PETROGRAPHY OF A DISCORDANT METABASITE FROM SKALLEN, LÜTZOW-HOLMBUKTA, EAST ANTARCTICA

Masaru YOSHIDA and Nobuyuki AIKAWA

Department of Geosciences, Faculty of Science, Osaka City University,
3-138, Sugimoto 3-chome, Sumiyoshi-ku, Osaka 558

Abstract: A discordant metabasite from Skallen is an olivine tholeiite resembling petrochemically with some of the Proterozoic Amundsen dikes of Enderby Land. Field occurrence, mineral association, and microstructure including zoning structure of minerals are not incompatible with the polymetamorphic interpretation of the area presented by YOSHIDA et al. (submitted to Antarctic Earth Science, 1982), and indicate that the rock intruded in synchronous with or earlier than possibly the second and probably the first tectono-metamorphic event of YOSHIDA et al.

Microprobe analyses and compositional zoning of constituent minerals of the metabasite are presented and some temperature and pressure values are calculated utilizing five different geothermometers and a geobarometer. Among calculated values, $693 \pm 3°C$, $768 \pm 3°C$, and $823 \pm 22°C$ obtained by averaging temperatures after margin pairs of garnet-clinopyroxene (ELLIS and GREEN: Contrib. Mineral. Petrol., 71, 13, 1979) and garnet-biotite (THOMPSON: Am. J. Sci., 276, 425, 1976) geothermometers, after core pairs of two pyroxenes (WOOD and BANNO: Contrib. Mineral. Petrol., 42, 109, 1973) and garnet-clinopyroxene geothermometers, and averaging highest temperatures after core pairs of two pyroxenes and garnet-clinopyroxene geothermometers are considered possible to be explained either by the polymetamorphic or by the monometamorphic history of the discordant metabasite. It is stressed that the peak of a dominant metamorphism is considered to have reached the temperature much higher than 823°C whichever the metamorphic history might have been.

1. Introduction

A metabasite specimen No. Y69020303 of the present study is the only discordant intrusive metabasite known throughout the region around Lützow-Holmbukta. YOSHIDA et al. (1976) and YOSHIDA (1977) termed this rock the discordant metabasite and gave brief petrography and bulk chemical composition, and discussed its role in the study of metamorphic history of the Skallen region.

A basic dike criterion (PORDERVAART, 1953) is exclusively effective in the study of metamorphic history of an area of crystalline basement rocks. The present study gives petrography of the metabasite which may provide some data for the current discussions (*e.g.*, YOSHIDA et al., 1982b; HIROI et al., 1983) of metamorphic history of the region around Lützow-Holmbukta.

2. Geologic Setting and Occurrence of the Discordant Metabasite

General geology of the Skallen region was given by YOSHIDA et al. (1976) and

YOSHIDA (1977). The region is composed of alternations of gneissose charnockites, paragneisses, metabasites, marbles and quartzite, all of them constituting a typical column of the Skallen Group. The Skallen Group suffers superposed foldings and metamorphisms common throughout the Lützow-Holmbukta region as follows (YOSHIDA, 1978, 1979a, YOSHIDA et al., 1982a, revised by YOSHIDA et al., 1982b).

The first event (ca. 1900 Ma ago) is recumbent and isoclinal folds and high-pressure granulite facies metamorphism (M_1). The second event (ca. 1100 Ma ago) is the intermediate-pressure granulite facies metamorphism (M_2) probably associated with some folding. The third event (ca. 560 Ma ago or earlier) is the E-W upright close to open fold and high amphibolite facies metamorphism (M_3). The fourth event (ca. 460 Ma ago) is the N-S upright gentle folding and faults associated with the pink granite intrusion and local low amphibolite facies metamorphism (M_4). Greenschist facies or slightly lower grade metamorphism (M_5) is considered to have taken place locally during the late epoch of this event. YOSHIDA et al. (1982b) mentioned that mineral parageneses of metamorphites from the Lützow-Holmbukta region principally reflect conditions of the second (M_2) and the third (M_3) metamorphisms. In the following pages, these metamorphisms are termed M_2 and M_3 metamorphisms respectively.

BANNO et al. (1964) and SUWA (1968), however, considered that the mineral parageneses of rocks from the Lützow-Holmbukta region reflect one dominant metamorphic event under the low (or lower pressure) granulite facies conditions; according to their view, M_2 and M_3 metamorphisms of YOSHIDA et al. are joined together to form one metamorphism. This problem will be discussed later in Section 5.

The discordant metabasite of the present study crops out at the southwestern coastal slope of Skallen, about 1000 m southeast of Lake Skallen Ôike, intruding the alternations of quartz-feldspathic gneiss and metabasite. It is a semicircular mass of about 100 m in diameter. An ENE elongate mass of similar discordant metabasite about 50 × 300 m in size crops out 100 m to the west of the semi-circular mass, its distribution being distinctive from the country rocks (Fig. 1). Thus, these masses are considered to constitute an E-W trending, steep, possibly continuous (underground) dike intruded discordantly into the paragneiss-metabasite alternations.

The boundary between the dike and the country rocks observed at the northwestern margin of the semicircular mass is smooth without any trace of slip and is generally discordant. In detail, however, some portions of the boundary plane are parallel to the alternation or thin banding structures of the country rocks. Neither chilled margin in the dike, nor quartz-feldspathic pegmatitic vein at the boundary was found. The dike generally possesses the vague thin compositional banding-foliation structure (thin banding denotes the thin compositional alternation structure of millimeters thick, continued less than a few meters, and the foliation is the thin compositional alternation structure of millimeters thick with lief like form, cf. YOSHIDA, 1978, p. 98; the banding-foliation structure is not the intermediate but the compound of the two structures) which represents an upright and gentle microfold structure. The thin banding-foliation of the dike strikes N40°W and dips 12°W and the mineral distribution lineation on the banding-foliation plane plunges 7° toward S70°W. The thin banding-foliation, microfold structure and mineral lineation of the dike are concordant with those of the country paragneiss and discordant to the trend of the dike.
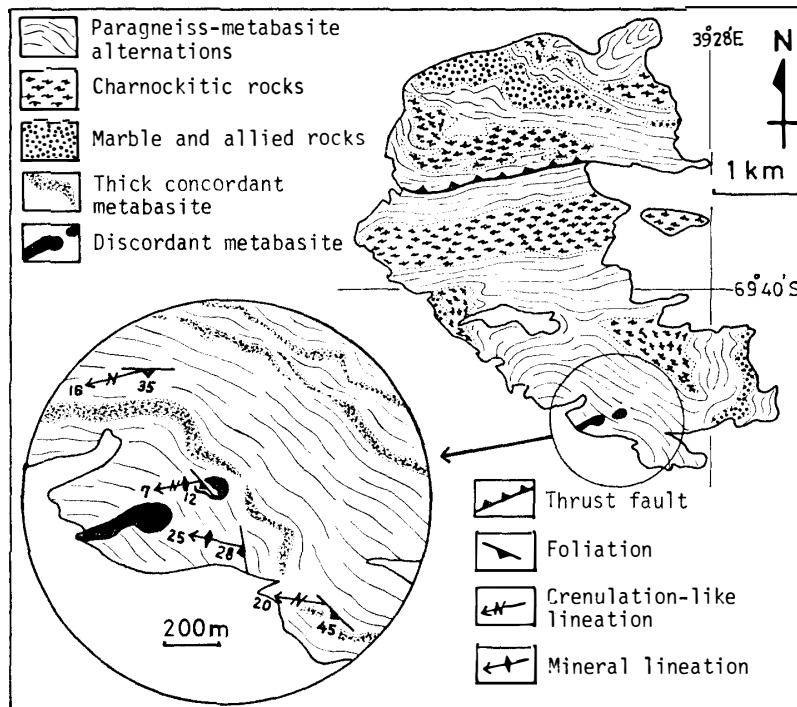
Fig. 1.   Locality and occurrence of the discordant metabasite (after YOSHIDA, 1977).

3.   General Petrography

The specimen is a dark gray and weakly and thinly banded and foliated rock.   The weathered surface is somewhat stained to represent heterogeneous dark brownish tint which makes the planar and linear structures distinctive.   Bulk chemical composition and norm of the metabasite were given by YOSHIDA *et al.* (1976) and YOSHIDA (1978) which are shown in Table 1.   Alkali-silica ratio (after KUNO, 1959) classifies the rock as alkali basalt, whereas norm constitution of the rock is plotted onto the olivine tholeiite after the YODER and TILLEY's (1962) classification.   These chemical characteristics of the metabasite resemble some Proterozoic basic dikes (some of the Amundsen dikes) from Enderby Land (SHERATON and BLACK, 1981).

The specimen possesses a thin banding-foliation structure made of continued distribution of mafic minerals; this structure is less distinctive in *ac* section (fabric axes *a*, *b* and *c* are referred to those of TURNER and WEISS, 1963) than in *bc* section of the rock.   Mineral lineation on the *ab* plane is also made of such continued distribution of mafic minerals as above, although much less distinctive than in *ac* section.

Under the microscope, the rock is principally fine-grained (0.15 mm in average diameter, the grain size classification as micro-fine-small-medium-coase-and very coarse follows that of TEUTSCHER, 1933) granoblastic equigranular polygonal (Fig. 2, the textural term follows that of MOOR, 1970) composed mainly of plagioclase, ortho-pyroxene, clinopyroxene, Fe-Ti oxides, greenish brown hornblende, reddish brown biotite, and garnet, with accessory apatite, zircon, calcite, hematite-goethite(?), hydromica and chlorite.   Modal composition is given in Table 2.

Table 1. Chemical composition and norm of the discordant metabasite.

SiO_2	45.32	Or	6.7
TiO_2	3.59	Ab	25.2
Al_2O_3	15.28	An	25.0
Fe_2O_3	4.68	Wo	5.0
FeO	10.21	En	7.7
MnO	0.41	Fs	4.7
MgO	6.27	Fo	5.6
CaO	8.58	Fa	3.9
Na_2O	2.97	Mt	6.7
K_2O	1.11	Il	6.8
P_2O_5	0.84	Ap	2.0
H_2O^+	1.22	Total	99.3
H_2O^-	0.08		
Cr_2O_3	—		
Total	100.56		

Cited from YOSHIDA et al. (1976) (chemical composition) and YOSHIDA (1978) (norm).

Table 2. Mode of the discordant metabasite.

Plagioclase	43.3	IC number	283
Hornblende	23.7	(CHAYES, 1956)	
Orthopyroxene	14.9	Measured area	125 mm^2
Clinopyroxene	6.1	Measuring points	1301
Biotite	4.6		
Fe-Ti oxide	4.3		
Apatite	1.1		
Garnet	0.8		
Others	1.2		
Total	100.0		

Others include hydromica, chlorite and the unidentified alteration mineral (can be zoisite?). Fe-Ti oxides include ilmenite, magnetite and hematite-goethite like material. Both pyroxenes include undifferentiated pyroxenes less than about 5% of each content.

Plagioclase and pyroxenes are generally equant, polygonal or granular, and distributed throughout. Some pyroxenes, however, are slightly elongated parallel to the fabric axis b. Plagioclase shows weak and smooth reverse zoning. Garnet occurs sporadically. It is granular to irregular, generally embedded in plagioclase aggregates, and rarely contacts with pyroxenes (Fig. 3). Both biotite and hornblende are somewhat elongated parallel to the fabric axis b, but lattice preferred orientation is inconspicuous, although over half of these minerals show greater absorption parallel to b. It may be noted that the basal plane of some biotites is parallel to the fabric axis b and highly inclined from the ab plane. Both hornblende and biotite are later products, surrounding or intruding pyroxenes (Figs. 4 and 5), or being in contact with garnet and Fe-Ti oxides (cf. Fig. 3). Some biotites cut the zoning of plagioclase. Fe-Ti oxides are scattered throughout. They are micro- to small-grained and elongated generally parallel to the fabric axis b. They are attached to all other mafic minerals. Marginal portions of these minerals surround generally the other anhydrous mafic minerals.
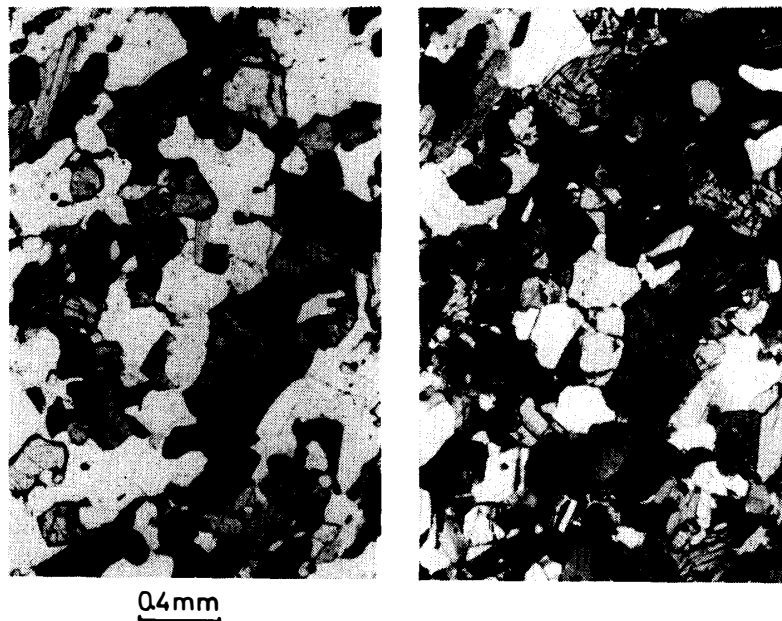
0.4mm

Fig. 2. *Photomicrograph of the discordant metabasite, plane polarized (left) and crossed (right). Plagioclase (white), ortho- and clinopyroxenes, hornblende, Fe-Ti oxides and biotite. Two garnet grains are seen at the lower left (high relief). This is a bc section, the thin banding-foliation structure is shown by continuous distribution of mafic and salic minerals.*

0.2mm

0.2mm

Fig. 3. *Occurrence of garnet. Three garnets (high relief) are embedded in plagio-clase aggregate. Plagioclase (white), hornblende (darker grain), Fe-Ti oxides (o), and salite (s) are seen. Attachment of salite with garnet as seen in this figure is a rare example throughout the slide.*

Fig. 4. *Occurrence of hornblende. Hornblende (darker grain) generally alters salite and intrudes grain boundaries of pyro-xenes. Plagioclase (white), salite (s), hypersthene (h), biotite (b), and Fe-Ti oxides (o) are seen.*
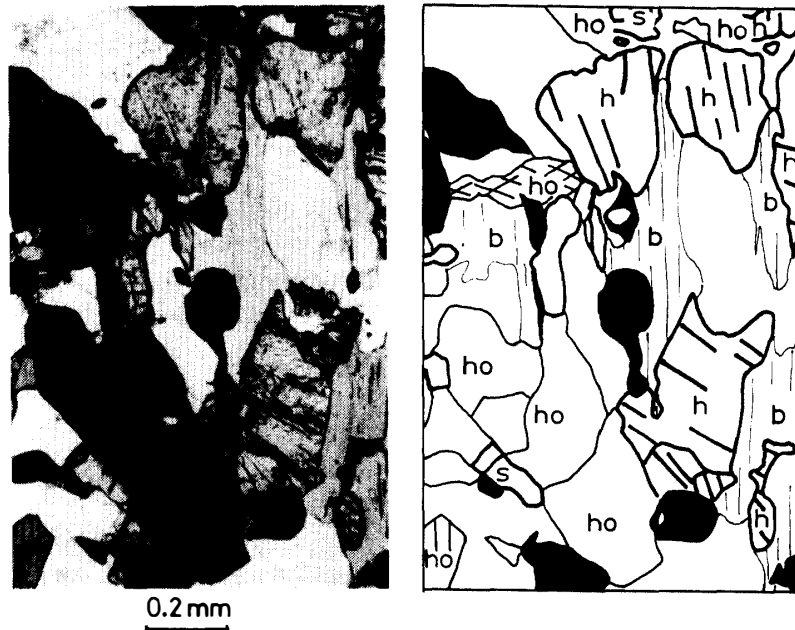
Fig. 5. Occurrence of biotite. Biotite (b) surrounds and intrudes into hypersthene (h). Plagioclase (white), Fe-Ti oxides (black), hornblende (ho), and salite (s) are seen.
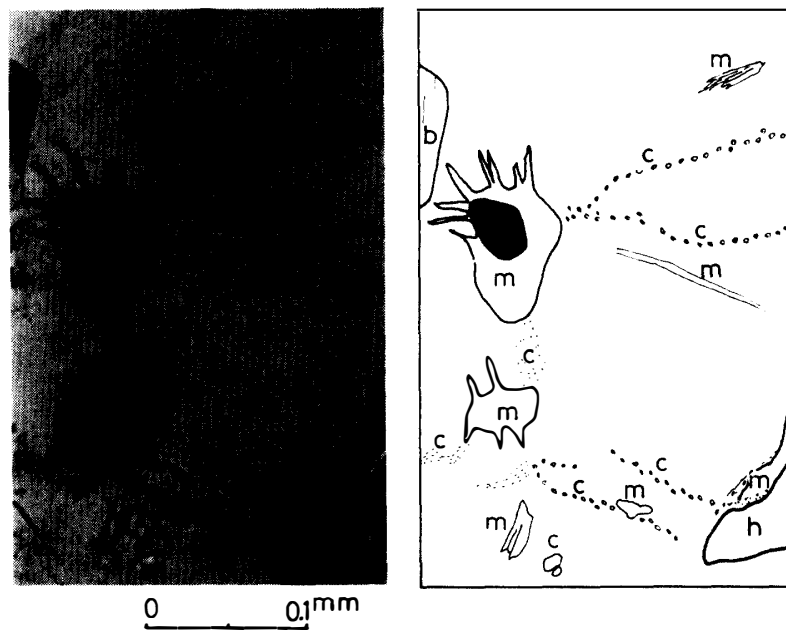
Fig. 6. Occurrence of lower grade minerals. White base: Plagioclase. m: Hydromica associated generally with chlorite. c: Carbonate mineral generally associated with hydromica. h: Hypersthene. b: Biotite. This is a bc section, the banding-foliation runs from top to bottom.

Hematite-goethite like material is developed locally attached to opaque minerals or to biotite. Small amounts of micro-grained chlorite, hydromica, and calcite are developed throughout, either at grain boundaries or along very thin cracks of other minerals (Fig. 6). These cracks are developed throughout the slide, cutting the banding-foliation structure at nearly right angles.

4. Mineral Chemistry

4.1. Analytical method

Chemical compositions of minerals were determined using a JXA-5A electron probe microanalyzer settled in the Geoscience Laboratory of Osaka City University. PET and RAP wavelength-dispersive crystal spectrometers were used. An accelerating potential of 15 kV and a sample current of 0.015 μA on MgO were the operating conditions. The beam current was digitalized with counting times of 10 s on each analysis point. Five points were analyzed and averaged to obtain each representative analysis of a distinctive portion of a mineral grain. Minerals for analysis were selected from three small domains of 1 mm^2 labeled as domains A, B and C. Central and marginal portions of a grain which are termed core and margin, respectively, were analyzed. Synthesized MgO, SiO_2, Al_2O_3, $CaSiO_3$, MnO, Fe_2O_3, natural albite (Amelia, Virginia) and natural adularia (Sent Goddhard, Switzerland) were used as standards. Analyses were carried out in the standard fashion with the focussed beam. Data sets were reduced following the method of Bence and Albee (1968) using the α-factor given by Nakamura and Kushiro (1970). Probe analysis by S. Yoshikura followed a nearly

Table 3. Chemical compositions of plagioclase.

		1	2	3	4	5	6
SiO_2		58.17	58.09	56.95	56.84	56.49	56.65
TiO_2		0.0	0.0	0.02	0.01	0.01	0.03
Al_2O_3		26.86	26.89	27.37	27.66	27.16	27.14
FeO*		0.11	0.31	0.12	0.31	0.12	0.58
MnO		0.01	0.02	0.03	0.06	0.01	0.02
MgO		0.02	0.07	0.01	0.0	0.0	0.11
CaO		7.79	9.28	9.27	9.69	9.20	8.75
Na_2O		6.45	6.55	6.36	5.99	6.18	6.07
K_2O		0.23	0.24	0.33	0.24	0.26	0.24
Total		99.62	101.44	100.47	100.78	99.44	99.59
Cations relative to 8 oxygens							
Si		2.604	2.574	2.549	2.538	2.551	2.555
Ti		0.9	0.0	0.001	tr.	tr.	0.001
Al		1.417	1.404	1.444	1.455	1.446	1.442
Fe		0.004	0.011	0.004	0.011	0.004	0.022
Mn		tr.	0.001	0.001	0.002	0.001	0.001
Mg		0.001	0.004	0.001	0.0	0.0	0.008
Ca		0.374	0.441	0.445	0.463	0.445	0.423
Na		0.560	0.562	0.551	0.518	0.541	0.531
K		0.013	0.014	0.019	0.014	0.015	0.014
	Ab	59	55	54	52	54	55
Mole%	An	40	44	44	47	44	44
	or	1	1	2	1	2	1

1: Core of grain No. 1, domain A.   2: Margin of grain No. 1, domain A, adjacent to garnet (analysis No. 2).   3: Core of grain No. 2, domain B.   4: Margin of grain No. 2, domain B, adjacent to garnet (analysis No. 5).   5: Core of grain No. 3, domain B.   6: Margin of grain No. 3, domain B, adjacent to garnet (analysis No. 8).   * All assumed to be Fe^{+2}.

similar method to the above using JXA-5A microanalyzer settled in the Geology Laboratory of Kochi University.

4.2. Analytical results

Results of the quantitative probe analysis of some constituent minerals are shown in Tables 3–9. Before analyses, a general pattern of zoning of contents of major elements in constituent minerals was examined by making scanning profiles. Most anhydrous minerals except Fe-Ti oxides were found to be weakly zoned smoothly and concentrically. Both the core and marginal portions were analyzed for the zoned mineral, whereas only the core portion was done for the unzoned mineral. Deviations from the general pattern of compositional zoning were not rare in the quantitative analysis. This may be caused mainly by the departure from the actual core due to the solid irregularity or local equilibrium limited within very small areas among or in the periphery of the mineral grain where some other mineral phases may contact it.

Plagioclase shows smooth (without step) reverse zoning. Composition of the core, preliminarily analyzed by optic means, varies from grain to grain and that of the margin is generally common to all grains; but its edge (outermost margin) is somewhat heterogeneous portion by portion according to mineral phases in contact with that portion. According to the probe analysis, the margin is depleted in Na and enriched in Ca and Fe relative to the core. The most sodic core is about An 30 and the most

Table 4. Chemical composition of orthopyroxene.

	1	2	3	4	5	6	7	8
SiO_2	51.25	51.50	50.52	50.67	50.05	49.67	50.11	50.35
TiO_2	0.10	0.07	0.13	0.15	0.10	0.10	0.11	0.19
Al_2O_3	1.67	1.21	1.64	1.22	1.27	1.41	1.44	1.30
FeO*	29.29	29.07	29.33	29.42	29.33	29.32	29.57	29.46
MnO	0.72	0.69	0.73	0.70	0.70	0.70	0.75	0.71
MgO	16.02	16.45	15.92	16.19	16.51	16.51	16.41	16.53
CaO	0.78	0.59	0.77	0.62	0.68	0.58	0.71	0.53
Na_2O	0.05	0.01	0.0	0.03	0.06	0.05	0.02	0.01
K_2O	0.01	0.0	0.0	0.03	0.01	0.01	n.d.	n.d.
Total	99.89	99.59	99.05	99.03	98.71	98.34	99.12	99.05
Cations relative to 6 oxygens								
Si	1.978	1.990	1.970	1.977	1.963	1.956	1.958	1.965
Ti	0.003	0.002	0.004	0.004	0.003	0.003	0.003	0.006
Al	0.076	0.055	0.076	0.056	0.059	0.065	0.066	0.060
Fe	0.945	0.939	0.957	0.960	0.962	0.965	0.966	0.962
Mn	0.024	0.023	0.024	0.023	0.023	0.023	0.025	0.023
Mg	0.921	0.947	0.925	0.942	0.965	0.969	0.956	0.962
Ca	0.032	0.024	0.032	0.026	0.029	0.024	0.030	0.023
Na	0.004	0.001	0.0	0.003	0.005	0.004	0.002	0.001
K	0.0	0.0	0.0	0.001	0.001	0.001	n.d.	n.d.

1: Core of grain No. 1, domain A.   2: Margin of grain No. 1, domain A, adjacent to plagioclase. 3: Core of grain No. 2, domain A.   4: Margin of grain No. 2, domain A, adjacent to biotite (analysis No. 2).   5: Core of grain No. 3, domain B.   6: Margin of grain No. 3, domain B, adjacent to hornblende (analysis No. 2).   7: Core of grain No. 4, domain C.   8: Margin of grain No. 4, domain C, adjacent to clinopyroxene (analysis No. 6).   7 and 8 were analyzed by S. YOSHIKURA.   *All assumed to be Fe^{+2}.

calcic margin is about An 50 by optic means, although six microprobe analyses range from An 40 to 47 (Table 3).

A large difference in the core and a small difference in the marginal portions between the optic and microprobe analyses need explanation; it is because the most sodic core by the optic means was selected from almost all grains throughout the slide, and that by the microprobe analysis was done only arbitrarily. Thus, An 30 after the optic means may be slightly calcic than, but nearly similar to, the actual core composition. This interpretation may possibly be adopted to microprobe analyses of other zoned minerals, i.e. the actual composition of the core has a large difference from the analyzed composition of cores.

Orthopyroxene is ferrohypersthene with about 50% of $Mg/Mg+Fe+Mn$. Composition of the core portion varies little from grain to grain. Individual grains of orthopyroxene are weakly zoned. Relative to the core, the margin is generally depleted in Al and Ca, enriched in Mg, and has a higher Mg/Fe ratio (Table 4).

Clinopyroxene is salite with En_{32-35} Fs_{20-25} Wo_{46-47} and represents smooth zoning. Composition of the core portion varies a little from grain to grain. Individual grains of clinopyroxene are zoned smoothly. Relative to the core portion, the margin is depleted in Al and Fe, enriched in Ca and Mg, and has a high Mg/Fe ratio (Table 5).

Garnet is almandine-pyrope, ranging in composition from 15 to 18 mole percent of pyrope. A sum of grossular and spessartine constitutes no more than 25 mole percent in any one garnet. Individual grains of garnet represent generally smooth zoning

Table 5. Chemical compositions of clinopyroxene.

	1	2	3	4	5	6
SiO_2	52.07	52.89	50.54	49.95	51.00	51.75
TiO_2	0.40	0.35	0.41	0.35	0.36	0.24
Al_2O_3	3.07	2.90	3.22	2.75	2.65	2.00
FeO*	12.64	11.87	15.07	12.25	12.13	11.21
MnO	0.34	0.36	0.34	0.34	0.36	0.31
MgO	10.70	11.23	11.52	11.15	11.44	12.16
CaO	21.26	21.62	18.71	21.66	21.40	22.11
Na_2O	0.67	0.64	0.70	0.67	0.55	0.41
K_2O	tr.	0.01	0.01	0.01	0.01	tr.
Total	101.15	101.85	100.50	99.13	98.81	100.19
Cations relative to 6 oxygens						
Si	1.948	1.957	1.917	1.918	1.934	1.950
Ti	0.011	0.010	0.012	0.010	0.010	0.007
Al	0.135	0.126	0.144	0.125	0.118	0.089
Fe	0.395	0.367	0.478	0.393	0.385	0.353
Mn	0.011	0.011	0.011	0.011	0.012	0.010
Mg	0.596	0.619	0.651	0.638	0.647	0.683
Ca	0.852	0.857	0.760	0.891	0.870	0.893
Na	0.049	0.046	0.051	0.050	0.040	0.030
K	tr.	tr.	tr.	tr.	0.001	tr.

1: Core of grain No. 1, domain A.   2: Margin of grain No. 1, domain A, adjacent to garnet (analysis No. 3).   3: Core of grain No. 2, domain B.   4: Margin of grain No. 2, adjacent to clinopyroxene. 5: Core of grain No. 3, domain C.   6: Margin of grain No. 3, domain C, adjacent to orthopyroxene (analysis No. 8).   5 and 6 were analysed by S. Yoshikura.   *All assumed to be Fe^{+2}.

Table 6. Chemical composition of garnet.

	1	2	3	4	5	6	7	8	9	10	11
SiO$_2$	38.78	38.93	38.63	37.46	37.65	37.39	36.98	37.28	37.71	37.43	38.02
TiO$_2$	0.04	0.05	0.02	0.06	0.04	0.06	0.05	0.04	0.05	0.04	0.07
Al$_2$O$_3$	20.63	20.70	20.51	20.08	20.41	20.02	19.99	19.85	20.67	20.80	20.87
FeO*	27.48	27.33	27.48	27.71	27.46	27.12	27.50	27.36	27.38	27.87	27.99
MnO	1.97	2.06	1.97	2.04	2.13	2.09	2.03	2.09	2.02	2.01	2.08
MgO	4.65	4.39	4.24	4.57	4.63	4.18	4.54	4.46	4.34	4.22	3.77
CaO	6.70	6.92	7.12	6.69	6.81	6.98	6.93	7.04	7.07	6.71	6.96
Na$_2$O	0.01	0.06	0.0	0.03	0.0	0.04	0.0	0.06	0.01	0.0	0.0
K$_2$O	0.02	0.02	0.01	0.0	0.0	0.0	0.01	0.01	0.01	0.01	0.02
Total	100.28	100.45	99.95	98.65	99.12	97.86	98.02	98.18	99.26	99.09	99.78
Cations relative to 12 oxygens											
Si	3.044	3.050	3.047	3.009	3.004	3.023	2.993	3.011	3.007	2.991	3.015
Ti	0.003	0.003	0.001	0.004	0.002	0.003	0.003	0.002	0.006	0.002	0.004
Al	1.909	1.912	1.906	1.901	1.919	1.908	1.906	1.889	1.938	1.959	1.951
Fe	1.804	1.791	1.812	1.861	1.832	1.833	1.861	1.847	1.821	1.862	1.857
Mn	0.131	0.136	0.131	0.139	0.144	0.143	0.139	0.143	0.136	0.136	0.140
Mg	0.544	0.512	0.498	0.547	0.551	0.503	0.548	0.536	0.514	0.503	0.446
Ca	0.564	0.581	0.601	0.576	0.582	0.604	0.601	0.609	0.602	0.574	0.591
Na	0.002	0.009	0.0	0.004	0.0	0.006	0.0	0.009	0.002	0.0	0.0
K	0.002	0.002	0.001	0.0	0.0	0.0	0.001	0.001	0.001	0.001	0.002

1: Core of grain No. 1, domain A. 2: Margin of grain No. 1, domain A, adjacent to plagioclase (analysis No. 2). 3: Margin of grain No. 1, domain A, adjacent to clinopyroxene (analysis No. 2). 4: Core of grain No. 2, domain B. 5: Margin of grain No. 2, domain B, adjacent to plagioclase. 6: Margin of grain No. 2, domain B, adjacent to plagioclase. 7: Core of grain No. 3, domain B. 8: Margin of grain No. 3, domain B, adjacent to plagioclase (analysis No. 6). 9: Core of grain No. 4, domain C. 10: Margin of grain No. 4, domain C, adjacent to plagioclase. 11: Margin of grain No. 4, domain C, adjacent to biotite (analysis No. 7). 9, 10 and 11 were analyzed by S. YOSHIKURA. *All assumed to be Fe^{+2}.

structure. Relative to the core, the margin is generally depleted in Mg, enriched in Ca, and has a lower Mg/Fe ratio (Table 6).

Biotite is rich in TiO$_2$ (5.1 to 8.0 weight percent). Individual grains of biotite are generally unzoned. However, their core compositions vary from grain to grain, and compositions of very thin and local margins also vary according to mineral species adjacent to the margins. An extraordinary compositional variation was observed at the edge in contact with ilmenite. Common to these various cases, the margin of biotite is generally depleted in Ti, enriched in Mg and Fe, and has a high Mg/Fe ratio relative to the core (Table 7).

Hornblende is rich in TiO$_2$ (about 4 weight percent). Individual grains of hornblende are unzoned. It is classed as pargasite on the basis of the number of Na + K (=0.96) and [Al]^{IV} (=1.90) atoms per formula unit (DEER et al., 1978) (Table 8).

Fe-Ti oxides are magnetite, ilmenite and ilmenite-magnetite compound. Magnetite includes about 1–2 mol % of ulvöspinel molecule and ilmenite includes about 5–8 mol % of hematite molecule (Table 9), assuming all TiO$_2$ to form ulvöspinel and all the excess FeO to form hematite respectively.

Table 7. Chemical compositions of biotite.

	1	2	3	4	5	6	7
SiO_2	35.75	35.87	34.45	35.15	35.81	35.44	35.80
TiO_2	7.09	7.04	7.97	6.23	5.12	7.03	6.84
Al_2O_3	13.67	13.67	13.43	13.88	14.48	13.83	13.88
FeO*	19.42	19.66	19.81	19.53	16.94	19.52	19.46
MnO	0.06	0.03	0.07	0.04	0.04	0.05	0.05
MgO	10.03	10.27	9.58	10.79	12.88	10.10	9.94
CaO	tr.	0.02	0.11	0.03	0.03	0.15	0.09
Na_2O	0.01	0.05	0.03	0.04	0.06	0.03	0.04
K_2O	9.32	9.51	9.71	9.61	9.65	9.18	9.10
Total	95.35	96.10	95.16	95.30	95.02	95.33	95.20
			Cations relative to 22 oxygens				
Si	5.480	5.466	5.342	5.413	5.450	5.438	5.488
Ti	0.817	0.806	0.929	0.722	0.586	0.811	0.789
Al	2.469	2.454	2.455	2.519	2.597	2.502	2.508
Fe	2.490	2.505	2.569	2.515	2.156	2.505	2.495
Mn	0.007	0.003	0.009	0.005	0.005	0.006	0.006
Mg	2.292	2.333	2.215	2.477	2.921	2.310	2.272
Na	0.004	0.014	0.009	0.013	0.017	0.004	0.006
K	1.823	1.848	1.920	1.888	1.873	1.797	1.780

1: Core of grain No. 1, domain A.   2: Margin of grain No. 1, domain A, adjacent to orthopyroxene (analysis No. 4).   3: Core of grain No. 2, domain B.   4: Core of grain No. 3, domain B.   5: Margin of grain No. 3, domain B, adjacent to ilmenite (analysis No. 2).   6: Core of grain No. 4, domain C. 7: Margin of grain No. 4, domain C, adjacent to garnet (analysis No. 11).   6 and 7 were analyzed by S. Yoshikura.   *All assumed to be Fe^{+2}.

Table 8. Chemical compositions of hornblende.

	1	2	3	4
SiO_2	40.33	40.20	39.07	40.57
TiO_2	3.67	3.96	3.93	3.65
Al_2O_3	12.56	12.85	12.65	12.50
FeO*	17.41	18.08	17.54	17.64
MnO	0.16	0.17	0.16	0.10
MgO	8.42	8.39	8.03	8.11
CaO	11.51	11.51	11.43	11.73
Na_2O	2.06	1.84	2.02	1.84
K_2O	2.04	2.01	1.94	1.98
Total	98.17	99.01	96.78	98.13
		Cations relative to 23 oxygens		
Si	6.133	6.074	6.046	6.169
Ti	0.420	0.450	0.457	0.417
Al	2.250	2.288	2.307	2.239
Fe	2.214	2.284	2.270	2.242
Mn	0.020	0.021	0.022	0.013
Mg	1.908	1.889	1.852	1.839
Ca	1.875	1.864	1.895	1.911
Na	0.608	0.538	0.607	0.544
K	0.396	0.387	0.383	0.383

1: Core of grain No. 1, domain A.   2: Core of grain No. 2, domain B.   3: Core of grain No. 3, domain A.   4: Core of grain No. 4, domain B.   *All assumed to be Fe^{+2}.

Table 9.   Chemical compositions of ilmenite and magnetite.

	1	2	3	4*
SiO_2	0.05	0.04	0.01	0.01
TiO_2	51.01	50.97	0.35	0.35
Al_2O_3	0.02	0.03	0.63	0.63
Fe_2O_3				67.96
FeO**	48.30	49.26	91.72	30.57
MnO	0.77	0.84	0.01	0.01
MgO	0.14	0.05	0.03	0.03
CaO	tr.	0.05	0.03	0.03
Na_2O	0.05	0.04	0.01	0.01
Total	100.33	101.33	92.85	99.66
Cations relative to 3 (ilmenite) and 4 (magnetite) oxygens				
Si	0.001	0.002	0.005	0.004
Ti	0.974	0.967	0.013	0.012
Al	tr.	0.001	0.038	0.035
Fe^{+3}	n.d.	n.d.	n.d.	1.864
Fe^{+2}	1.026	1.039	3.904	0.982
Mn	0.017	0.018	tr.	tr.
Mg	0.005	0.002	0.001	0.001
Ca	tr.	0.001	0.001	0.001
Na	0.002	0.002	0.001	0.001

1 and 2: Ilmenite, domain B.   3 and 4: Magnetite, domain B.   *Data of 4 were recalculated from data of 3 on the basis of the assumption of $2Fe^{+2} = Fe^{+3}$.   **All assumed to be Fe^{+2}.   n.d.: not determined.

4.3.   Geothermometry and geobarometry calculations

Element partitionings between garnet-biotite, orthopyroxene-clinopyroxene, garnet-clinopyroxene, garnet-orthopyroxene, clinopyroxene-hornblende and magnetite-ilmenite of the specimen appear possible to provide some temperature and pressure values following calculations of common geothermometries and a geobarometry premising that each mineral pair was in equilibrium.   The calculated pairs are composed of the margin-margin or the core-core portions for anhydrous mineral pairs, according to the assumption that the core of a mineral reflects conditions of the earlier metamorphism and the margin does conditions of the later metamorphism; this assumption will be discussed later in Subsection 5.3.   The composition of the central portion of hornblende is used as a counterpart of any portions of clinopyroxene because of the lack of zoning in hornblende.

Obtained values of temperature and pressure are somewhat scattered.   This may be due mainly to the deviation of the composition of either one or both of the analyses of the mineral pairs from the actual or the ordinary core or margin of the minerals as mentioned already.   In calculating temperature or pressure using geothermometries or a geobarometry, not all the analyses of minerals but only those minerals which occur within the small domain were used.   Thus, dozens of temperatures and pressures were calculated with respect to the margin pairs and core pairs.   Number of calculated values for core pairs and margin pairs were arithmatically averaged; these values are regarded as those of the average core or of the average margin.   The highest value among those of core pairs is designated as that of the maximum core pairs and the

Table 10.   Calculated temperature and pressure.

Mineral pair (reference)	Core(C) pair or margin(M) pair	T °C	P kb
Garnet-biotite (Thompson, 1976)	$C_{No.4}^{gt} - C_{No.3}^{bio}$ max.	780	
	$C^{gt} - C^{bio}$ av.	740	
	$M^{gt} - M^{bio}$ av.	690	
	$M_{No.8}^{gt} - M_{No.5}^{bio}$ min.	615	
Orthopyroxene-clinopyroxene (Wood and Banno, 1973, Wood, 1975)	$C_{No.5}^{opx} - C_{No.3}^{cpx}$ max.	835*	
	$C^{opx} - C^{cpx}$ av.	769*	
	$M^{opx} - M^{cpx}$ av.	744*	
	$M_{No.6}^{opx} - M_{No.4}^{cpx}$ min.	737*	
	$C_{No.5}^{opx} - C_{No.3}^{cpx}$ max.	832**	
	$C^{opx} - C^{cpx}$ av.	771**	
	$M^{opx} - M^{cpx}$ av.	746**	
	$M_{No.6}^{opx} - M_{No.4}^{cpx}$ min.	725**	
Garnet-clinopyroxene*** (Ellis and Green, 1979)	$C_{No.7}^{gt} - C_{No.3}^{cpx}$ max.	801	
	$C^{gt} - C^{cpx}$ av.	765	
	$M^{gt} - M^{cpx}$ av.	696	
	$M_{No.11}^{gt} - M_{No.6}^{cpx}$ min.	654	
Clinopyroxene-hornblende (Kretz and Jen, 1978)	$C_{No.1}^{cpx} - C_{No.1}^{ho}$ max.	640	
	$C^{cpx} - C^{ho}$ av.	615	
	$M^{cpx} - M^{ho}$ av.	<600	
	$M_{No.2}^{cpx} - M_{No.2}^{ho}$ min.	<600	
Ilmenite-magnetite (Spencer and Lindsley, 1981)	$C^{il} - C^{mag}$	550	
Garnet-orthopyroxene (Wood and Banno, 1973)	$C_{No.7}^{gt} - C_{No.5}^{opx}$ max.		6.5*
	$C^{gt} - C^{opx}$ av.		5.0±1.0*
	$M^{gt} - M^{opx}$ av.		4.5±2.0*
	$C_{No.7}^{gt} - C_{No.5}^{opx}$ max.		10.0**
	$C^{gt} - C^{opx}$ av.		6.4±3.5**
	$M^{gt} - M^{opx}$ av.		4.1±3.0**

* Calculated values were obtained, assuming to be $Al^{IV} = Al^{VI}$.   ** Calculated values were obtained, assuming to be $Al^{IV} + Si = 2.0$.   *** Temperature were calculated on the basis of the assumption of P=6 kbar.   The symbols of max., min. and av. are maximum, minimum, and average temperatures or pressures, respectively.   The symbols of gt, bio, opx, cpx, ho, il and mag are garnet, biotite, orthopyroxene, clinopyroxene, hornblende, ilmenite and magnetite, respectively.   Subscripts represent analysis numbers.

lowest value among those of the margin pairs as that of the minimum margin pairs. Thus, temperatures and pressures after the average core, average margin, maximum core, and minimum margin pairs are obtained (Table 10).   These temperatures and pressures are used in the description and discussion hereafter in this article.

The garnet-biotite geothermometry after Thompson (1976) provided the values from 780 to 615°C.   Though the temperature using garnet-biotite geothermometry is considered to be affected by the contents of Ti and Fe^{3+} in biotite (Thompson, 1976; Grew, 1981), their effect was not taken into consideration.   The two pyroxene geo-

thermometry after WOOD and BANNO (1973) has been generally considered to provide somewhat higher temperatures and hence 50°C reduction was proposed by WOOD (1975). This method gave from 835 to 725°C, estimating $[Al]^{IV} = [Al]^{VI}$ or $Si + [Al]^{IV} = 2.0$ in orthopyroxene. The garnet-clinopyroxene geothermometry after ELLIS and GREEN (1979) gave from 801 to 654°C, estimating the pressure to be about 6 kb. The clino-pyroxene-hornblende geothermometry after KRETZ and JEN (1978) gave from 640 to below 600°C. Since the geothermometry temperature is strongly affected by the Fe^{3+}/Fe^{2+} ratio of hornblede and clinopyroxene, these temperatures may include some un-certainties.

The garnet-orthopyroxene geobarometry after WOOD and BANNO (1973) gave from 10.0 to 1.3 kb, estimating $[Al]^{IV} = [Al]^{VI}$ or $Si + [Al]^{IV} = 2.0$ in orthopyroxene, and tem-peratures of the two pyroxene geothermometry using the corresponding orthopyroxenes with those of the calculated geobarometry pairs. The pressure after the minimum margin pair is too low and therefore is omitted from the list in Table 10.

The Fe-Ti partitioning between magnetite and ilmenite provides equilibrium tem-perature and oxygen fugacity of the rock, premising that the rock suffered no later oxidation or reduction of the oxide minerals (SPENCER and LINDSLEY, 1981). Composi-tions of coexistent magnetite and ilmenite plotted in the SPENCER and LINDSLEY's diagram show the conditions of *ca.* 550°C and fO_2, about 10^{-20} atm. Later oxidation of Fe-Ti oxides, however, is estimated by the occurrence of the hematite-goethite like material as mentioned in Section 3.

5. Discussions

5.1. Polymetamorphism or monometamorphism

As mentioned previously, there have been some discussions about the polymeta-morphism-monometamorphism problem for the rocks around Lützow-Holmbukta. BANNO *et al.* (1964) and SUWA (1968) studied facies petrology from the viewpoint of monometamorphism; they have concluded that the metamorphic grade of the region is of low (or low-pressure subfacies) granulite facies, regarding hydrous minerals to be in equilibrium with anhydrous ones. But RAVICH and KAMENEV (1975), YOSHIDA (1978) and YOSHIDA *et al.* (1982b) stressed the polymetamorphic interpretation; they have concluded that the main mineral parageneses of the metamorphites are affected by the earlier dominant granulite facies (M_2 of YOSHIDA *et al.*) and by the later dominant amphibolite facies (M_3) metamorphisms. This problem is still under discussion (*e.g.* YOSHIDA *et al.*, 1982b; HIROI *et al.*, 1983). The present study does not intend to discuss this problem but to offer some data which may be of some use to discussions on this problem and to try their attribution to both the monometamorphic and polymeta-morphic interpretations.

Most of microstructures including zoning patterns of minerals of the discordant metabasite can be interpreted by a time-thermal structure of a single dominant granulite facies metamorphism. Later occurrence of hydrous minerals than anhydrous ones can be interpreted as an indication of continued growth of hydrous minerals later than that of anhydrous ones during one dominant metamorphism as mentioned in Subsection 5.4. Thus, geothermometry temperatures ranging from over 800°C to below 600°C

from maximum core pairs to minimum margin pairs through average core and average margin pairs may be explained as reflection of the temperature conditions changing from the peak to the later epoch of the metamorphism (evaluation of geothermometry and geobarometry values after various mineral pairs are mentioned in Subsection 5.5).

However, the polymetamorphic history of the rock referred to that of the rocks around Lützow-Holmbukta after YOSHIDA et al. (1982b) is also not incompatible with the occurrence and zoning patterns of minerals and various geothermometry-geobarometry values of the discordant metabasite. Field occurrence and tectonics of the rock appear somewhat favorable to the polymetamorphic history. HIROI et al. (1983) throw a question to a part of the YOSHIDA's (1978) polymetamorphic interpretation on the rocks from Lützow-Holmbukta and the Prince Olav Coast and considered one progressive amphibolite-granulite facies metamorphism that grades up from the Prince Olave Coast to Lützow-Holmbukta. However, the fact that zoning pattern of garnet as well as that of some other minerals of the present study differs significantly from that of the Prince Olave Coast (YOSHIKURA et al., 1979; KANISAWA and YANAI, 1982) may be a problem to the HIROI et al.'s (1983) interpretation. In the following sections, tentative attributions of the petrographic data to the polymetamorphic scheme will be discussed.

5.2. Time relation between the intrusion of the metabasite and recurrent tectono-metamorphic events

Foliated and microfolded nature as described in Section 2 as well as granoblastic microstructures of the metabasite as described in Section 3 indicate that the dike suffered some metamorphism and tectonics. The microfold and mineral lineation of the dike, as well as those of the country paragneiss, may be correlated (as YOSHIDA, 1977, 1978) to the E-W upright fold of the third event of YOSHIDA et al. (1982b). Elongation of hornblende and biotite along the lineation may support this correlation. The lack of chilled margins and boundary pegmatite indicates the intrusion to have taken place under a somewhat high temperature condition. The rock is considered to have suffered the granulite facies metamorphism as indicated by the mineral constitution of granoblastic equant granular plagioclase, orthopyroxene, and clinopyroxene; this metamorphism is considered to be referred to that of the second event as YOSHIDA (1977) stated. Thus, the metabasite might have intruded during a high temperature condition earlier than or synchronously with the second tectono-metamorphic (M_2) event of YOSHIDA et al.

YOSHIDA (1977) considered that the dike might have intruded before the recumbent-isoclinal folds of the first event; he attributed the thin banding-foliation structure of the metabasite as well as that of the country rocks to the folding tectonics. In summary, it is probable that the dike intruded synchronously with or earlier than the first tectono-metamorphic event of YOSHIDA et al.

The E-W upright fold could only have disturbed the pre-existent s-structures or provided the upright schistosity parallel to the axial surface (YOSHIDA, 1978). Somewhat indistinct nature of the banding-foliation structure in *ac* section in comparison with the distinct banding-foliation in *bc* section, and occurrence of some biotite with highly inclined basal plane from the *ab* plane appear also favorable to the above interpretation.

Development of alteration minerals such as chlorite, hydromica, and calcite may reflect lower conditions surrounding the greenschist facies. This event is considered possible to be referred to the fifth metamorphism (M_5) of YOSHIDA *et al.* (1982b). It may be noted that the cracks associated with this alteration run nearly normal to the banding-foliation structure. It is probable that this fact reflects some tectonic condition during the alteration.

5.3. Genesis of garnet

Garnet occurs generally among aggregates of polygonal plagioclases and only rarely is attached to pyroxenes. It is generally granular; but some smaller grains are irregular in shape. Biotite, hornblende, and Fe-Ti oxides sometimes are attached to garnet. The garnet shows generally smooth zoning with enriched Ca and depleted Mg towards the margin.

Occurrence of the garnet as mentioned above is not incompatible with the YOSHIDA *et al.*'s (1982b) scheme of metamorphic history of the Lützow-Holmbukta region; garnet formed during the first high-pressure granulite facies metamorphism (M_1) might have been reduced in size and quantity, and homogenized during the second intermediate-pressure granulite facies metamorphism (M_2) and finally the composition might have changed from the margin to form the zonal structure during the third amphibolite facies metamorphism (M_3) (*cf.* YOSHIDA, 1979b, p. 109). The marginal portion of garnet might not have been added to the core portion, *i.e.* the garnet might not have enlarged, during M_3 metamorphism because the shape of the garnet constitutes the polygonal structure which is regarded (by YOSHIDA, 1978) as the representative structure of the M_2 metamorphic event.

The validity of such attribution of garnet occurrence in the discordant metabasite to the YOSHIDA *et al.*'s scheme of metamorphic history as above should be further examined in future. Whatever the actual genesis of the garnet or every portion of the garnet may be, it is possible that the composition of the core portion of garnet reflects earlier metamorphic conditions and that of the marginal portion does the later conditions. These conditions are tentatively referred to those of M_2 and M_3 metamorphisms hereafter in this article, since mineral parageneses of the rocks around Lützow-Holmbukta are considered (by YOSHIDA *et al.*, 1982b) to have been reflected principally by these two metamorphisms. This interpretation may also be possible to be adopted tentatively to the zoning of pyroxenes. But these are tentative. Further studies on growth history and zoning mechanism of each mineral are needed.

5.4. Genesis of biotite and hornblende

As mentioned previously in Section 3, biotite and hornblende grow generally later than plagioclase and pyroxenes. According to PORDERVAART (1953), later growth of biotite and/or hornblende in metabasite of the granulite terrain may rather be a reflection of the lowered temperature conditions of the granulite facies metamorphism during its later epoch than a general indication of the superposition of later amphibolite facies metamorphism. His preference appears to conform with the recent YARDLEY's (1981) statement that some portions of expelled H_2O component through the dehydration reactions during the peak of metamorphism may form hydrous minerals during the early stage of cooling. This H_2O component may result in the grain boundary hydra-

tion (Vernon, 1976, p. 55) of the pre-existent anhydrous minerals which have adjusted grain boundaries (so as to form the polygonal structure). These interpretations appear probable. However, if such process fully affects metamorphism, no pyroxene granulite free from hydrous minerals should exist in the earth crust. In the following pages, we will tentatively explain the occurrence of biotite following the polymetamorphic scheme of Yoshida et al.

Yoshida (1978, 1979b) stated that in the Lützow-Holmbukta region, biotite and hornblende might have been stable during the granulite facies metamorphism in some rocks, but have been formed afterwards during the later dominant amphibolite facies metamorphism in others; chemical composition, H_2O content, and tectono-metamorphic history of a rock might affect the genesis of hydrous minerals in the rock. Some examples follow:

    i) Xenocrystic biotite and hornblende in anhydrous minerals in charnockitic rocks are the relic of either the early epoch of the dominant progressive granulite facies metamorphism (M_2) or the relic of the metamorphism of the first event earlier than the dominant granulite facies metamorphism (Yoshida et al., 1982b). ii) Some biotites in charnockitic rocks, showing postdating occurrence than anhydrous minerals and lattice preferred orientation parallel to the axial surface of the E-W upright fold of the third tectono-metamorphic event, belong to the later dominant amphibolite facies metamorphism (M_3). iii) Other biotite and hornblende which show the stable polygonal structure with anhydrous minerals are considered to have been stable during the granulite facies metamorphism (M_2) of the second event (Yoshida, 1978).

Biotite and hornblende of the present study show general alteration occurrence after anhydrous minerals but appear to represent no distinctive lattice preferred orientation (statistical fabric analysis, however, has not been made) parallel to the axial surface of the E-W upright folds; such schistosity develops in some metamorphites in Skallen. Thus the genesis of biotite and hornblende of the discordant metabasite cannot be determined easily. A complex explanation may or may not be adopted to the genesis of these minerals; some xenocrystic biotite and hornblende (example i) and polygonal ones (example iii) have enlarged during the amphibolite facies metamorphism of the third event (example ii) to intrude into and to alter anhydrous minerals. A possibility exists that some biotites with their basal planes highly inclined from the ab plane of the rock are referred to the biotite of the third event. Somewhat elongate nature of both hornblende and biotite along the fabric axis b supports this possibility. Compositions of almost all these minerals, however, might reflect the dominant metamorphic conditions they have suffered lastly, i.e. M_3 metamorphism. Thin, strongly zoned and local margin of biotite may reflect conditions of a later epoch or epochs during or postdating the last dominant metamorphism, i.e. M_3, and/or M_4 metamorphisms.

5.5. Evaluation of geothermometry-geobarometry values

Geneses of constituent minerals of the discordant metabasite may be complex and are invalid at the present stage of our knowledge; some of the problems have been mentioned previously. But coincidences of geothermometry temperature values after different geothermometers may be of some significance. Therefore, a tentative correlation of the geothermometry-geobarometry values with conditions of recurrent meta-

morphisms of YOSHIDA *et al.* (1982b) is presented in the following based on the tentative interpretation of zoning of minerals as mentioned in Subsections 4.2, 5.3 and 5.4.

Temperatures after the average margin pairs of garnet-biotite and garnet-clinopyroxene fall within $693 \pm 3°C$, which may reflect the temperature during M_3 metamorphism. Temperatures after the margin pairs of two pyroxenes appear not suitable for consideration because zoning of orthopyroxene is too weak. Problems on the interpretation of the minimum temperatures after the margin pairs will be mentioned later.

Temperatures after the average core pairs of garnet-clinopyroxene and of clinopyroxene-orthopyroxene fall within $768 \pm 3°C$, and this may possibly reflect the temperature condition of the M_2 metamorphism. But all analyses were made on mineral grains which were selected arbitrarily and their core portions are smoothly zoned; accordingly, none of them are considered to represent the composition of the pre-zoning epoch of the mineral (*cf.* descriptions of plagioclase zoning in Subsection 4.2). For these reasons, $768 \pm 3°C$ may point some intermediate temperature between M_2 and M_3 metamorphisms, and thus may limit the minimum temperature of the former.

The maximum core pairs of garnet-clinopyroxene and of two pyroxenes provided 801, 835 and 832°C. The average of these temperatures, $823 \pm 22°C$, possibly points the temperature nearer to M_2 metamorphism than the temperature after the average core pairs mentioned above. But the temperature after the maximum core pairs may be even much lower than that of the peak of the metamorphism, because the similar interpretation of the compositional zoning of minerals to the one made on the average core pairs is considered applicable also to the maximum core pair. Thus, the temperature of the peak of M_2 metamorphism may be much higher than *ca.* 823°C. Temperatures after the core pairs of garnet-biotite appear not suitable for consideration because of the nearly unzoned nature of biotite.

Low temperature of 550°C and oxigen fugacity of 10^{-20} atm obtained for a magnetite-ilmenite pair conform with the observation that the contact edge of biotite with nilmenite has different composition from the ordinary margin of biotite. This local zoning of biotite, as well as the magnetite-ilmenite temperature, may reflect conditions of much later events during or postdating M_3 metamorphism. But evidence of later oxidation eliminates the validity of these values. The minimum margin pairs of garnet-biotite and garnet-clinopyroxene provided somewhat lower temperatures, which may possibly reflect temperatures of the late epoch during or postdating M_3 metamorphism. But mechanism of the local equilibrium or possibility of deviation from equilibrium may be problems for the interpretation of these temperatures.

Temperatures after the clinopyroxene-hornblende geothermometry are somewhat scattered and low. The low temperature may be favorable to the assumption (Subsection 5.4) of the later generation of hornblende. But no analysis of Fe^{3+} causes considerable inaccuracy to these temperatures.

The garnet-orthopyroxene geobarometry provided pressures of 6.5 and 10.0 kb for the maximum core pair, 5.0 ± 1 and 6.4 ± 3.5 kb for the average core and 4.5 ± 2 and 4.1 ± 3 kb for the average margin pairs with assumptions of $[Al]^{IV} = [Al]^{VI}$ and $Si + [Al]^{IV} = 2.0$, respectively. These values with two assumptions are averaged, and thus 8.2 ± 2 kb for the maximum core, 5.7 ± 3.5 kb for the average core, and 4.3 ± 3 kb for the average margin pairs are obtained. The former two pressures may limit the lower

pressure of the M_2 metamorphism and the last one may reflect the pressure of M_3 metamorphism, adopting the similar interpretation to that made for the geothermometry temperatures.   The geobarometry value is sensitive to the Al content of orthopyroxene and its distribution between tetrahedral and octahedral sites.   Since the estimation of site occupancy of Al in orthopyroxene is too arbitrary as pointed out by Wilson (1976), and since the microprobe analysis involves some inaccuracy in analysis of Si, deviation of the geobarometry values from the actual conditions or from those estimated from the mineral parageneses cannot be ruled out.   Poorly zoned nature of orthopyroxene in comparison with the ordinary zoned nature of garnet would increase the possibility that some pairs of these minerals are not in equilibrium.   Furthermore, calculated pressure values are greatly scattered.   These appear to result in lessening the reliability of these pressure values.

6.   Summary

A discordant metabasite from Skallen is an olivine tholeiite petrochemically resembling some of the Proterozoic Amundsen dikes of Enderby Land.   Field occurrence, mineral association, and microstructure indicate that the rock intruded synchronously with or earlier than possibly the second, and probably the first tectono-metamorphic event of Yoshida et al. (1982b).

The metabasite is composed of plagioclase (reversely zoned with ca. An 30 core and ca. An 50 rim), ferrohypersthene (weakly zoned with Mg richer rim), salite (zoned with more calcic and magnesian margin), biotite (nearly unzoned with about 5 to 8% TiO_2), hornblende (unzoned pargasite with about 4% TiO_2), Fe-Ti oxides (magnetite, ilmenite, and magnetite-ilmenite compound), and garnet (almandine-pyrope with about 15–18% of pyrope molecules, weakly zoned with Ca-rich margins), with some other accessories including hydromica and chlorite.   Texture of the rock is fine-grained granoblastic equigranular polygonal; plagioclase and pyroxenes are typomorphic constituents of the rock formed under the granulite facies metamorphism, while some biotite and hornblende are of later production formed under the lower temperature and hydrous conditions.

These textural characteristics are not incompatible with the polymetamorphic interpretation (Yoshida et al.) of metamorphites around Lützow-Holmbukta; tentative interpretations are as follows.   Compositions of all biotite and hornblende are supposed to have changed completely during the later dominant amphibolite facies metamorphism (M_3).   Genesis of garnet is problematic; but composition of its core is supposed to reflect the conditions of the earlier dominant granulite facies metamorphism (M_2), and that of the marginal portion is supposed to reflect conditions of the later dominant metamorphism (M_3).   Zoning patterns of pyroxenes are also supposed to be interpreted in the similar fashion to garnet.

Calculations of geothermometry temperatures and geobarometry pressures were made, utilizing element partitionings between two pyroxenes, garnet-biotite, garnet-clinopyroxene, clinopyroxene-hornblende, garnet-orthopyroxene and magnetite-ilmenite. The results are tentatively interpreted under the polymetamorphic scheme of Yoshida et al.   The temperature $693\pm3°C$ for the average margin pairs of garnet-biotite after

the Thompson's (1976) and of garnet-clinopyroxene after the Ellis and Green's (1979) geothermometries possibly reflects the temperature of M_3 metamorphism. The temperature of the peak of M_2 metamorphism is considered to be higher than $768 \pm 3°C$ for the average core pairs of two pyroxenes after Wood and Banno's (1973) geothermometry with 50°C reduction and of garnet-clinopyroxene after Ellis and Green's method; it is probably much higher than $823 \pm 22°C$ which was obtained by averaging maximum temperatures after the core pairs.

The minimum temperatures obtained for the margin pairs after garnet-biotite and garnet-clinopyroxene are 615 and 654°C, respectively, and Fe-Ti distribution between magnetite and ilmenite provided a temperature of 550°C and oxigen fugacity of 10^{-20} atm after the Spencer and Lindsley's (1981) diagram. These values may reflect conditions of much later stage during or postdating M_3 metamorphism; but the local compositional heterogeneity of minerals and later oxidation cause problems to these values which should be examined in future. The clinopyroxene-hornblende geothermometry temperatures ranging from 640 to below 600°C are considered to involve considerable inaccuracy and should be further examined.

A garnet-orthopyroxene geobarometry after Wood and Banno (1973) provided pressures of 8.2 ± 2, 5.7 ± 3.5, and 4.3 ± 3 kb for the maximum core, the average core and the average margin pairs respectively, averaging pressure values calculated through two assumptions as $[Al]^{IV} = [Al]^{VI}$ and $[Al]^{IV} + Si = 2.0$. The estimation of site occupancy of Al in orthopyroxene may have caused large inaccuracy of these values, although the values appear to conform with the pressure conditions of M_2 and M_3 metamorphisms estimated by Yoshida (1979b) mainly from mineral parageneses of the rocks around Lützow-Holmbukta.

Development of alteration minerals such as chlorite, hydromica, and calcite along cracks nearly normal to the banding-foliation structure is considered referable to the fifth metamorphism (M_5) of Yoshida et al. (1982b).

Zoning patterns of minerals and various geothermometry-geobarometry values are considered possible to be interpreted by a monometamorphic history of the rock; in this case, the rock might have suffered the high granulite facies metamorphism, the temperature of the peak of the metamorphism is considered much higher than ca. 823°C. Further studies on mesoscopic to microscopic tectonics, microstructures including compositional heterogeneities in each mineral grain in relation to occurrence may provide a key to the metamorphic history of the discordant metabasite.

Acknowledgments

References

Banno, S., Tatsumi, T., Ogura, Y. and Katsura, T. (1964): Petrographic studies on the rocks from the Lützow-Holmbukta. Antarctic Geology, ed. by R. J. Adie. Amsterdam, North Holland, 405–414.

Bence, A. B. and Albee, A. L. (1968): Empirical correction factors for the electron microanalysis of silicate and oxide. J. Petrol., **76**, 382–403.

Chayes, F. (1956): Petrographic Modal Analysis; An Introductory Statistical Appraisal. New York, J. Wiley, 113p.

Deer, W. A., Howie, R. A. and Zussman, J. (1978): Rock-Forming Minerals, Vol. 2A, Single-chain Silicates. 2nd ed. London, Longman, 588–613.

Ellis, D. J. and Green, D. H. (1979): An experimental study of the effect of Ca upon garnet-clinopyroxene Fe-Mg exchange equilibria. Contrib. Mineral. Petrol., **71**, 13–22.

Grew, E. S. (1981): Granulite-facies metamorphism at Molodezhnaya Station, East Antarctica. J. Petrol., **22**, 297–336.

Hiroi, Y., Shiraishi, K., Yanai, K. and Kizaki, K. (1983): Aluminum silicates in the Prince Olav and Sôya Coasts, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **28**, 115–131.

Kanisawa, S. and Yanai, K. (1982): Metamorphic rocks of the Cape Hinode district, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **21**, 71–85.

Kretz, R. and Jen, L. S. (1978): Effect of temperature on the distribution of Mg and Fe^{2+} between calcic pyroxene and hornblende. Can. Mineral., **16**, 533–537.

Kuno, H. (1959): Origin of Cenozoic petrographic provinces of Japan and surrounding areas. Bull. Volcanol., Ser. II, **20**, 37–76.

Moor, A. (1970): Descriptive terminology for the textures of rocks in granulite facies terrains. Lithos, **3**, 123–127

Nakamura, Y. and Kushiro, I. (1970): Compositional relations of coexisting orthopyroxene, pigeonite and augite in a tholeiitic andesite from Hakone Volcano. Contrib. Mineral. Petrol., **26**, 265–275.

Pordervaart, A. (1953): Metamorphism of basic rocks; A review. Bull. Geol. Soc. Am., **64**, 259–274.

Ravich, M. G. and Kamenev, E. N. (1975): Crystalline Basement of the Antarctic Platform. New York, Halsfed Press, 582p.

Sheraton, J. W. and Black, L. P. (1981): Geochemistry and geochronology of Proterozoic tholeiite dykes of East Antarctica; Evidence for mantle metasomatism. Contrib. Mineral. Petrol., **78**, 305–317.

Spencer, K. J. and Lindsley, D. H. (1981): A solution model for coexisting iron-titanium oxides. Am. Mineral., **66**, 1189–1201.

Suwa, K. (1968): Petrological studies on the metamorphic rocks from the Lützow-Holmbukta area, East Antarctica. 23rd Int. Geol. Congr., **4**, 171–187.

Teutscher, E. O. (1933): Methodisches zur quantitativen Struckturgliederung korniger Gesteine. Tschermaks Mineral. Petrogr. Mitt., **44**, 410–420.

Thompson, A. B. (1976): Mineral reactions in pelitic rocks, II. Calculation of some P-T-X (Fe-Mg) phase relations. Am. J. Sci., **276**, 425–454.

Turner, F. J. and Weiss, L. E. (1963): Structural Analysis of Metamorphic Tectonites. New York, McGraw-Hill, 545p.

Vernon, R. H. (1976): Metamorphic Processes. London, Thomas Murby, 243p.

Wilson, A. F. (1976): Aluminium in coexisting pyroxenes as a sensitive indicator of changes in metamorphic grade within the mafic granulite terrane of the Fraser Range, Western Australia. Contrib. Mineral. Petrol., **56**, 255–277.

Wood, B. J. (1975): The influence of pressure-temperature and bulk composition on the appearance of garnet in orthogneisses; An example from South Harris, Scotland. Earth Planet. Sci. Lett., **26**, 299–311.

Wood, B. J. and Banno, S. (1973): Garnet-orthopyroxene and orthopyroxene-clinopyroxene relationships in simple and complex systems. Contrib. Mineral. Petrol., **42**, 109–124.

Yardley, B. W. D. (1981): Effect of cooling on the water content and mechanical behavior of metamorphosed rocks. Geology, **9**, 405–408.

Yorder, H. S., Jr. and Tilley, C. E. (1962): Origin of basalt magma; An experimental study of natural and synthetic rock system. J. Petrol., **3**, 342–532.

Yoshida, M. (1977): Geology of Skallen region, Lützow-Holmbukta, East Antarctica. Mem. Natl

Inst. Polar Res., Ser. C (Earth Sci.), **11**, 38p.

YOSHIDA, M. (1978): Tectonics and petrology of charnockites around Lützow-Holmbukta, East Antarctica. J. Geosci., Osaka City Univ., **21**, 65–152.

YOSHIDA, M. (1979a): Tectonics and metamorphism of the region around Lützow-Holmbukta, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **14**, 28–40.

YOSHIDA, M. (1979b): Metamorphic conditions of the polymetamorphic Lützow-Holmbukta, East Antarctica. J. Geosci., Osaka City Univ., **22**, 97–139.

YOSHIDA, M., YOSHIDA, Y., ANDO, H., ISHIKAWA, T. and TATSUMI, T. (1976): Geological map of Skallen, Antarctica. Antarct. Geol. Map Ser., Sheet **9** (with explanatory text 16p.). Tokyo, Natl Inst. Polar Res.

YOSHIDA, M., YANAI, K., YOSHIKURA, S., ISHIKAWA, T. and KANISAWA, S. (1982a): Tectonics and microstructure of charnockites around Lützow-Holmbukta, East Antarctica. Antarctic Geosciences, ed. by C. CRADDOCK. Madison, Univ. Wisconsin Press, 511–519.

YOSHIDA, M., SUZUKI, M., SHIRAHATA, H., KOJIMA, H. and KIZAKI, K. (1982b): A review of the tectonic and metamorphic history of the region around Lützow-Holm Bay, East Antarctica. submitted to Antarctic Earth Science; Proc. 4th Int. Symp., Adelaide, 1982.

YOSHIKURA, S., NAKAI, Y. and KANO, T. (1979): Petrology and geothermometry of the clinopyroxene-garnet rock from Cape Ryûgû, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **14**, 172–185.