

TECTONICS AND METAMORPHISM OF THE REGION AROUND LÜTZOW-HOLMBUKTA, EAST ANTARCTICA

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Abstract: Reviewing recent studies of the region around Lützow-Holmbukta, the scheme of the superposing tectonics and metamorphism is summarized in chronological order as follows.

1) Formation of the Skallen and Ongul groups of the southern part of the region, in the age considerably earlier than 1100 Ma. 2) The D_1 tectonics of earlier nappe and later isoclinal folds with axes trending nearly parallel to the coast line of Lützow-Holmbukta, associated with the M_1 high pressure granulite facies metamorphism with the P-T conditions around 880°C -13.5 kb. 3) Formation of the Okuiwa group of the northern part of the region. 4) The M_2 intermediate pressure granulite facies metamorphism with the P-T conditions around 880°C -8.8 kb, in the age around 1100 Ma. 5) The D_2 tectonics of open to close folds with axes trending east-west, associated with the M_3 high grade amphibolite facies metamorphism with the P-T conditions around 680°C -5.5 kb, dominating the northern part of the region. 6) The D_3 tectonics of gentle folds with axes trending nearly north-south and faults of the similar trend, associated with the intrusion of pink granites and the late phase of the M_3 low grade amphibolite facies metamorphism with the P-T conditions around 520°C -3.8 kb, in the age around 400 Ma. 7) The M_4 greenschist facies or slightly lower grade metamorphism. 8) The D_4 tectonics of conjugate shear fractures with acute bisectrix in the east-west direction indicating the northerly extensional stress field; the stress field is probably attributed to the beginning of the Gondwana dispersion which occurred during the Mesozoic era.

1. Introduction

The tectonic and metamorphic sequences of the region around Lützow-Holmbukta (bay) were summarized by TATSUMI and KIZAKI (1969), ISHIKAWA (1976), YOSHIDA (1975, 1978), and YOSHIDA *et al.* (1977); among which, YOSHIDA (1978) presented a full summary of this theme in his study on the charnockites of this region. He also presented a preliminary summary on the metamorphic conditions of the same region (YOSHIDA, 1979). The detailed geologic maps published successively since 1974 (Antarctic Geological Map Series, Natl Inst. Polar Res., Tokyo) and the accumulation of petrochemical data facilitated the recent summarizing studies.

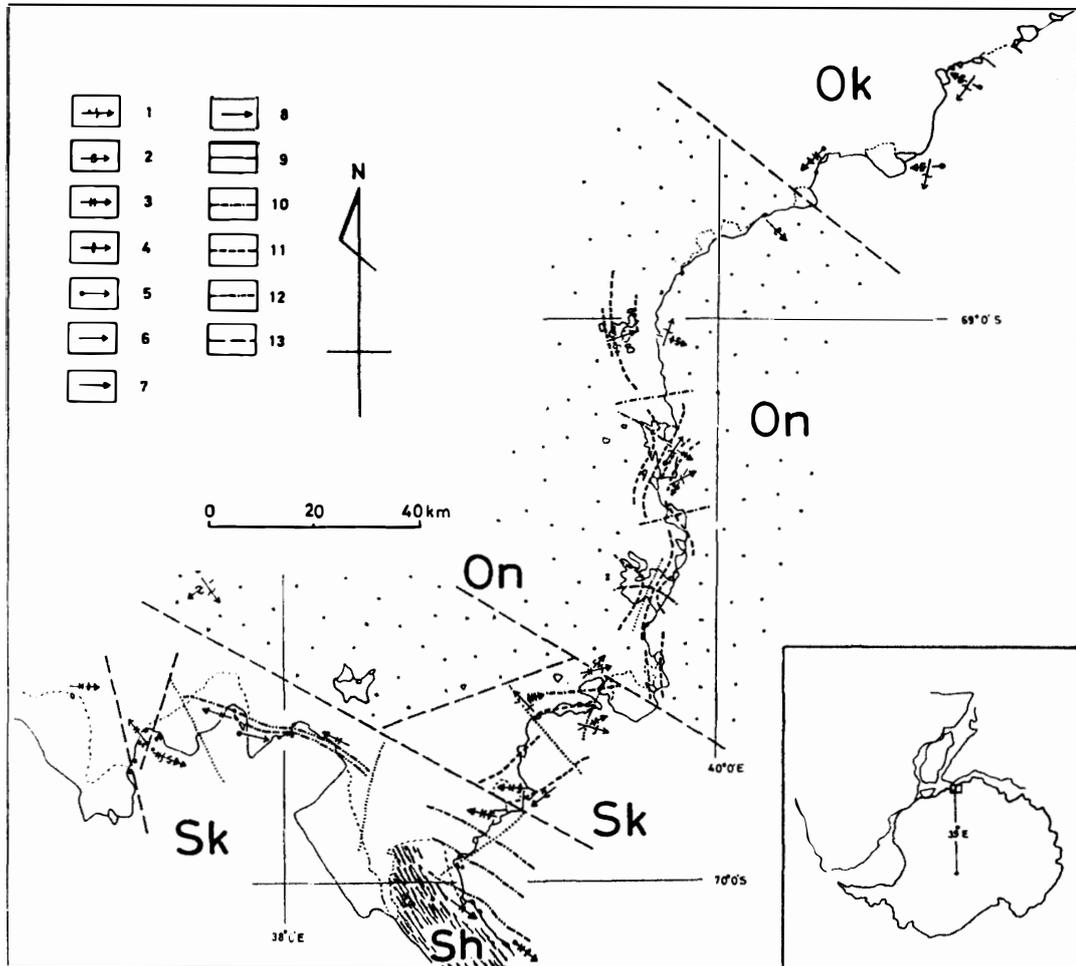


Fig. 1. Geologic and tectonic outline of the region around Lützow-Holmbukta.

1: Hinge of gentle-open minor folds. 2: Hinge of close-isoclinal minor folds. 3: Crenulation lineation or elongation of salic minerals. 4: Lineation made of mafic minerals. 5: Lineation associated with granitic rocks (either the mineral lineation developed in the pink granites, or the axis of minor fold, along the axial surface of which the pink granites are distributed). 6: Lineation or hinge of folds associated with the D_3 tectonics. 7: Lineation or hinge of folds associated with the D_2 tectonics. 8: Lineation or hinge of folds associated with the D_1 tectonics. 9: Axial trace of the D_3 folds. 10: Axial trace of the D_2 folds. 11: Axial trace of the D_1 folds. 12: Axial trace of the D_1 folds or superposed D_1 and D_2 folds. 13: Inferred fault.

Blank area with Ok: Area occupied by the Okuiwa group (northern Sôya Coast). Dotted area with On: Area occupied by the Ongul group (central Sôya Coast). Blank area with Sk: Area occupied by the Skallen group (east of Shirase Hyoga is the southern Sôya Coast and west of Shirase Hyoga is the region around Botnneset). Clot of thin bars with letter Sh indicates Shirase Hyoga (Glacier). Inset figure at the lower right indicates the Gondwana-fit of SMITH and HALLAM (1970) which was accepted by YOSHIDA (1978) as the location of Lützow-Holmbukta from the tectonic considerations. Fig. 1 is cited from YOSHIDA (1978), compiling some of his figures.

This article gives the present knowledge of the tectonics and metamorphism of the region around Lützow-Holmbukta by reviewing the recent studies. Fig. 1 and Table 1 give the geologic outline and the summarized scheme of the tectonic and metamorphic history of the present region.

Table 1. Geotectonic development of the region around Lützow-Holmbukta.

Stratigraphy	Tectonics	Metamorphism	Plutonism	Age (Ma)
Okuiwa group	D ₄ Fractures	M ₄ Greenschist facies or slightly lower grade	P ₃ Pink granite	200-?
	D ₃ Gentle folds (N-S trend) (F ₄)	M ₃ (late phase) low grade amphibolite facies	P ₂ Biotite granite	400
	D ₂ Open to close folds (E-W) (F ₃)	M ₃ (main phase) high grade amphibolite facies		
	Transverse joint	M ₂ Intermediate P-granulite facies	P ₁ Charnockite	1100
	D ₁ Recumbent (F ₁) and isoclinal (F ₂) folds	M ₁ High P-granulite facies	P ₀ Granitic rock ?	
Skallen and Ongul groups	D ₀ Plunging recumbent folds ? (F ₀)			

Zero mark at the right foot of the letters D and P indicates uncertainty as to the existence of the event concerned. (D₀ is explained in YOSHIDA, 1977 and 1978, p. 86, and P₀, in YOSHIDA, 1978, p. 64 and 1979). Question mark also indicates uncertainty.

2. Tectonics

2.1. Stratigraphy

Earlier descriptions of the distribution of rock types and stratigraphic summary were given by KIZAKI (1964) and TATSUMI and KIZAKI (1969); the latter authors introduced the Lützow-Holm Bay system for the gneisses and associated rocks distributed throughout the Lützow-Holmbukta, Botnnuten, and Yamato Sanmyaku (Mountains) areas.

Three lithostratigraphic groups, *i. e.*, Skallen group, Ongul group, and Okuiwa group, were introduced by YOSHIDA *et al.* (1977) and YOSHIDA (1977, 1978), the latter

author (YOSHIDA, 1977) having described four formations of the Skallen group. The Skallen group is composed mainly of charnockitic gneisses and alternating gneissic rocks including marbles and quartzite, the Ongul group is composed mainly of charnockitic plutonites and biotite-garnet gneiss, and the Okuiwa group is composed mainly of biotite gneiss and pink granites; the latter group is distinguished from other two groups by the lack of the structure of the D_1 tectonics and granulite facies gneisses. The distribution of these groups is shown also in Fig. 1.

2.2. *Foldings and faultings*

The tectonic sequence of the region around Lützow-Holmbukta has been studied by ISHIKAWA (1976), YOSHIDA *et al.* (1977), and YOSHIDA (1978). Superposing tectonic events were stressed by these studies.

The outline of the tectonics is shown in Table 1 and Fig. 1 referring to YOSHIDA's study. In Table 2 is given the probable classification (after DONATH and PARKER, 1964) of various superposing folds, extrapolated and summarized from the descriptions of the previous studies.

2.3. *Planar and linear structures of rocks*

2.3.1. Mesoscopic structures

Many specimens collected from various parts of the present region show some tectonic characteristics of planar and linear structures which can be correlated with the macroscopic tectonics. YOSHIDA (1978) described and discussed these structures in some detail which are summarized in Table 3 and Fig. 2. The correlation of the planar structures with the folds is indicated in Table 2, summarized also from YOSHIDA's study. Since such tectonic characteristics of rock specimens as in Fig. 2 are well observed throughout the region in association with the appropriate macroscopic tectonics, the superposition and areal extension of tectonics as summarised in Tables 1 and 4 are considered to be evidenced.

2.3.2. Microscopic structures

The microscopic structures of rocks were preliminarily investigated by YOSHIDA (1978). Microscopic observations of thin sections of oriented rock specimens clarified the microscopic constitution of various tectonic elements and their superposition relationships. The result of this study is schematically shown in Fig. 3 and Table 3. The possible genesis of the planar structures is also shown in Table 3, having been summarized and extrapolated from the descriptions and discussions by YOSHIDA (1978), mainly referring to HOBBS *et al.* (1976) and VERNON (1976).

2.4. *Location of Lützow-Holmbukta in the Gondwana reconstruction*

YOSHIDA (1978) assumed that, in the Gondwana reconstruction, Lützow-Holmbukta might have been tied in the southern terminus of the Indian Peninsular, just as has been reconstructed by SMITH and HALLAM (1970). Similarity in geology and conformity in tectonics have been pointed out, among which the trend of the first

Table 2. Classification of folds and their correlation with planar structures.

Tectonic stages	Foldings		Planar structures	Remarks
	Style	Classification		
Sedimentation and diagenesis			Compositional banding, bedding fissility	Intrafolial folds appear to have taken place, in synchronous with or predating to the D ₁ tectonics.
D ₁	Recumbent folds (F ₁)	Flexural slip folding	Bedding schistosity, compositional banding	
	Isoclinal folds (F ₂)	Passive flow folding	Axial plane foliation, schistosity-D, and schistosity-L	
D ₂	Open to close folds (F ₃)	Passive, and quasi-flexural folding	Axial plane foliation, schistosity-D, and L	Flow fold in the northern Sôya Coast, gentle fold and kink fold in the central and southern Sôya Coast, and faulting in the region around Botnneset.
D ₃	Gentle folds, and faults (F ₄)	Variable according to areas	Flow schistosity-L. Axial plane schistosity-L	

The classification of folds is tentative, referring to that of DONATH and PARKER (1964). D and F with numerals refer to those in Table 1. Schistosity-D and schistosity-L are explained in Table 3.

Table 3. Planar structures of rocks from Lützow-Holmbukta.

Planar structures	Characteristics of microstructure	Possible interpretation of the genesis of the planar structures
Banding	Made of alternating layers of different mineral composition, the minerals exhibit no lattice preferred orientation, and are generally equant in shape.	A. Primary igneous or sedimentary structure. B. Metamorphic segregation along the bedding cleavage which developed during the flexural slip folding.
Foliation	Made of planar mafic clots, the mafics are random in orientation.	A. Tectonic blocking or stretching of the banding, and overlapping recrystallization. B. Deformation and overlapping recrystallization of an original mafic grain. C. Metamorphic differentiation along the axial plane cleavage which developed during the passive folding.
Schistosity-D type	Made of dimensional preferred orientation of single crystal grains of Qz, feldspars, Ga, Pxs, or Ho, the periphery of the grains is sometimes smooth (some Qz and feldspars) but generally distinctly irregular and the edge does not show smooth thinning but terminates abruptly or irregularly.	A. Coalescent porphyroblastasis of the foliation-B (all minerals). B. Porphyroblastasis under stress perpendicular to the foliation plane (Kf in some granitic gneiss). C. Flattening of original phenocryst by deformation and recrystallization (some Qz and Kf). D. Crystallization under subliquidus flow (Qz and Kf in some pink granites).
Schistosity-L type	Made of lattice preferred orientation of Bi, Opx, or sillimanite; the dimensional preferred orientation is also the general case.	A. Mimetic recrystallization after the pre-existent minerals which were preferentially orientated (Bi, Sill). B. Crystallization on the pre-existent s-plane (Bi, Sill). C. Porphyroblastasis under stress perpendicular to the schistosity plane (Bi, Sill, Opx ?). D. Mechanical rotation by flow paralleling the schistosity plane (Bi, in the pink granite). E. Coalescent porphyroblastasis of the foliation-B (Opx).

Mineral abbreviations are explained in Fig. 4.

No.	Field	Hand Specimen	
		$\longrightarrow l_1$ and/or l_2	$\longrightarrow l_3$
1			
2			
3			

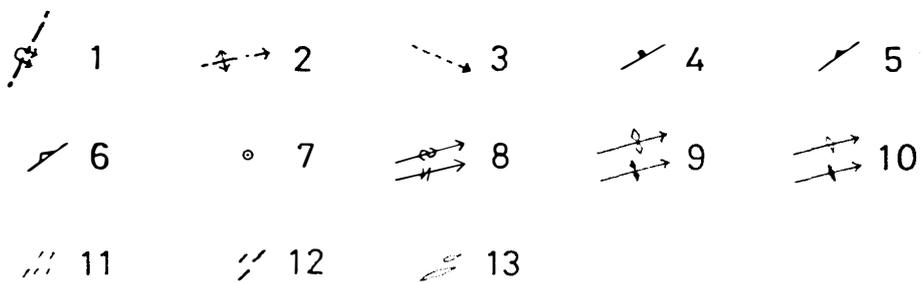


Fig. 2. Tectonics of rock specimens from the region around Lützow-Holmbukta.

Specimen No. 1: Charnokitic plutonite collected from East Ongul Island. Specimen No. 2: Banded gneiss collected from Skallen. Specimen No. 3: Charnokitic gneiss collected from Instekleppane, southern Sôya Coast.

1: Axial trace of a recumbent antiform with the axial surface inclined east (F_1 , F_2 , and F_3 indicate first, second, and third folds, respectively, explained in Table 1). 2:

major fold providing the specifically valuable key. SMITH and HALLAM's reconstruction is shown along with the location of Lützow-Holmbukta in the inset of Fig. 1.

3. Metamorphism

3.1. Metamorphic history

The polymetamorphic aspect of the region has been clarified by KIZAKI (1964), as a combination of the earlier granulite facies and the later amphibolite facies metamorphisms.

YOSHIDA (1975), studying the southwestern part of the region, found also the similar sequence of metamorphism, but in addition to that, he described the greenschist facies or slightly lower grade metamorphism as the latest event. YOSHIDA *et al.* (1977) and YOSHIDA (1978) recently clarified the superposition of microstructural episodes (development of rock fabrics observed under the microscope) and their correlation with the tectonics, as a result of the extensive observations of thin sections of the charnockitic rocks. This study provided a somewhat realistic figure of the superposition of the metamorphism so far revealed mainly by field studies. Summarizing these studies, the metamorphic history of the present region is clarified as follows: M_1 high pressure granulite facies (represented by relic clinopyroxene, garnet, and quartz), M_2 intermediate pressure granulite facies (represented by polygonal plagioclase and ortho- and clinopyroxenes, followed by the formation of the charnockitic plutonite, M_3 amphibolite facies (development of hornblende and biotite replacing pyroxenes and garnet, followed by the formation of the pink granites), and M_4 greenschist facies or slightly lower grade (scanty development of chlorite, epidote, and sericite) metamorphisms. Summary of these studies by YOSHIDA is schematically shown in Fig. 4 and Table 1.

The radiometric age determinations (compiled by YANAI and UEDA, 1974) indicate that the M_3 amphibolite facies metamorphism overwhelmed the region,

Axial trace of a plunging fold. 3: Plunge of the hinge line. 4: Banding. 5: Foliation. 6: Schistosity. For 4-6, S_1 , S_2 , and S_3 indicate the S-planes related to the F_1 , F_2 , and F_3 folds, respectively. 7: Location of the specimen collected. 8: Axis of minor folds (upper symbol) or crenulation lineation (lower symbol). 9: Lineation made of mineral clots, either of salic (open) or mafic (solid) minerals. 10: Lineation made of scattered salic (open) or mafic (solid) minerals. For 8-10, l_1 is the minorfold of S_1 by the D_1 deformation or mineral lineation paralleling the minorfold, l_2 is the intersection of S_1 and S_2 , and l_3 is the intersection of S_1 (or S_2) and S_3 . 11: Dimensional preferred orientation of scattered mafic minerals. 12: Dimensional preferred orientation of mafic clots. 13: Dimensional preferred orientation of coarse salic minerals or their clots.

The hand specimen tectonics is determined in laboratory from the oriented specimen. Although the field tectonics is written in an arbitrary scale, the good conformity between the macroscopic tectonics and the hand specimen tectonics will be found in all specimens. The figure is modified from YOSHIDA (1978).

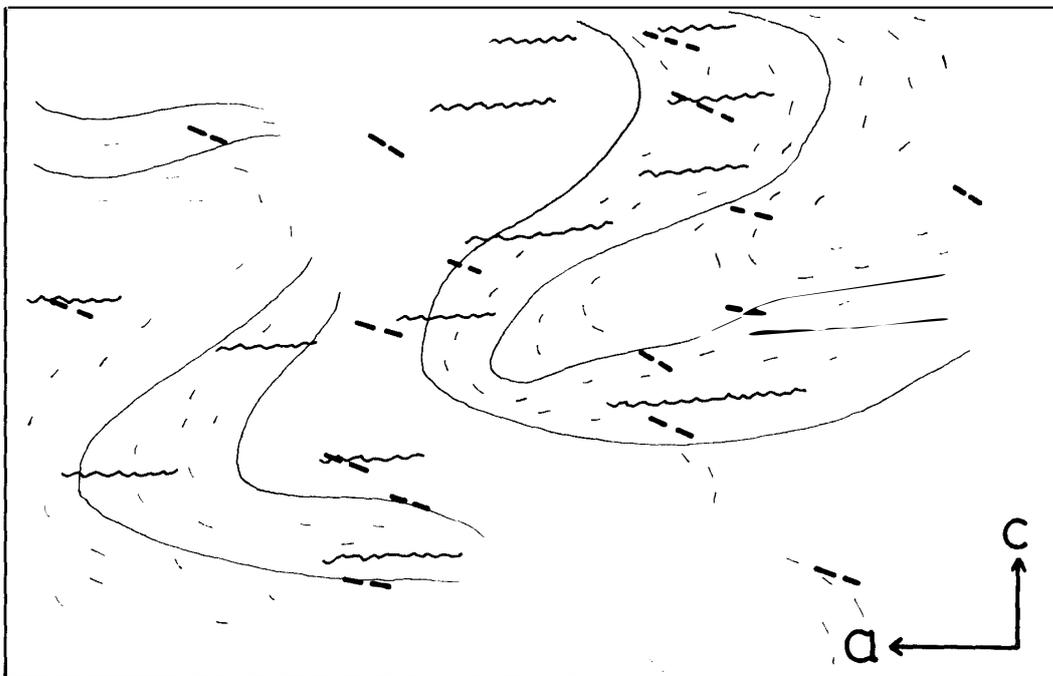
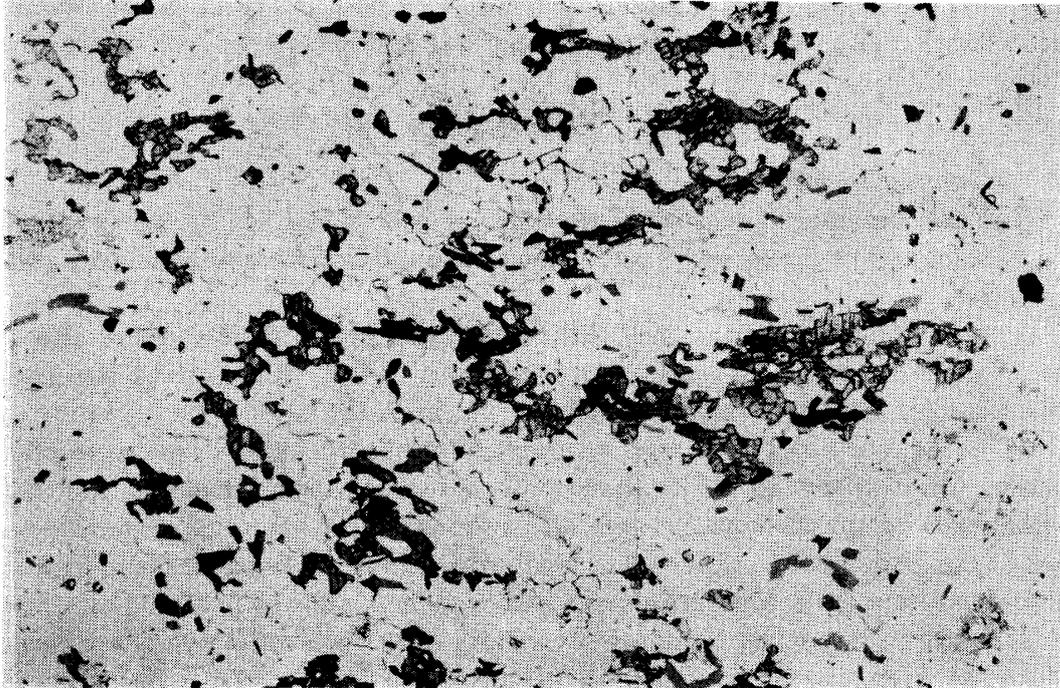


Fig. 3. Superposition of the microscopic tectonics.

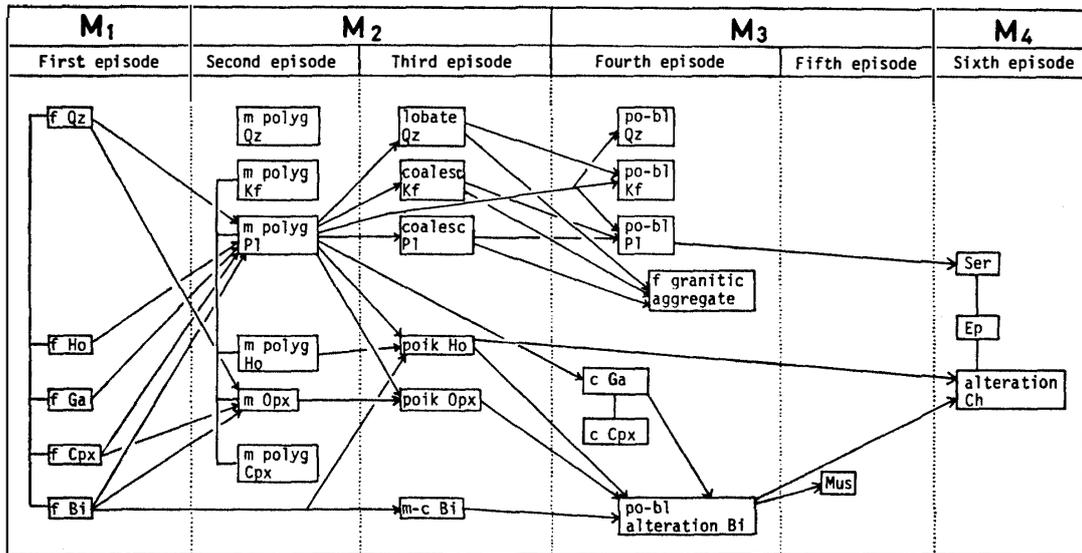


Fig. 4. Timing of the microstructure in relation to the observed occurrence of minerals mainly of the charnockitic rocks.

The arrow indicates the observed time relationships (head is younger than root), and the tie line without an arrow indicates the simultaneous growth. Abbreviations are as follows.

Bi: Biotite. c: Coarse-grained. Ch: Chlorite. coalesc: Coalescent. Cpx: Clinopyroxene. Ep: Epidote. f: Fine-grained. Ga: Garnet. Ho: Hornblende. Kf: Potash feldspar. m: Medium-grained. m-c: Medium- to coarse-grained. Mus: Muscovite. Opx: Orthopyroxene. Pl: Plagioclase. po-bl: Porphyroblastic. poik: Poikiroblastic. polyg: Polygonal. Qz: Quartz. Ser: Sericitic matter developed among some plagioclases.

M_1 , M_2 , M_3 , and M_4 refer to the M_1 , M_2 , M_3 , and M_4 metamorphisms, respectively, as in Table 1. Comparing with the similar figure of YOSHIDA (1978, his figure 5.11), the paragenesis c Cpx-c Ga is moved to the late period, muscovite is newly written as the fifth episode, and chlorite, sericite, and epidote are also newly shown as the sixth episode. This figure is cited mainly from YOSHIDA (1978), but slightly modified, referring to the descriptions in his other two studies (YOSHIDA, 1975, 1979).

Fig. 3. Superposition of the microscopic tectonics.

A photomicrograph shows an ac section of a charnockitic plutonite from West Ongul Island. A typical set of microscopic tectonics is seen in the photomicrograph as schematically indicated in the lower explanation figure, referring to the descriptions by YOSHIDA (1978, 98–110). S_1 is shown by the vague continuation of mafic (mainly coarse hypersthene) clots, which are microfolded (shown by bands outlined by thin full lines). S_2 is indistinctly shown by the elongation of mafic clots subparallel to the trace of the axial surface of the microfold (indicated by waving short lines). S_3 is shown by the dimensional or lattice preferred orientation of scattered medium biotite which are also very indistinct (indicated by scattered thick bars). In some specimens, fine xenocrystic biotites included in hypersthene and plagioclase are arranged parallel to such microfold structures as S_1 (schematically shown by thin short bars in the explanation figure, although not well distinguished in this specimen). Salic minerals are granoblastic and structureless.

rejuvenating almost all the radiometric age of minerals and rocks to be placed around 400–500 Ma (including one biotite isochron age of 458 Ma by MAEGOYA *et al.*, 1968), and the previous events, indicated as only one K-feldspar isochron age of 1100 Ma (MAEGOYA *et al.*, 1968), are almost wholly concealed.

3.2. Metamorphic conditions

Metamorphic conditions of the region around Lützow-Holmbukta was studied by BANNO *et al.* (1964) and SUWA (1968). They have clarified the conditions of the main metamorphism of the region to belong to the lower grade or intermediate to lower pressure subfacieses of the granulite facies.

From the microstructural study of the charnockitic rocks in the present region, YOSHIDA (1978) preliminarily estimated the conditions of each of the superposing metamorphisms as already shown. YOSHIDA (1979) further gave a more or less quantitative estimation of the conditions of the superposing metamorphisms by utilizing the recently accumulated chemical analyses of rocks and minerals, and by referring to the experimental and theoretical studies. The following scheme is cited from his results.

- M₁ metamorphism: Around 880°C–13.5 kb and water deficient conditions.
- M₂ metamorphism: Around 880°C–8.8 kb and almost dry conditions.
- M₃ metamorphism: Around 680°C–5.5 kb and almost water sufficient conditions for the main phase, and around 520°C–3.8 kb and water deficient conditions for the late phase.

Table 4. Areal extension of tectonics and metamorphism around Lützow-Holmbukta.

Area	Northern Sôya coast	Central Sôya coast	Southern Sôya coast	Region around Botneset
Group	Okuiwa group	Ongul group	Skallen group	
D ₁	—	+++	+++	+++
M ₁	—	++	+	+
M ₂	—	++	+++	++
P ₁	—	+++	++	++
D ₃	+++	+	+	+
M ₃	+++	++	+	+
P ₃	+++	+	+	+

+++ , ++ , + , — indicate dominant, common, minor, and no development, respectively. Other abbreviations are indicated in Table 1. Areal division is based on that of YOSHIDA (1978), which is indicated in Fig. 1 by the distribution area of each group.

4. Areal Extension of the Tectonics and Metamorphisms

Reviewing the data so far presented (papers summarized by YOSHIDA, 1978, and more recent studies presented at the titled symposium in Tokyo in 1978, most of which are included in the present volume), each of the superposing tectonics and metamorphisms appears to have widely affected the region around Lützow-Holmbukta, but not with the uniform intensity throughout the region. Table 4 indicates the present understanding of the areal extension of each tectonic and metamorphic event in the region around Lützow-Holmbukta.

5. Tectonic and Metamorphic History of the Region around Lützow-Holmbukta

Summarizing the above, the tectonic and metamorphic history of the present region is obtained as shown in Table 1. The areal variation of the conditions of each metamorphism, the radiometric age of each metamorphism, and the correlation of geologic events with other Gondwanian regions are open problems for the future studies.

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