, however, photographed aerially by the 6th and 10th JARE (Fig. 44).

Basement rocks in this area are pyroxene gneiss and garnet gneiss, with

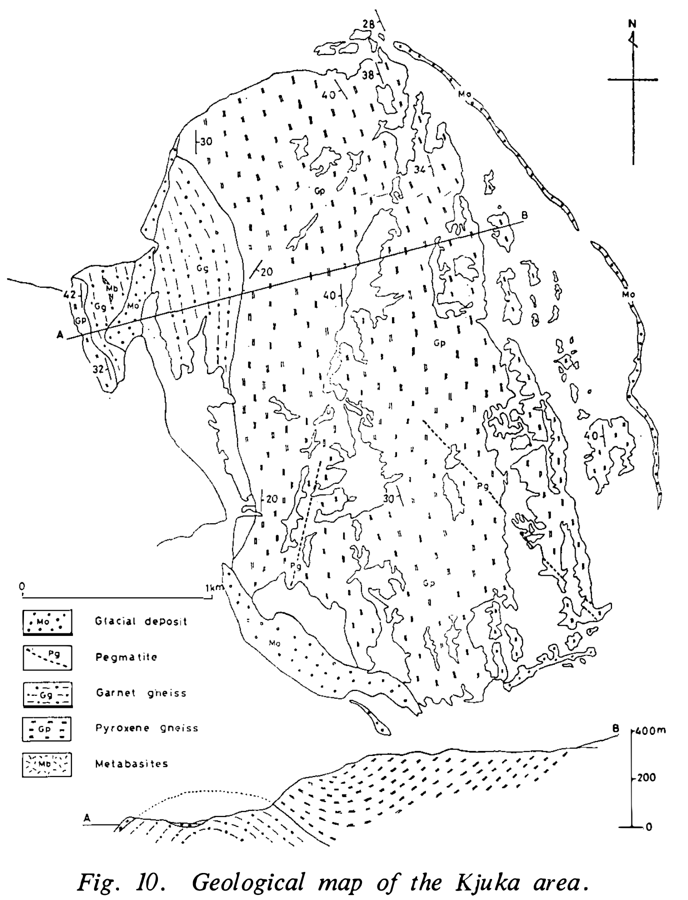

Fig. 10. Geological map of the Kjuka area.

subordinate amounts of metabasites and pegmatite. In a small lens of metabasites exposed at the western part of the Kjuka area are contained large amounts of pyroxene.

Pyroxene gneiss occupies the most of outcrops in the Kjuka area (Fig. 36). The rock is massive and dark brown in colour, and composed of plagioclase, quartz, biotite, hornblende and pyroxene. It is a homogeneous, and fine-grained rock with a slightly foliated structure.

Garnet gneiss occurs in the western part of the Kjuka area. It is a medium-grained, massive and white to pink granitic rock, composed of quartz, potassium feldspar, plagioclase and biotite, with a minor amount of garnet.

The gneissic rocks west of the Kjuka area strike N-S and dip to the west, whereas the garnet gneiss strikes N-S and dips to the east. In the garnet gneiss there are many small-scaled similar folds with N-S axial traces. Pyroxene gneiss east of the Kjuka area strikes NNW-SSE and dips to the west. These structures represent a combination of antiform and synform (Fig. 10).

2.6. Skallen area (Fig. 11)

The Skallen area, including Skallevikholsen, is located about 72 km south of the Syowa Station of JARE, East Ongul Island. This area was previously survey in detail (TATSUMI and KIKUCHI, 1959a, b ; TATSUMI *et al.*, 1964 ; TATSUMI and KIZAKI, 1969 ; YOSHIDA and ANDO, 1971 ; YOSHIDA, 1970). The present writer studied this area again in 1972. Radiometric age data obtained on the rocks of this area are listed in Table 6 (NICOLAYSEN *et al.*, 1961 ; SAITO *et al.*, 1961).

Garnet gneiss is widely distributed at the Skallen area (Fig. 25). The rock is generally white and massive, sometimes alternating with metabasite (Fig. 33). Predominantly composed of quartz and feldspar, this gneiss commonly contains garnet together with biotite in a small amount. In places, it

Table 6. Radiometric ages of rocks from the Skallen area.

Sample No.	Locality	Rock	Mineral	Method	Age (m.y.)	Ref.
JARE 57102622	69°38′S, 39°18.5′E	Granitic pegmatite in dioritic gneiss	Biotite	Rb-Sr	530±16	1
		Granitic pegmatite in dioritic gneiss	Euxenite	Pb^{206}/U^{238}	485± 6	2
		〃	〃	Pb^{207}/U^{235}	468±12	2
		〃	〃	Pb^{208}/U^{232}	375±27	2
		〃	〃	Pb^{207}/U^{206}	458±21	2

(1) NICOLAYSEN *et al.*, 1961.
(2) SAITO *et al.*, 1961.

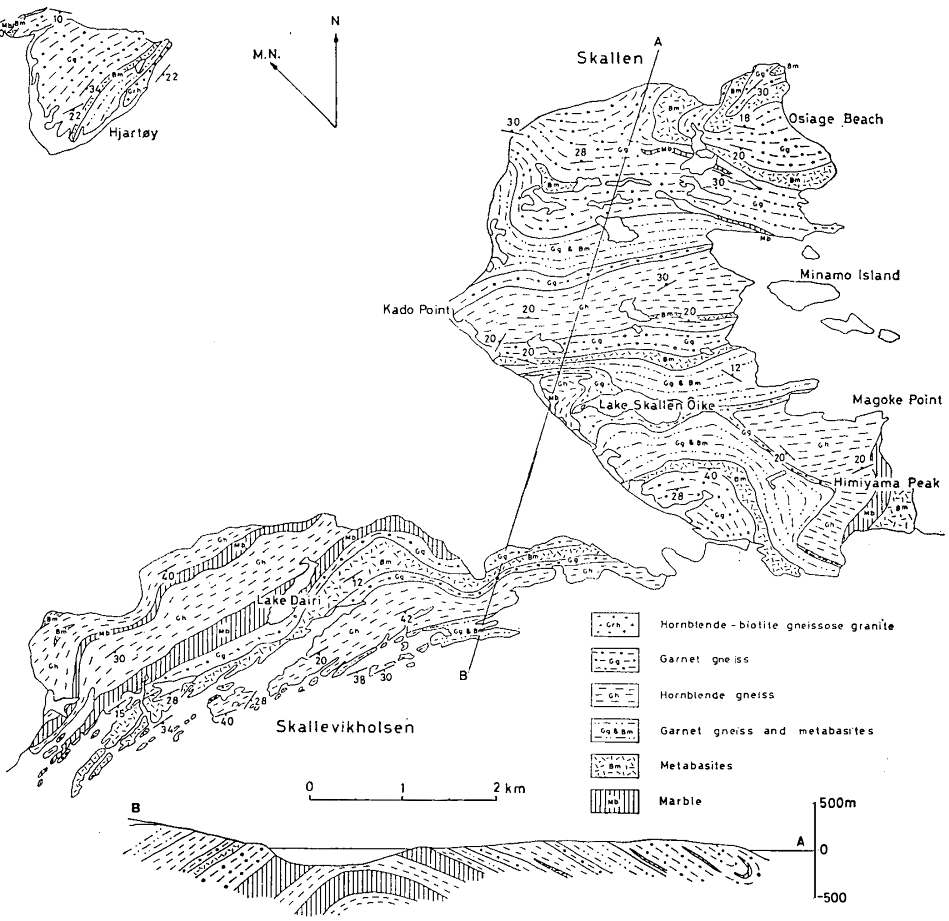

Fig. 11. Geological map of the Skallen area.

shows a faint gneissose structure.

Metabasite occurs as a thin layer in garnet gneiss, generally concordant with the foliation of the gneiss ranging in width from less than 1 m to 2 m. The rock is composed mainly of pyroxene ; biotite of muscovite occurs in a small amount.

Hornblende gneiss, abundantly developed in Skallevikholsen, is a uniform fine- to coarse-grained granulitic textured rock with gray colour in a hand specimen. It consists of quartz, potassium feldspar, plagioclase and hornblende, and rarely garnet and biotite. The rock commonly has a foliation along which concentration of hornblende and biotite flakes are often found. The texture is characterized by the alignment of flat grains of quartz or feldspar.

Marble beds have been observed in the gneissic complex at a number of localities. The marbles range from white and massive marble to granular brittle marble, and impure marble characterized by the presence of minerals such as diopside, pargasite, phlogopite and scapolite is also reported from this area (Tatsumi *et al.*, 1964; Banno *et al.*, 1964). Irregular masses, lenses, bands or veins within the marbles have been altered to skarns.

Hornblende biotite gneissose granite occurs in a small amount in Hjartoy. It is characterized by grains of pink potassium feldspar.

The gneisses have a prominent compositional layering or foliation, defined by alternation of garnet gneiss, metabasite, hornblende gneiss or marble layers on all scale from a fraction of a centimeter to several tens of meters. In garnet gneiss and hornblende gneiss, the foliation is accentuated by parallel flat lenticles of quartz.

Rocks in the northern part of the Skallen area exhibit an NE striking axis of fold. This direction of folding is recognized as crenulations in metabasitic intercalations within garnet gneiss; the intervening leucocratic intercalations show similar deformations. This type of fold is interpreted to be of the first phase of deformation designated as F_1.

From the central part to the southern termination of the Skallen area, all gneisses in the northern side of the Lake Skallen Ôike dip invariably northerly, while those in the southern side southerly. Marble is recognized under the hornblende gneiss at the west of the Lake Skallen Ôike and the east to Himiyama Peak. This structure is a gentle curving concentric fold, and is assigned to an antiform with a horizontal E-W fold axis. From the comparative-tectonic viewpoint, this folding corresponds to F_2 fold of the Skarvsnes area. Gneiss formations of Skallevikholsen are developed in a parallel zonal distribution trending ENE-WSW, and dipping to the south, and show a homoclinal structure.

3. Geological Structure

3.1. Superimposed folding

In the Skarvsnes and Breidvågnipa area, three generations of macroscopic folds are recognized. They are successively designated as F_1, F_2 and F_3 for the first, the second and the third major fold, respectively. F_1 folds with a wave length of 1.5 km are tight or isoclinal and show a strongly developed axial-plane schistosity, while F_2 folds are open with an associated strain-slip cleavage which deforms the earlier schistosity. F_2 folds are superimposed upon F_1 fold. F_3 folds are open in structure, too, and were superimposed upon F_2 folds. The megascopic features of F_1 folds are observed at East Ongul Island, Langhovde, Skarvsnes, Kjuka and Skallen. In Knappen of the Skarvsnes area F_1 folds appear to have been arched over a later antiformal axis. Erosion has worn away their higher part, leaving a lower part or core of the structure there. Near the hinge of F_1 synform, disharmonic folds are observed (Fig. 29). They are minor in scale and was formed during a stage of F_1 fold. When competent and incompetent rocks alternate, folding is commonly accompanied by formation of minor fold within some of the units. Disharmonic minor folds described above are probably drag fold of this kind. A recumbent isoclinal antiform (F_1) is observed on East Ongul Island (Fig. 2). Although the deformation pattern assignable to F_1 fold is observed in the East Ongul Island, no evidence of later modification is found there. According to KIZAKI (1962), the structure associated with many small folds is found to occur in a zone about 1 km wide and 6 km long in the eastern part of the island. It is clear that drag folds were formed by shearing at the time of folding.

On the northern part of the Langhovde area, the first major folds (F_1) are observed at Mt. Tyôtô and around the Kominato Inlet. These first folds are isoclinal in form with a wave length of 2 km. An axial trace of F_1 passing through Mt. Tyôtô is curved by later F_2 fold (Fig. 41). In the vicinity of Mt. Tyôtô the distribution pattern of pyroxene gneiss assumes

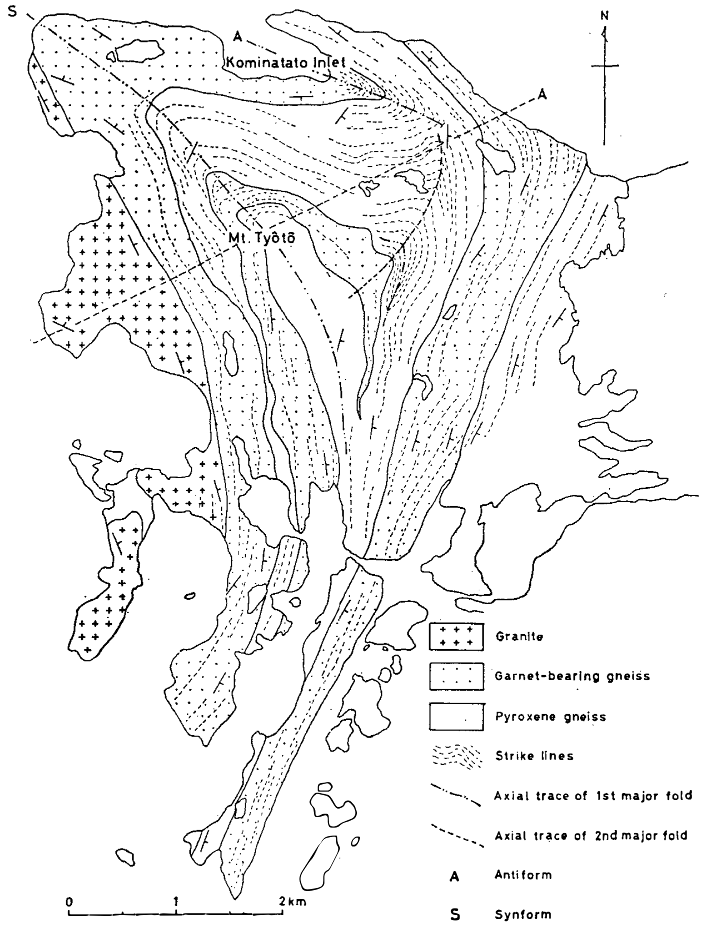

Fig. 12. Sketch map of the northern part of the Langhovde area.

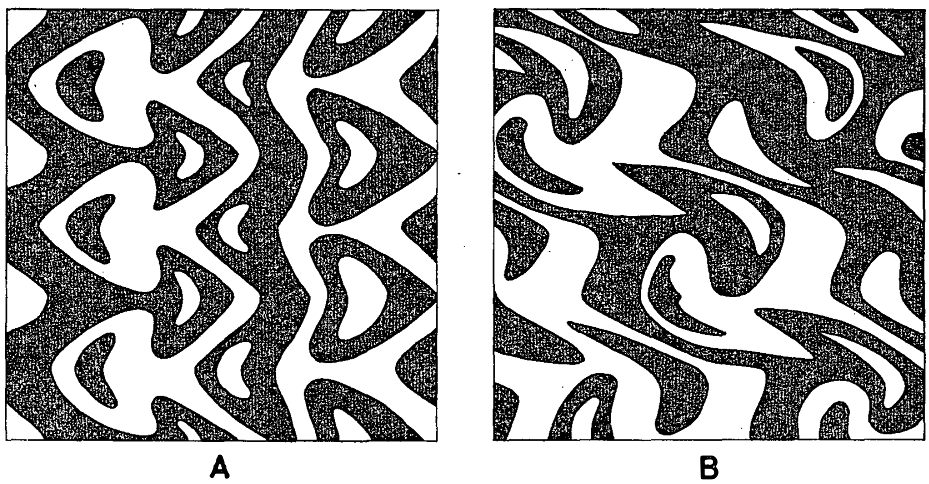

Fig. 13. Interference pattern produced by two successive foldings: A shows symmetric crescents and mushroom-like forms, B shows asymmetric forms.

a crescent shape (Fig. 12). If two sets of simple folds cross one another at right angles, the pattern thus produced shows on a plane perfectly symmetric mirror-image forms on either side of the axial trace of the second fold (Fig. 13-A). If they do not cross exactly in this way, the two-dimensional interference pattern of crescents and mushroom-like forms are asymmetric (Fig. 13-B). Fig. 14-1 shows a set of isoclinal intraformational folds whose axial

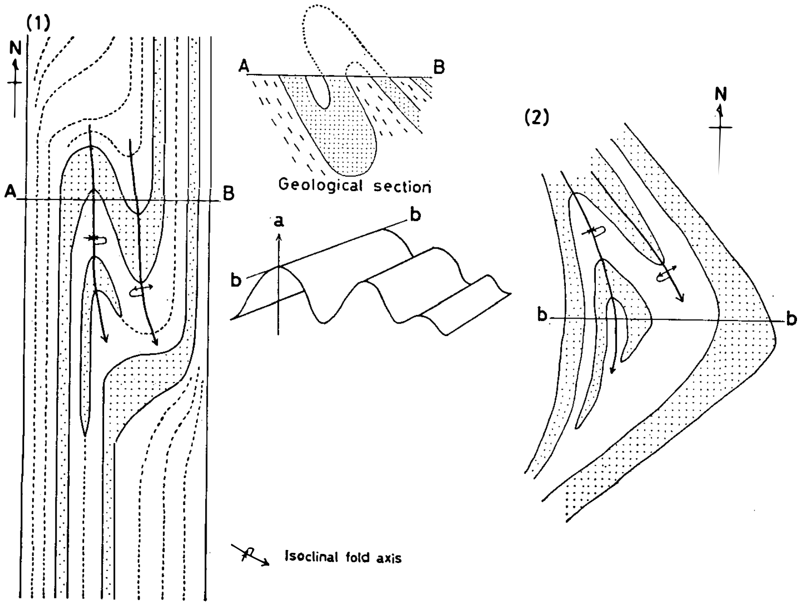

Fig. 14. Interference pattern of the Langhovde area: (1) illustrates the original form of the first fold, (2) shows the interference pattern which results from the superimposition of another deformation on the fold of (1).

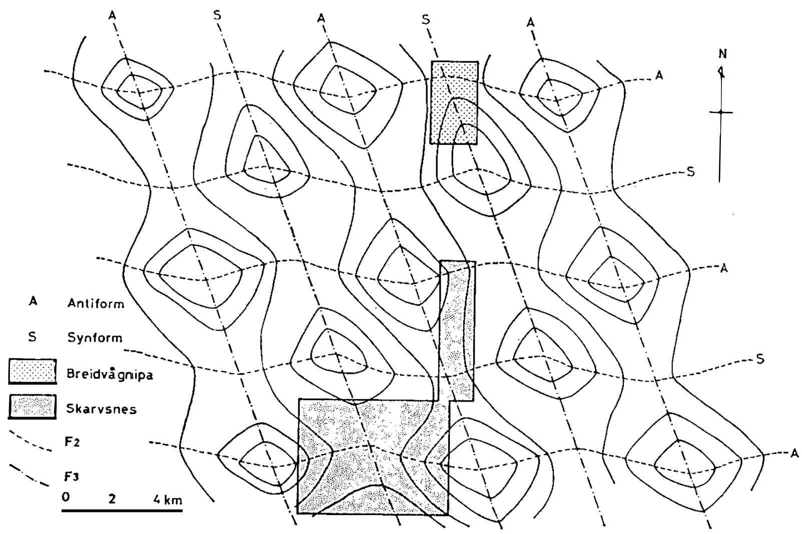

Fig. 15. Interference pattern in the vicinity of the Skarvsnes area and the Breidvågnipa area.

traces trend N-S and axes plunge to the south. Fig. 14-2 shows the result of superimposing on the first folds a wave form produced by heterogeneous simple shear with shear plane ab, and flow direction a. As a result of this flow of material the first folds are distorted and their limbs become refolded about new axial directions. During this kind of refolding, drag fold is developed in the pyroxene gneiss of the southern side to axial trace of F_2.

On the Skarvsnes and Breidvågnipa areas, F_2 axial planes are slightly deformed and F_3 axial planes are planar, it is reasonable to conclude that these fold sets were formed separately. A set of approximately E-W trending folds were developed during the second folding, and these were superimposed in the F_3 time by another set of folds whose axial traces trended approximately N-S. F_3 fold in Breidvågnipa assumes clearly a horseshoe shape and its axial trace runs N30°W. If two sets of folds cross obliquely one another, the two dimensional interference patterns are asymmetric as in Fig. 15. Wherever the antiformal third folds are superimposed on and across an antiform of the second time, there is a common culmination in both sets of folds resulting in the formation of a dome-like structure. Similarly, crossing synforms produce a common depression or a basin structure. Where antiform of a fold set crosses synform

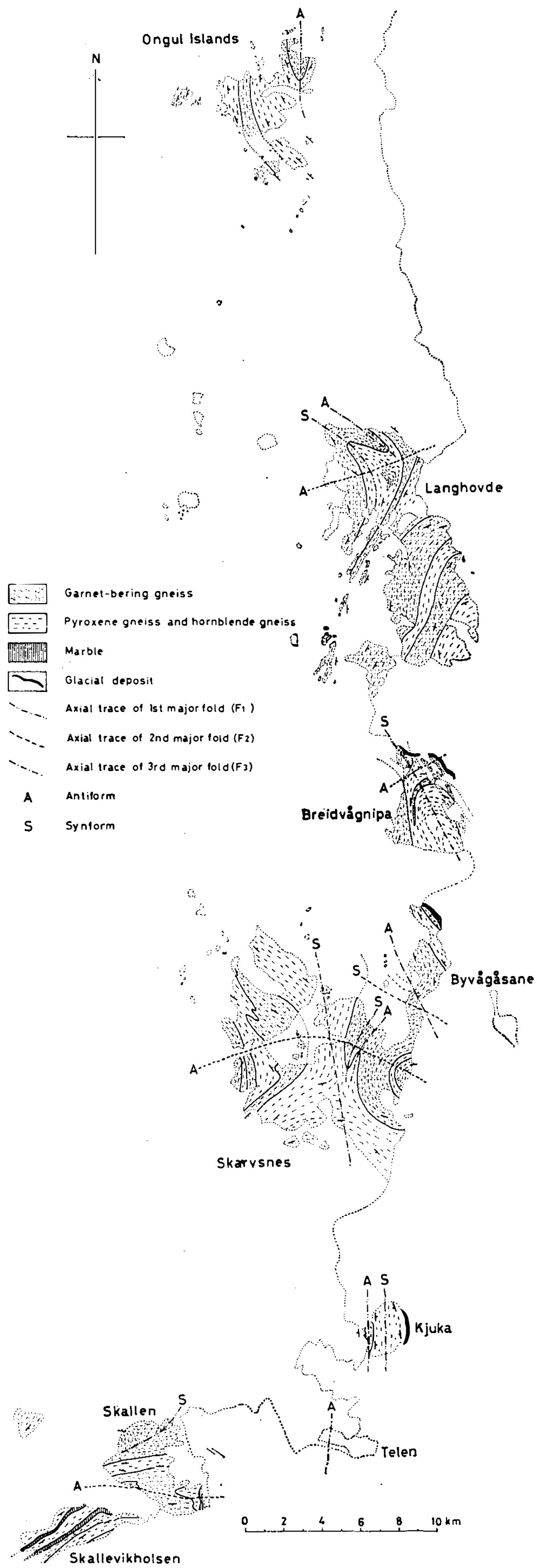

Fig. 16. Tectonic map of the Lützow-Holm Bay region.

of another set, the antiformal hinge shows a culmination. Where this occurs, a saddle structure develops on the surface. Dome-like structures on the eastern and western sides of the Skarvsnes area are found in such a structural situation as a common culmination where two sets of antiform cross. Similarly, basin-like structure on the Breidvågnipa area appears in depression where the two sets of synform cross.

As shown in Fig. 16, F_2 folds were developed in the Langhovde, Breidvågnipa, Skarvsnes and Skallen areas. They are flexural fold with a wave length of about 7 km having an axial trace trending E-W. F_3 folds were developed in the Skarvsnes and Breidvågnipa areas. They are also flexural fold with a wave length of about 10 km and with an axial trace trending N-S.

3.2. Fracturing

A conspicuous feature of the megascopic structure is strong lineaments recognizable in almost all of ice-free areas. Indeed, the present configuration is due in large part to physical weathering along these WNW and ENE planes of weakness. On aerial photographs, two principal classes of fractures can be recognized: major fractures and minor ones. As to length, the one grades into the other. An arbitrary unit of length for the minor fractures is 1 km. The major fracture, on the other hand, ranges 3 to 6 km in length. They are almost planar, regular and persistent. Although there are no apparent movement along the fractures, the lineament with WNW-ESE trend through Maruyama Peak of the Skarvsnes area exceptionally furnishes an evidence of lateral movement about 10 m in amount. The azimuth frequency diagrams of lineaments are shown in Fig. 17. The Lützow-Holm Bay region exhibits a fracture

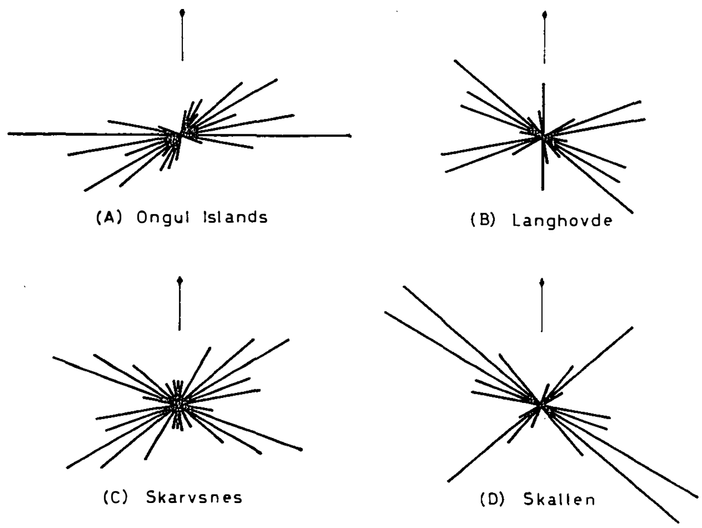

Fig. 17. Azimuth frequency diagrams of lineament of the Ongul Islands, Langhovde, Skarvsnes and Skallen areas.

system in which the dominant trend is represented by N60°E and N60°W lineaments. Their conjugate shear angle is approximately 60°, and this suggests a regional compression under the intermediate overburden condition as the force system responsible for the pattern. The coastal range of the Lützow-Holm Bay appears to have been affected by E-W horizontal compression during the stage of fracturing as showing Fig. 18.

In all probabilities, these lineament directions are closely associated with the fold axis of F_3 folds. It is reasonable to assume that in the stress field of the F_3 stage the maximum compressive stress was E-W horizontal and perpendicular to F_3 axial plane striking N-S. Two sets of joints that intersect at a high angle to form a conjugate system are often considered shear fractures, especially if they are symmetrically disposed about the strain

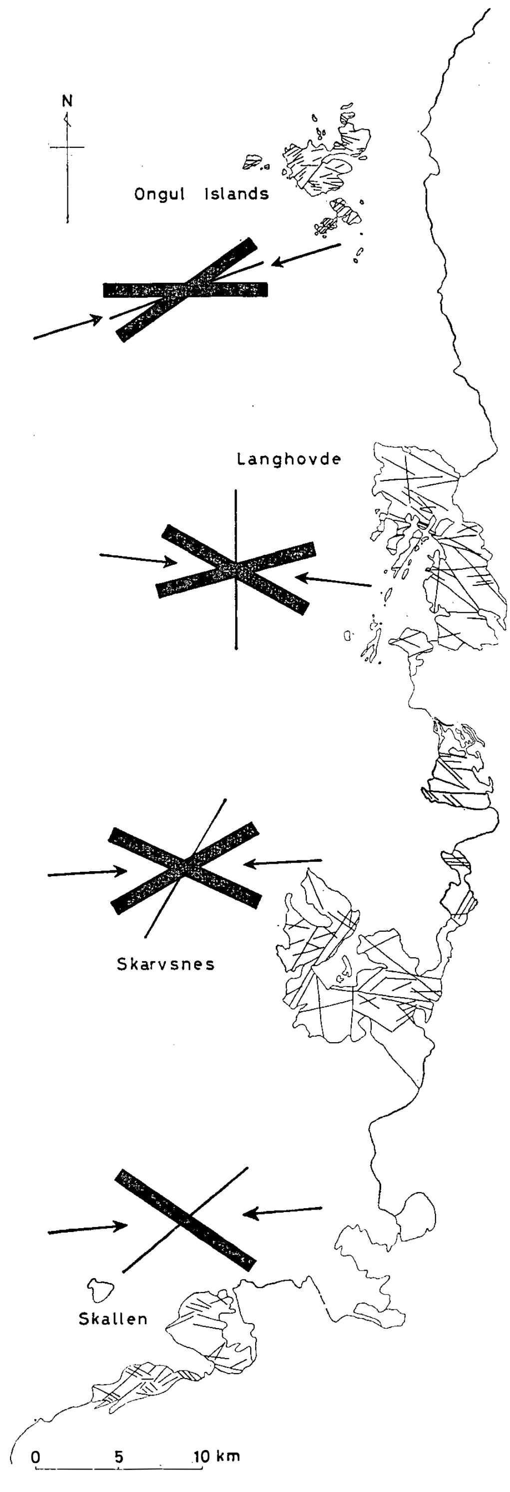

Fig. 18. Fracture pattern, azimuth frequency diagram and stress field for individual areas in the Lützow-Holm Bay region.

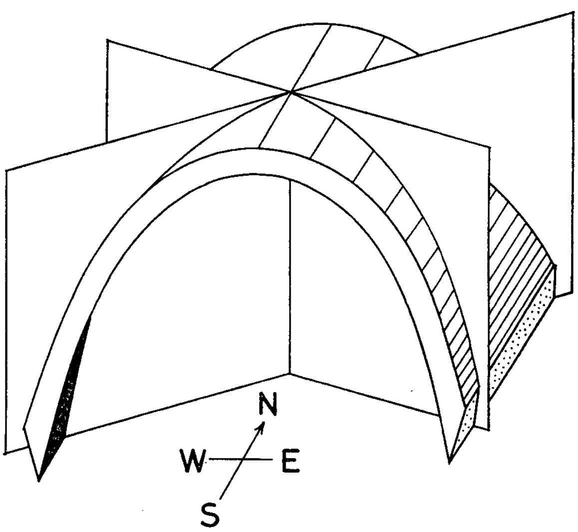

Fig. 19. Block diagram of fold with a conjugate set of joint system.

axes. Fig. 19 is a schematic block diagram of an area in which horizontal F_3 fold axes trend N-S. There are two sets of vertical joints, one of which strikes N60°W, and the other N60°E. The attitude of the fold indicates that the compressive stress was acting along an E-W direction. In the light of experimental observations, the joints could be interpreted as shear fractures due to a compressive stress acting in an E-W direction. Therefore, the E-W horizontal compressive stress of fracturing corresponds to the stress field of F_3 fold. At least it can be said that the directional pattern of stress field was retained unchanged throughout the entire stage of folding and fracturing. The fracturing was probably associated with the uplift of the post-F_3 tectonic movements, and the joint sets were developed in the metamorphic rocks as pressure and/or temperature were decreased.

3.3. Polyphase deformation on the East Antarctic shield

Rock types, structural trend and radiometric ages of the East Antarctic shield indicate a complicated early Precambrian history probably involving several orogenies. KLIMOV *et al.* (1964) recognized three principal rock groups in East Antarctica ; the pre-Riphean to basement complex, Riphean to Lower Palaeozoic strata, and Middle Palaeozoic to Mesozoic strata. The basement complex consists mainly of high-grade metamorphic rocks of the granulite and amphibolite facies accompanying the diverse plutonic intrusive rocks. KRYLOV (1972) recognized eleven age groups in the Antarctic Continent ; about 3,000, 2,000-1,700, 1,600-1,500, 1,200-1,000, 900-800, 700-600, 570-440, 380-360, 260-220, 200-160, and 10-0 m.y. Among them, the radiometric ages of East Antarctic rocks suggest that they belong to the age group older than 380-360 m.y. Most of age determination carried out on them fall in the 570-440 m.y. group, and the remainings belong to the 1,200-1,000 m.y. group of the East Antarctic shield (RAVICH, 1972 ; KRYLOV, 1972). The rocks of the 570-440 m.y. group occur in all area of the crystalline basement, and they are particularly widespread in Queen Maud Land. This age corresponds to the Ross orogeny which formed the Transantarctic Mountains and the other major fold systems of the continent. The rocks of the 1,200-1,000 m.y. group occur in Bunger Hill, the Windmill Oasis, the Prudz Bay and the Transantarctic Mountains (KRYLOV, 1972). These rocks are considered as the basement of Ross geosyncline formed at the time of the Nimrod orogeny.

On the Lützow-Holm Bay region, over 40 radiometric age determinations have been carried out on the rocks and minerals. YANAI and UEDA (1974) indicated two main age groups, 500 m.y. and 700-1,100 m.y., and suggested at least two period of metamorphism. The ages of the 700-1,100 m.y. group were obtained by Rb-Sr method on potassium feldspar in gneissic rock from the Lützow-Holm Bay region (MAEGOYA *et al.*, 1968). The rocks belonging to the 500 m.y. group are most extensively distributed and distinguished from the other of the East Antarctic region. Since the age determination was performed with the K-Ar method, the result does not show its true age, but represents the time of later tectonic events that disturbed the initial argon balance. And hence it may be responsible for a considerable rejuvenation of the crystalline basement rocks, and it was the time of a major tectonic event in East Antarctica. The rocks of the 500 m.y. group were developed retrogressively from the oldest granulite facies rocks as a result of a later stage of metamorphism under the amphibolite facies condition ; in other words, they are products of polymetamorphism. This is clearly recognized on their mineral assemblages typical of the polymetamorphic rocks.

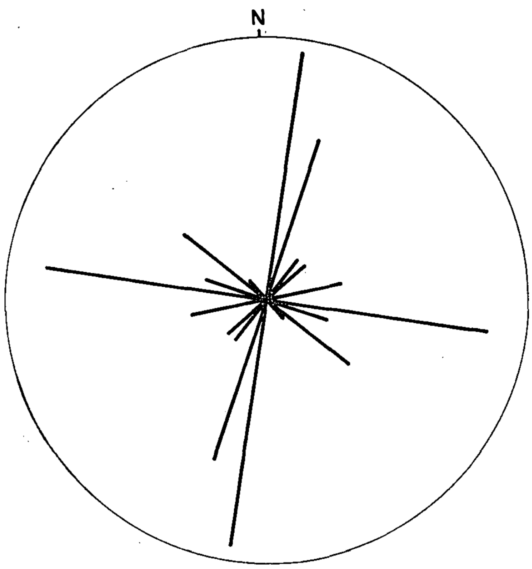

Fig. 20. Azimuth frequency diagram of axial traces in Queen Maud Land, East Antarctica.

Forty five axial traces are observed on geological maps reported from an ice-free area of Queen Maud Land, East Antarctica. Trend of the axial traces is graphically shown in an azimuth frequency diagram (Fig. 20). The diagram shows two maxima, *i.e.* N-S and E-W trend. N-S maximum corresponds with the trend of axial trace of F_1 or F_3 fold in the Lützow-Holm Bay region. E-W maximum corresponds definitely with the trend of axial trace of F_2 fold. If Queen Maud Land received the same tectonic movements as those of the Lützow-Holm Bay region, it has undergone more than three times of tectonic movements, at least. Trend of F_2 fold at Queen Maud Land corresponds closely to the trend of the Transantarctic Mountains (Fig. 21). The axial trace in the Transantarctic Mountains region is almost parallel to the trend of the Transantarctic Mountains themselves formed by the Ross orogeny. It is thought that the stress field of the Ross orogeny was widespread in the same fashion over the whole East Antarctica. The Ross orogen was formed during the early Palaeozoic (500 m.y.) and extends from the northern Victoria Land across the continent near to the Weddell Sea. Judging from this age, coeval with the rock samples of Queen Maud Land dated at 500 m.y., it is considered that the East Antarctica shield during this period underwent the same tectonic movement as the Ross orogeny.

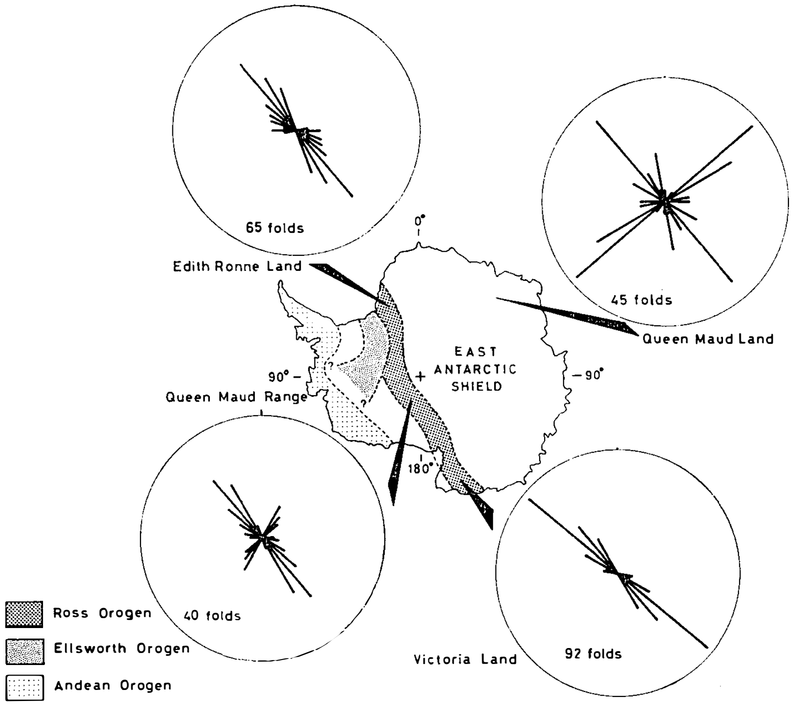

Fig. 21. Structural trend in the Antarctic shield and Transantarctic Mountains. Azimuth frequency diagrams represent axial trace published at Antarctic Geology (ed. ADIE, 1964), Geological Maps of Antarctica (ed. BUSHNELL, 1970) and Antarctic Geology and Geophysics (ed. ADIE, 1972).

Deformation belonging to F_1 fold, perpendicular to the trend of the Transantarctic Mountains, is the result of a tectonic movement before the Ross orogeny. On the other hand, F_2 fold, parallel to the Transantarctic Mountains, represents another tectonic movement referable to the Ross orogeny. F_3 fold, also perpendicular to the Transantarctic Mountains, shows a tectonic movement probably after the Ross orogeny.

3.4. Rock deformation in relation to metamorphism

Three generations of macroscopic folds are recognized in the Lützow-Holm Bay region. Distinctive characters of the three types of fold produced are as follows:

1. Recumbent isoclinal folds (F_1) with a wave length of 2 km and an axial trace trending N-S.
2. Concentric fold (F_2) with a wave length of about 5 km and an axial trace trending E-W.
3. Concentric fold (F_3) with a wave length of about 7 km and an axial trace trending N-S.

Distinction between F_1 and F_2 folds is made on the basis of style and orientation. Distinction between F_2 and F_3 folds is made solely on the basis of orientation. Fracturing is recognized to have taken place after F_3 fold. An azimuth frequency diagram of fractures shows the fractures to be conjugate sets and the stress field very similar to that of F_3 fold. During the tectonic history, ductile behaviour of rock formations in the highest grade of metamorphism changed to brittle in nature along with decrease of temperature and pressure. In fact, the wave length had been increased with decrease of the metamorphic grade. Type of rock deformation changed from flow fold into flexure fold as metamorphism retrograded. Comparatively, rock formation was incompetent in nature under the highest grade of metamorphism (the granulite facies) and competent under the lower grade of metamorphism (the amphibolite facies).

As was described and discussed, four kinematic and/or metamorphic episodes are superimposed. Relicts of the event earlier than F_1 folds are hardly confirmed ; probably they had been completely faded away. When metamorphism and deformation gradually progressed up to the granulite facies, records of tectonic movements before the highest grade of metamorphism might be obliterated.

According to GRINDLEY (1972), the Miller range in the central Transantarctic Mountains was occupied by the metamorphic rocks of the amphibolite facies. Recumbent isoclinal folds (F_1) are recognized during the early stage of metamorphism. The folds show a style, probably of similar fold, with rounded hinges in psammitic layers and sharp hinges in pelitic layers. Moderately to tightly appressed folds (F_2) were formed during the amphibolite facies metamorphism. This type of folding has been termed flexural flow folding by DONATH and PARKER (1964). Flow has taken place parallel to the limbs probably by crystal glinding, solution and recrystallization of minerals at moderately high temperatures and pressures. Moderately to tightly appressed folds (F_3) were formed during the later stage of metamorphism. In addition, open folds (F_4) were formed during the retrogressive metamorphism.

All rocks and minerals are believed to have behaved themselves as a brittle and ductile solid depending on the given pressure and temperature condition. The transition point of the behaviour in the progressive metamorphism. On the Lützow-Holm Bay region the transition from the fold of similar type to that of concentric type occurred between the granulite facies and the amphibolite facies. But the transition of the tectonic property of the rock formations in the Miller Range took place in a metamorphic condition lower than the amphibolite facies.

4. Summary

The Lützow-Holm Bay region, East Antarctica, was surveyed as a geological operation of the 13th JARE, 1971-73. The structures of the Lützow-Holm Bay region are summarized as follows:

(1) In the Lützow-Holm Bay region, crystalline basement is extensively exposed trending approximately N-S, and it consists of pyroxene gneiss, garnet-biotite gneiss, hornblende gneiss, garnet gneiss, garnet-bearing granitic gneiss, amphibolite, pyroxenite, marble and granites. The Ongul Islands, Langhovde, Breidvågnipa, Skarvsnes, Kjuka and Skallen areas were geologically investigated in detail, and the geological maps of these areas are presented.

(2) The gneissose rocks in East Ongul Island are zonally distributed assuming a horseshoe shape convex to the south. The geological structure is an isoclinal recumbent antiform plunging to the south.

(3) In the Langhovde area, the gneissose rocks show a superimposed fold. F_1 fold, its wave length and its amplitude being 2 km and 2 km, respectively, was refolded at the time of formation of F_2 fold. This folding structure shows a gentle antiform plunging to the east.

(4) In the Breidvågnipa area, the gneissose rocks are distributed assuming a horseshoe shape convex to the north. The geological structure is a concentric flexure fold with gentle curve and synform plunging to the south. This fold (F_3) refolded the earlier fold (probably F_2), whose style and orientation are uncertain because of the overlying ice.

(5) In the Skarvsnes area, relation between F_1, F_2 and F_3 folds was observed in detail. F_1 folds are intrafolial isoclinal folds with a large amplitude, locally at several hundred meters, and a wave-length about 2 km. F_2 folds are mostly open flexural slip folds with an axial trace trending E-W, amplitude of 2 km and wave length of 6 km. F_3 folds are flexural slip fold with an axial trace trending N-S, amplitude of 2 km and wave length of 10 km; they are very similar in style to F_2 folds. F_2 folds and F_3 folds cross one another at right angles.

(6) In the Kjuka area, pyroxene gneiss and a subordinate amount of garnet gneiss crop out showing the fold structure trending N-S. The folds are gently wavy and open fold. In addition, there are many minor similar fold with N-S trending axial trace.

(7) In the Skallen area, gneiss formations show an antiform structure with a horizontal fold axis. The structure represent a gentle curving concentric flexure fold.

(8) In the Lützow-Holm Bay region, a fold system composed of F_1, F_2 and F_3 folds is recognized. F_1 folds are refolded by F_2 folds, and F_2 folds are again refolded by F_3 folds.

(9) F_1 folds are formed in the earliest stage of the tectonic evolution under the metamorphic condition of granulite facies in this region, showing similar fold with an axial trace trending N-S. F_2 folds were formed in the second stage under the metamorphic condition of amphibolite facies, showing concentric flexure fold with an axial trace trending E-W. F_3 folds were formed by a tectonic movement of the third stage, showing concentric flexure fold with an axial trace trending N-S.

(10) Joint sets are well developed throughout the Lützow-Holm Bay region. The present lineaments are mostly due to physical weathering along these N60°E and N60°W planes of weakness. Joint sets which strike N60°E and N60°W are well developed and form a conjugate system. The direction of compressional stress is perpendicular to the axial plane of F_3 fold. The jointing was probably associated with upheaval of the East Antarctic region after the third stage of the tectonic evolution, and the joint sets were developed as reflection of change of physical property from ductile to brittle.

(11) In Queen Maud Land, axial traces of folds show two major trends on the azimuth frequency diagram. One corresponds to an axial trend of F_1 and F_3 folds, and the other is parallel to F_2 folds.

(12) Axial trace of F_2 folds is parallel to the trend and extention of the Transantarctic Mountains. It is suggested that F_2 folds in Queen Maud Land have been formed during the Ross orogeny.

(13) The East Antarctic shield, including Queen Maud Land, underwent three or four times of tectonic movements. One of them, designated as F_2, was the product in the same stress field as that of the Ross orogeny.

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