GRANULITE-FACIES ROCKS IN SEVERAL ISLANDS WEST OF LANGHOVDE, EAST ANTARCTICA

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Abstract: Several islands in the west of Langhovde (69°08′–69°17′S, 39°24′–39°36′E), East Antarctica, are underlain by granulite-facies metamorphic rocks. Among them pyroxene gneiss is the most dominant rock type. It includes garnet-bearing layers, in which orthopyroxene, clinopyroxene, garnet and hornblende are present in equilibrium. These minerals are generally rich in Fe, reflecting the bulk chemistry of the host rocks. Especially, the orthopyroxenes in two specimens of pyroxene gneiss have Fe/(Fe+Mn+Mg) ratios higher than 0.9. The stability field of such Fe-rich orthopyroxenes has been estimated to be more than 9 kb at 800°C. On the other hand, the calculated results by the geothermometers using orthopyroxene-clinopyroxene and garnet-clinopyroxene pairs and the geobarometers using a garnet-orthopyroxene-plagioclase association range 750–800°C and 7–8 kb.

1. Introduction

Several islands in the west of Langhovde, tentatively named West Langhovde Islands here, are situated between 69°08′–60°17′S in latitude and 39°24′–39°36′E in longitude in the northeastern part of Lützow-Holm Bay, East Antarctica. Geology and petrography of the rocks exposed in the islands have been reported by KATSUSHIMA and YANAI (1984). In their neighboring areas including the Ongul Islands, Langhovde and Skallen, geological investigations have been carried out since the first Japanese Antarctic Research Expedition (JARE-1). BANNO *et al.* (1964) and SUWA (1968) first revealed that the main metamorphism in this region has attained to the lower grade of granulite facies based on the petrological and mineralogical characters. YOSHIDA (1978, 1979) and SUZUKI (1983) estimated the metamorphic conditions under which the granulite-facies rocks were formed. Recently, HIROI *et al.* (1984) proposed to name collectively the metamorphic rocks in the Lützow-Holm Bay and Prince Olav Coast regions "the Lützow-Holm Complex", which is characterized by a sequence of kyanite-sillimanite type metamorphism from amphibolite- to granulite-facies graded from east to west. MOTOYOSHI *et al.* (1984) suggested that the maximum grade of the metamorphism of the complex exists in the southern Lützow-Holm Bay region based on the petrologic study mainly of pyroxene gneiss.

In the present area, the association of orthopyroxene, clinopyroxene, garnet and hornblende is common among pyroxene gneiss. Previously this association was reported only for one specimen in the Lützow-Holm Bay region (YOSHIDA, 1978). This paper presents the mineralogical characteristics of the garnet-bearing pyroxene

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gneiss and some related metamorphic rocks, and the discussion on the metamorphic conditions in this area.

2. Outlines of Geology and Petrography

The West Langhovde Islands consist of seven islands, *i.e.*, Nabböya, Ungane, Systerflesene, Ytrehovdeholmen, Indrehovdeholmen, Sigaren and Rumpa (Fig. 1). They are underlain by the granulite-facies metamorphic rocks such as metabasite, pyroxene gneiss, garnet-biotite gneiss, garnet gneiss and leucocratic biotite gneiss, with a minor quantity of pegmatite intrusions. The mineral assemblages of the rocks are presented in Table 1. Pyroxene gneiss occurs as the most dominant rock type in the central and western parts of this area. It is characterized by the presence of orthopyroxene and

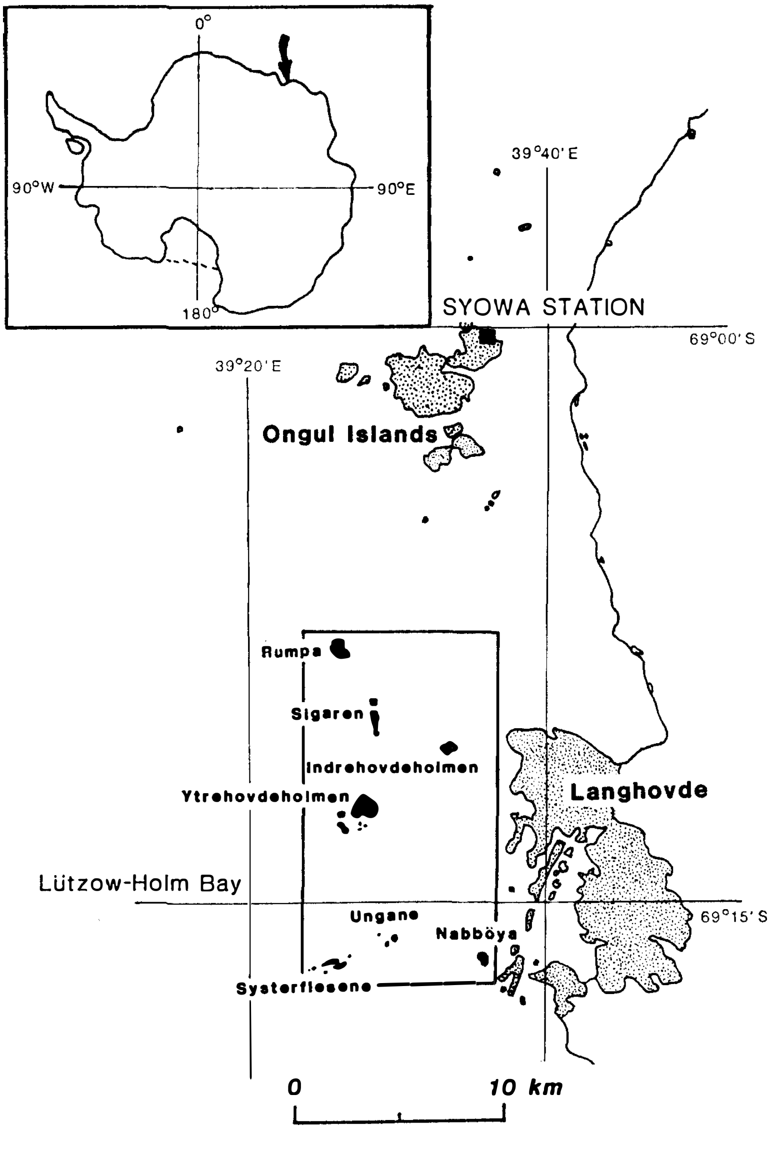

Fig. 1. Location map of several islands in the west of Langhovde (West Langhovde Islands).

Table 1. Mineral assemblages of the metamorphic rocks.

1)	Metabasite
	Amphibolite
	Hb+Bi+Opx±Cpx±Gar+Pl+Qz
	Hb+Bi±Cpx+Pl
	Basic pyroxene gneiss
	Opx+Cpx+Bi±Hb+Pl+Kf+Qz
	Garnet-pyroxene rock
	Gar+Cpx+Opx+Hb+Pl+Kf+Qz
2)	Pyroxene gneiss
	Opx+Cpx+Gar±Hb+Pl+Kf+Qz
	Opx+Cpx+Bi+Pl+Kf+Qz
	Opx+Cpx+Hb+Pl+Kf+Qz
	Opx+Bi±Gar+Pl±Kf+Qz
	Opx+Bi+Hb+Pl+Kf+Qz
3)	Garnet-biotite gneiss
	Gar+Bi+Pl+Kf+Qz
4)	Garnet gneiss
	Gar+Bi+Pl+Kf+Qz
	Gar+Hb+Pl+Kf+Qz
5)	Leucocratic biotite gneiss
	Bi±Hb±Gar+Pl+Kf+Qz

Abbreviations: Hb=Hornblende, Bi=Biotite, Opx=Orthopyroxene, Cpx=Clinopyroxene, Gar=Garnet, Pl=Plagioclase, Qz=Quartz, Kf=Potash feldspar

the maple brown color in the field. Garnet-biotite gneiss and garnet gneiss appear as subordinate rock types mainly in the eastern part, *i.e.*, Nabböya and Indrehovdeholmen. These rock types are also widely distributed as main constituents in the surrounding areas, and their petrographical features are similar to each other except for the occurrence of the garnet-bearing layers in pyroxene gneiss. Geologic structure of the islands is also consistent with that of the surrounding areas. Geological and petrographical descriptions of this area were given by KATSUSHIMA and YANAI (1984), and the geologic maps of some islands are presented in Fig. 2, in which the localities of the specimens studied are also shown.

3. Analytical Methods

Five pyroxene gneisses, three metabasites and one garnet-biotite gneiss from Sigaren, Systerflesene, Ungane, Indrehovdeholmen and Ytrehovdeholmen were selected for EPMA analyses. Table 2 shows their mineral assemblages and the referential numbers used in the following analytical data.

Microprobe analyses of orthopyroxene, clinopyroxene, garnet, hornblende, biotite and plagioclase in these specimens were carried out using JEOL JCXA-733 at the National Institute of Polar Research with an acceleration voltage of 15 kV, a beam current of 0.014 μA and a beam diameter of 3 μm. Synthesized pure oxides and natural minerals were used for standards, with intensity data having been adjusted to BENCE and ALBEE's (1968) correction method.

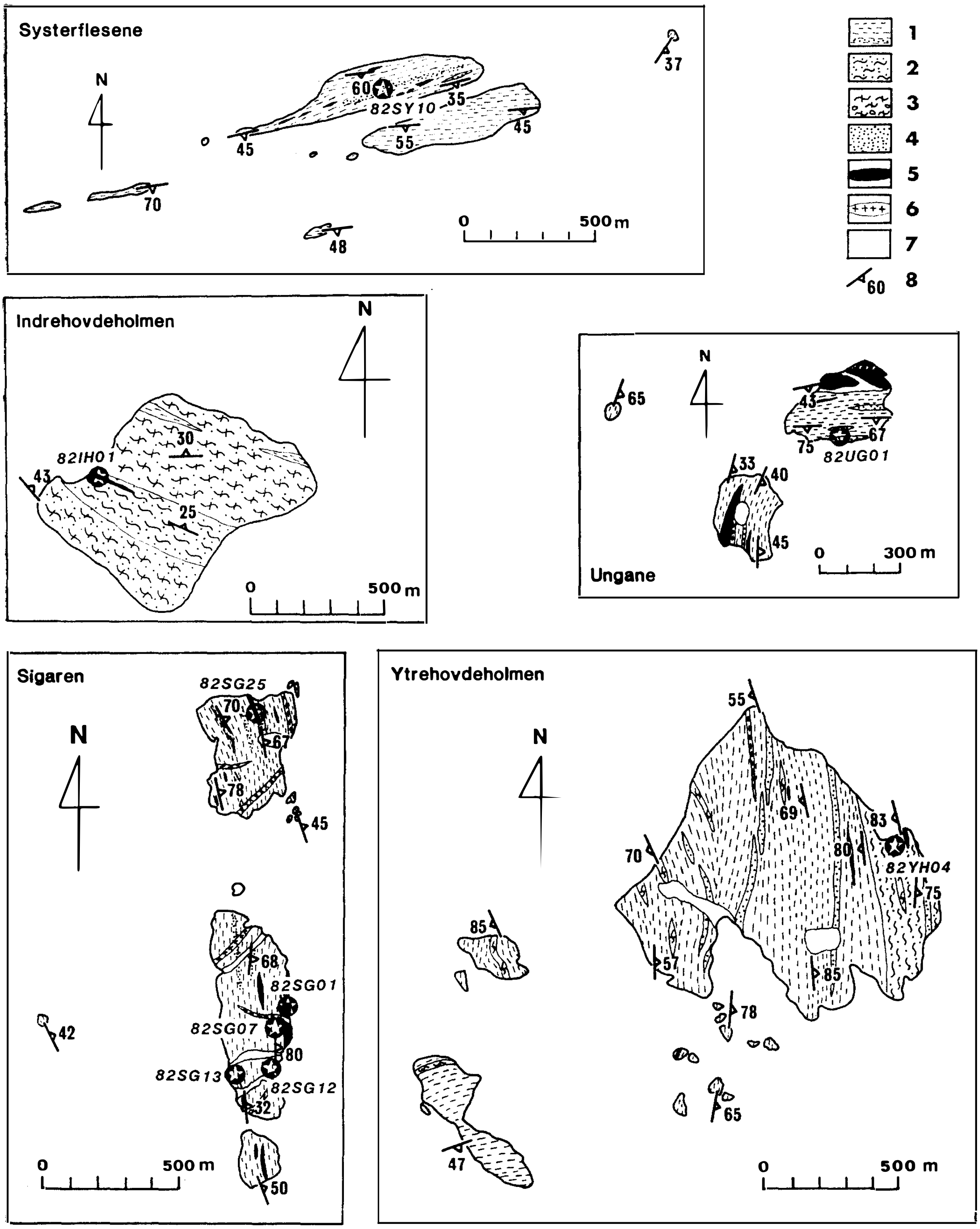

Fig. 2. Geologic maps of the islands, with the locations of the specimens investigated.
1. Pyroxene gneiss; dotted parts indicate garnet-bearing. 2. Garnet-biotite gneiss. 3. Leucocratic biotite gneiss; ellipsoidal parts indicate potash feldspar porphyroblast-bearing. 4. Garnet gneiss. 5. Metabasite. 6. Pegmatite. 7. Moraine. 8. Strike and dip of foliation.

Table 2. Rock types, mineral assemblages, and the referential numbers of the specimens from the West Langhovde Islands and the surrounding area in the Lützow-Holm Bay region.

Sample	No.	Rock type	Opx	Cpx	Gar	Bio	Hor	Il	Qz	Pl	(An %)	Kf
West Langhovde Is.												
	82SY10	pgn	1	8	13	—	24	+	+	+	(26–28)	+
	82SG01	pgn	2	9	14	—	—	+	+	+	(14–21)	+
	82SG07	pgn	3	10	15	—	25	+	+	+	(18–19)	+
	82SG25	mb	4	11	16	—	26	+	+	+	(26–29)	+
	82SG13	pgn	5	12	—	—	27	+	+	+	(14–18)	+
	82UG01	pgn	6	—	17	19, 20	—	+	+	+	(26–28)	—
	82IH01	mb	7	—	—	21	28	+	+	+	(40–41)	—
	82SG12	mb	—	—	—	22	29, 30	+	—	+	(21–28)	—
	82YH04	gbgn	—	—	18	23	—	+	+	+	(25–33)	+
Langhovde	77020603	pgn?	+	—	+	+	—	+	+	+		+
Skarvsnes	77012314	pgn?	+	—	+	+	—	+	+	+		+
	57110802	pgn?	+	+	—	+	+	+	—	+		+
	57110505	ggn	—	—	+	+	—	+	+	+		+
	57110506	gbgn	—	—	+	+	—	+	+	+		+
	57111105	ggn	—	—	+	+	—	+	+	+		+
Skallen	69020601	ggn?	—	—	+	+	—	+	+	+		+
	69020613	mb	+	+	+	—	+	+	+	+		—
	69020615	mb	+	+	+	+	+	+	+	+		—

Abbreviations of rock types: pgn=pyroxene gneiss, mb=metabasite, gbgn=garnet-biotite gneiss, ggn=garnet gneiss.

4. Mineral Compositions

Orthopyroxene is a characteristic mineral in the granulite-facies pyroxene gneiss. The analytical results of major oxides in seven orthopyroxenes are presented in Table 3. Both Al_2O_3 and alkali contents are very low except for SG25 which contains Al_2O_3 up to 4 wt%. Some of the analyzed orthopyroxenes coexisting with clinopyroxene are extremely Fe-rich, attaining the Fe/(Fe+Mn+Mg) ratios more than 0.9. GREW (1984) reported that in the Antarctic granulites Fe-rich orthopyroxenes with more than Fs 70% had not been found, although similar iron-rich orthopyroxenes have been described in some other granulite-facies terrains, such as the Adirondack Mountains, Labrador Trough and Loften (JAFFE *et al.*, 1978; KLEIN, 1978; ORMAASEN, 1977; BOHLEN and BOETTCHER, 1981). Further mineralogical details on them will be discussed in a separate paper.

Clinopyroxene in pyroxene gneiss from this area always coexists with orthopyroxene. The analytical results for major oxides in five clinopyroxenes are presented in Table 4. They are ferroaugite–ferrohedenbergite in composition with very low Al_2O_3 and alkali contents. As Fig. 3 shows, their Mg/Fe ratios are systematically correlated with those of the coexisting orthopyroxenes. Fe^{3+} contents of both pyroxenes estimated by the method of EDWARDS (1976), are extremely low as shown in Tables 3 and 4. This is consistent with the absence of magnetites in these rocks. Thus, calculated Fe^{3+} contents are ignored in all graphical plots and all Fe is treated as Fe^{2+}.

Table 3. Chemical compositions of orthopyroxene.

	1	2	3	4	5	6	7
SiO_2	47.95	46.72	45.22	46.09	47.49	50.76	51.39
TiO_2	.09	.11	.11	.15	.05	.09	.07
Al_2O_3	.40	.20	.26	4.16	.28	1.48	.83
Cr_2O_3	—	.01	—	—	.04	.04	.01
FeO*	42.31	47.98	50.56	43.53	46.85	30.02	28.59
MnO	1.20	1.97	1.84	.62	1.68	.59	1.04
MgO	7.31	1.35	1.59	4.40	3.13	16.93	17.99
CaO	.75	1.08	.93	.91	.80	.23	.52
Na_2O	.06	.02	.04	—	.01	.02	.02
K_2O	.02	.01	—	.03	—	.01	.01
Total	100.09	99.45	100.55	99.89	100.33	100.17	100.47
Number of atoms per 6 oxygens							
Si	1.985	2.017	1.962	1.917	2.010	1.959	1.970
Al^{IV}	.015	—	.013	.083	—	.041	.030
Al^{VI}	.005	.010	—	.121	.014	.027	.007
Ti	.003	.004	.004	.005	.002	.003	.002
Cr	—	.000	—	—	.001	.001	.000
Fe^{3+}**	.010	—	.009	—	—	.009	.021
Fe^{2+}	1.450	1.733	1.820	1.514	1.659	.955	.885
Mn	.042	.072	.068	.022	.060	.019	.034
Mg	.451	.087	.103	.273	.198	.974	1.028
Ca	.033	.050	.043	.041	.036	.010	.021
Na	.005	.002	.003	—	.001	.001	.001
K	.001	.001	—	.002	—	.000	.000
Molecular proportions (%) of major components							
Fs	73.6	89.2	89.6	81.9	84.9	49.1	45.8
Rh	2.1	3.7	3.3	1.2	3.1	1.0	1.7
En	22.7	4.5	5.0	14.8	10.1	49.4	51.4
Wo	1.7	2.6	2.1	2.2	1.9	.5	1.1

* Total Fe as FeO. ** Calculated after EDWARDS (1976).
Fs: $FeSiO_3$, Rh: $MnSiO_3$, En: $MgSiO_3$, Wo: $CaSiO_3$.

Table 4. Chemical compositions of clinopyroxene.

	8	9	10	11	12
SiO_2	50.22	48.51	48.60	49.66	49.51
TiO_2	.14	.14	.18	.13	.13
Al_2O_3	1.00	.71	.70	1.21	.73
Cr_2O_3	.02	—	.02	—	—
FeO*	21.74	28.05	29.12	24.08	25.85
MnO	.49	1.02	.97	.38	.62
MgO	6.17	1.38	1.55	3.83	2.89
CaO	20.40	19.25	18.40	20.72	20.49
Na_2O	.42	.55	.41	.33	.40
K_2O	.01	.01	—	.01	—
Total	100.61	99.62	99.95	100.35	100.62

Table 4. Continued.

	8	9	10	11	12
	Number of atoms per 6 oxygens				
Si	1.976	1.993	1.993	1.982	1.990
Al^{IV}	.024	.007	.007	.018	.010
Al^{VI}	.022	.028	.027	.039	.024
Ti	.004	.004	.006	.004	.004
Cr	.001	—	.001	—	—
Fe^{3+}**	.026	.015	.001	—	.009
Fe^{2+}	.677	.941	.996	.804	.855
Mn	.016	.035	.034	.013	.021
Mg	.362	.085	.095	.228	.173
Ca	.860	.847	.808	.886	.882
Na	.032	.044	.033	.026	.031
K	.001	.001	—	.001	—
	Molecular proportions (%) of major components				
Fs	36.6	49.9	51.6	41.6	44.7
Rh	.8	1.8	1.7	.7	1.1
En	18.5	4.4	4.9	11.8	8.9
Wo	44.0	43.9	41.8	45.9	45.4

* Total Fe as FeO. ** Calculated after EDWARDS (1976).
Fs: $FeSiO_3$, Rh: $MnSiO_3$, En: $MgSiO_3$, Wo: $CaSiO_3$.

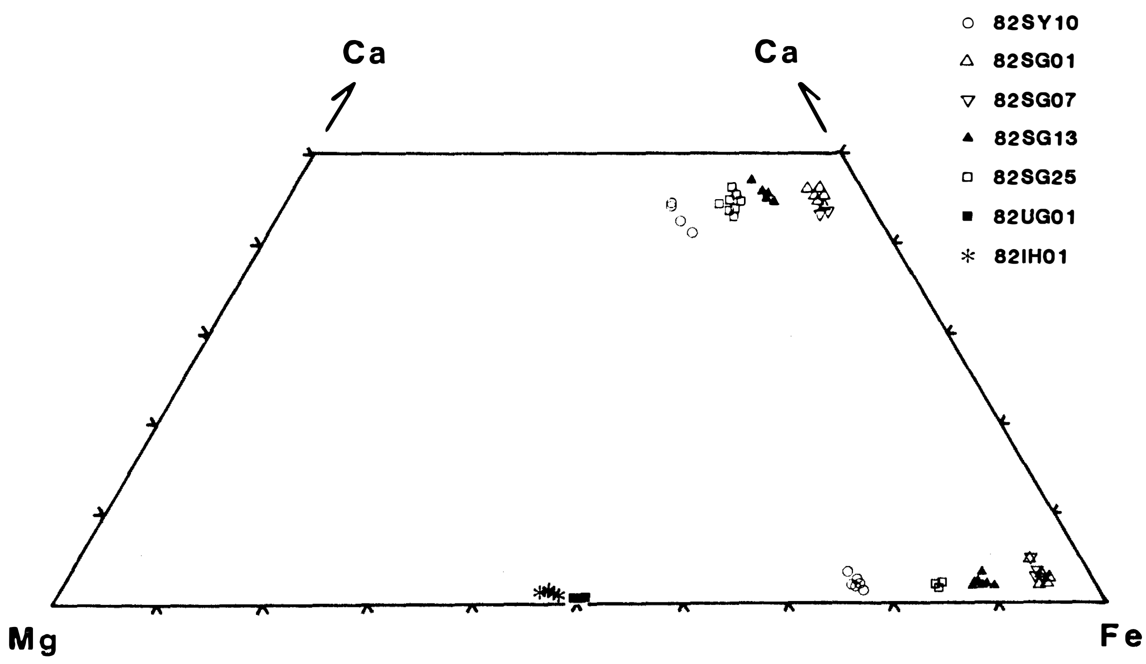

Fig. 3. Quadrilateral diagram showing compositions of coexisting orthopyroxenes and clinopyroxenes.

Representative chemical compositions of the cores of garnets in four pyroxene gneisses, one metabasite and one garnet-biotite gneiss are listed in Table 5. They are essentially almandine garnets. Garnets coexisting with clinopyroxene have more grossular and less pyrope components than those in the rocks without clinopyroxene, *i.e.*, UG01 and YH04. Garnet in garnet-biotite gneiss (YH04) has especially low Mn content. Compositional zoning of garnets with slightly increasing Ca and Fe from core to margin is observed. Garnets in the pyroxene gneiss with the association of orthopyroxene and clinopyroxene are not observed to be in direct contact with both pyroxenes and are enclosed by plagioclase, whereas in specimen SG25 hornblende is formed between garnet and clinopyroxene.

Chemistry of biotites is listed in Table 6. They are rich in TiO_2 (5–6 wt%), as

Table 5. Chemical compositions of garnet.

	13	14	15	16	17	18
SiO_2	37.08	36.37	37.12	37.10	38.37	37.69
TiO_2	.08	.01	—	.11	—	.04
Al_2O_3	20.23	20.34	19.87	19.82	22.01	21.10
Cr_2O_3	—	.01	—	.01	.07	.04
FeO*	31.25	29.41	31.19	33.12	29.98	34.89
MnO	2.87	3.76	3.52	1.73	2.27	.16
MgO	1.29	.30	.31	.98	5.18	4.95
CaO	7.32	7.65	7.83	7.15	2.47	2.05
Na_2O	—	.09	.08	.03	.04	—
K_2O	—	.01	.01	.01	—	.01
Total	100.12	97.95	99.93	100.06	100.39	100.93
			Number of atoms per 24 oxygens			
Si	5.998	6.010	6.045	6.027	6.014	5.963
Al^{IV}	.002	—	—	—	—	.037
Al^{VI}	3.854	3.961	3.814	3.795	4.065	3.898
Ti	.010	.001	—	.013	—	.005
Cr	—	.001	—	.001	.009	.005
Fe^{3+}**	.136	.036	.186	.191	—	.092
Fe^{2+}	4.023	4.010	3.969	4.214	3.929	4.478
Mn	.393	.526	.486	.238	.301	.021
Mg	.311	.074	.075	.237	1.210	1.168
Ca	1.269	1.354	1.366	1.244	.415	.348
Na	—	.029	.025	.009	.012	—
K	—	.001	.001	.001	—	.001
			Molecular proportions (%) of major components			
Alm	67.1	67.2	67.3	71.0	67.1	74.5
Sps	6.6	8.8	8.2	4.0	5.1	.4
Pyr	5.2	1.2	1.3	4.0	20.7	19.4
Grs	17.5	21.7	18.5	15.8	6.9	3.2
And	3.6	.9	4.7	5.1	—	2.4
Uvr	—	.0	—	.0	.2	.1

* Total Fe as FeO. ** Calculated on the basis of $Fe^{3+}=4-(Al^{VI}+Ti+Cr)$.

Alm: Almandine, Sps: Spessartine, Pyr: Pyrope, Grs: Grossular, And: Andradite, Uvr: Uvarovite.

those in the Lützow-Holm Bay region (*e.g.*, KANISAWA *et al.*, 1979). Its Fe/Mg ratio is nearly 1 in most specimens, except for the Mg-rich biotite in No. 20, occurring as inclusions in garnet of the pyroxene gneiss with the garnet-biotite-orthopyroxene assemblage. It is worthy of note that the biotites occurring as inclusions have higher Mg/Fe ratios than those in the matrix as reported by GREW (1981) and KANISAWA and YANAI (1982). Probably these biotites may represent products at the retrogressive stage.

Analytical results of amphiboles in three pyroxene gneisses and three metabasites are shown in Table 7. Amphiboles coexisting with clinopyroxene and orthopyroxenes in pyroxene gneiss and metabasite are rich in Fe and belong to ferro pargasitic hornblende—ferro pargasite of LEAKE (1978). These amphiboles are either isolated from or associated with pyroxenes, and are relatively rich in TiO_2 except for that from SG25 (No. 26). These facts may suggest that they have been produced at a retrogressive stage. On the other hand, the amphiboles occurring as the main constituent of the biotite amphibolites, most common among metabasites in this area, are ferroan pargasitic hornblende—ferroan pargasite of LEAKE (1978). Fine-grained cummingtonite (*e.g.*, No. 30) rarely appears in some amphibolites as a retrogressive product associated with calcite and hornblende at the expense of pyroxene.

Table 6. Chemical compositions of biotite.

	19	20	21	22	23
SiO_2	36.72	38.63	36.37	36.90	35.18
TiO_2	5.03	5.40	5.83	5.90	6.03
Al_2O_3	14.49	15.27	13.53	13.50	14.83
Cr_2O_3	.12	.21	.02	.01	.01
FeO*	18.16	12.60	19.75	21.13	21.66
MnO	.06	.06	.09	.13	.01
MgO	11.71	15.21	10.97	9.63	8.47
CaO	.05	.13	—	.01	.04
Na_2O	.04	.05	.02	.20	.07
K_2O	9.21	9.19	9.20	9.29	8.79
Total	95.59	96.75	95.78	96.70	95.09
	Number of atoms per 22 oxygens				
Si	5.555	5.593	5.545	5.606	5.446
Al^{IV}	2.445	2.407	2.431	2.394	2.554
Al^{VI}	.138	.199	—	.023	.151
Ti	.572	.588	.669	.674	.702
Cr	.014	.024	.002	.001	.001
Fe	2.297	1.526	2.518	2.684	2.804
Mn	.008	.007	.012	.017	.001
Mg	2.641	3.283	2.494	2.181	1.955
Ca	.008	.020	—	.002	.007
Na	.012	.014	.006	.059	.021
K	1.777	1.698	1.790	1.800	1.736
Fe/(Fe+Mg)	.465	.317	.502	.552	.589

* Total Fe as FeO.

Table 7. Chemical compositions of amphibole.

	24	25	26	27	28	29	30
SiO_2	39.84	37.47	41.05	38.78	40.02	40.26	52.27
TiO_2	2.05	2.16	.87	2.56	2.22	2.82	.10
Al_2O_3	10.17	10.02	9.81	9.33	11.91	11.64	.97
Cr_2O_3	.03	—	—	—	—	.05	—
FeO*	26.80	33.22	28.59	30.59	20.14	19.92	28.18
MnO	.23	.54	.23	.42	.36	.26	1.35
MgO	3.93	.94	3.84	1.58	8.06	6.95	12.96
CaO	10.57	9.97	10.81	10.33	10.94	11.20	.75
Na_2O	1.88	2.02	1.49	1.90	1.43	2.14	.20
K_2O	1.53	1.67	1.26	1.85	2.14	1.82	.01
Total	97.03	98.01	97.95	97.34	97.22	97.06	96.79
			Number of atoms per 23 oxygens				
Si	6.391	6.189	6.538	6.358	6.216	6.262	7.939
Al^{IV}	1.609	1.811	1.462	1.642	1.784	1.738	.061
Al^{VI}	.314	.140	.379	.161	.397	.396	.112
Ti	.247	.268	.104	.316	.259	.330	.011
Cr	.004	—	—	—	—	.006	—
Fe	3.463	4.285	3.574	4.079	2.430	2.591	1.768
Mn	.031	.076	.031	.058	.047	.034	.174
Mg	.940	.231	.912	.386	1.866	1.611	2.934
Fe	.132	.304	.234	.115	.186	—	1.811
Ca	1.817	1.764	1.845	1.815	1.821	1.866	.122
Na	.051	—	—	.070	—	.134	.059
Na	.534	.647	.460	.534	.431	.512	—
K	.313	.352	.256	.387	.424	.361	—
Fe/(Fe+Mg)	.793	.952	.807	.916	.584	.617	.550

* Total Fe as FeO.

Anorthite contents of the plagioclases are given in Table 2. Iron-oxide minerals are mostly ilmenite, and magnetite has not been observed.

5. Mineral Parageneses

Systematic compositional variations of minerals support that the minerals were crystallized in equilibrium, and that their compositions reflect the physical conditions under which the minerals were formed. As described by KATSUSHIMA and YANAI (1984), the rocks occurring in the present area have undergone the uniform granulite-facies metamorphism. The equilibrium relationships among the main constituent minerals, namely, orthopyroxene, clinopyroxene, garnet, biotite and hornblende are checked by the Fe-Mg partitioning.

Figure 4 shows the variations of Mg/Fe ratios of garnet and associated minerals. As described before, garnets in pyroxene gneiss carrying two pyroxenes are not in direct contact with pyroxenes. However, distribution coefficients of Mg and Fe among them are similar to each other and constant. Between garnet and orthopyroxene in the different kind of pyroxene gneiss with association of orthopyroxene,

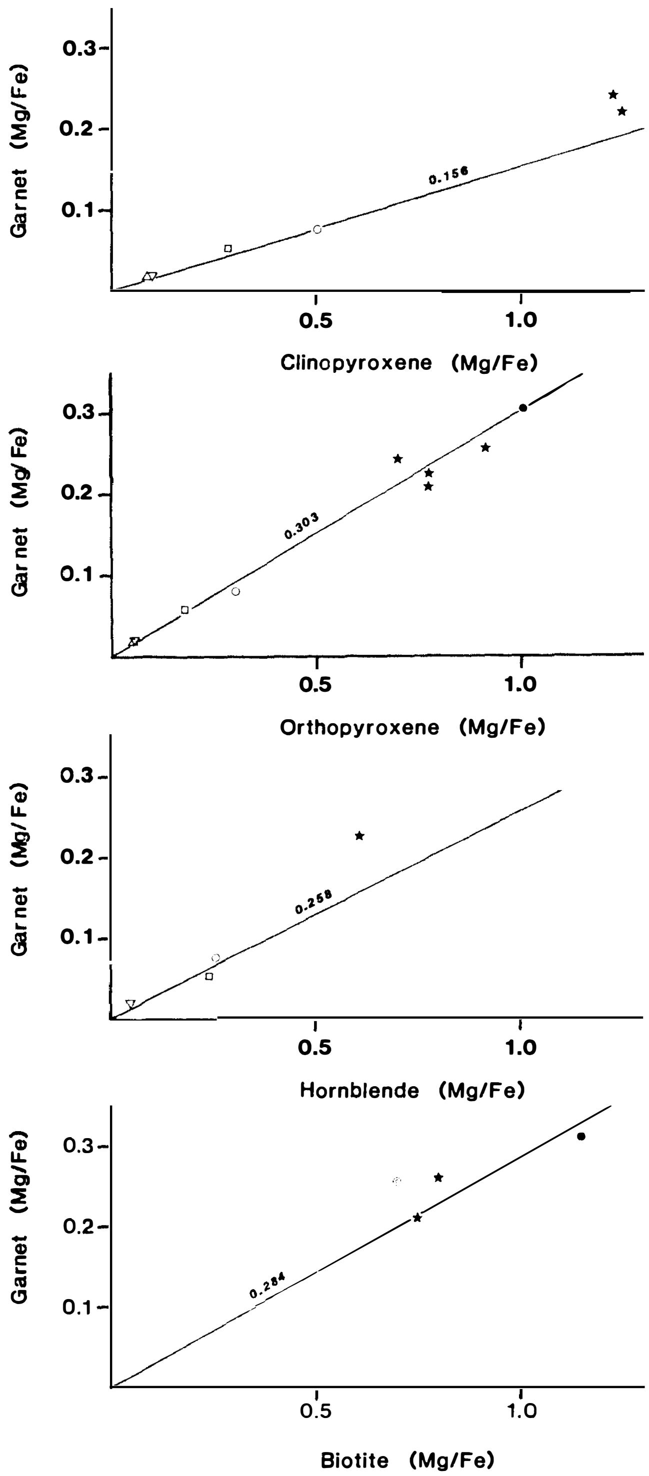

Fig. 4. Mg-Fe distributions between garnet and coexisting orthopyroxene, clinopyroxene, hornblende and biotite, respectively. Double circle: 82YH04, closed star: specimen in the surrounding region of this area. Other symbols are the same as those in Fig. 3.

garnet and biotite, the Mg-Fe distribution is also similar and is plotted on the line of KD=0.303. Distribution coefficients between garnet and hornblende in pyroxene gneiss and garnet-pyroxene rock are more or less dispersed as compared with those between other pairs with garnet. The pair of garnet and biotite occurs in two specimens, and their Mg-Fe distributions are rather different. Judging from the fact that biotites which occur as inclusions in garnet are more Mg-rich than those in the matrix in specimen UG01, biotites seem to be easily reequilibrated on the Mg-Fe distribution at a retrogressive stage. Therefore, the estimation of metamorphic temperatures using the pair of garnet and biotite must be examined carefully. Orthopyroxene and clinopyroxene are closely associated in pyroxene gneiss, and their Mg/Fe ratios show good correlation (Fig. 5). As Fig. 5 shows, the distribution coefficients are nearly constant and close to 0.613 not only for the present specimens but

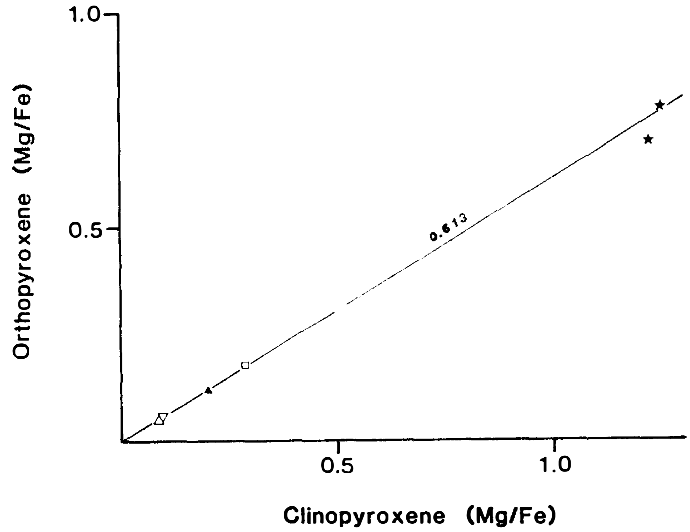

Fig. 5. Mg-Fe distribution between coexisting orthopyroxene and clinopyroxene. Symbols are the same as those in Figs. 3 and 4.

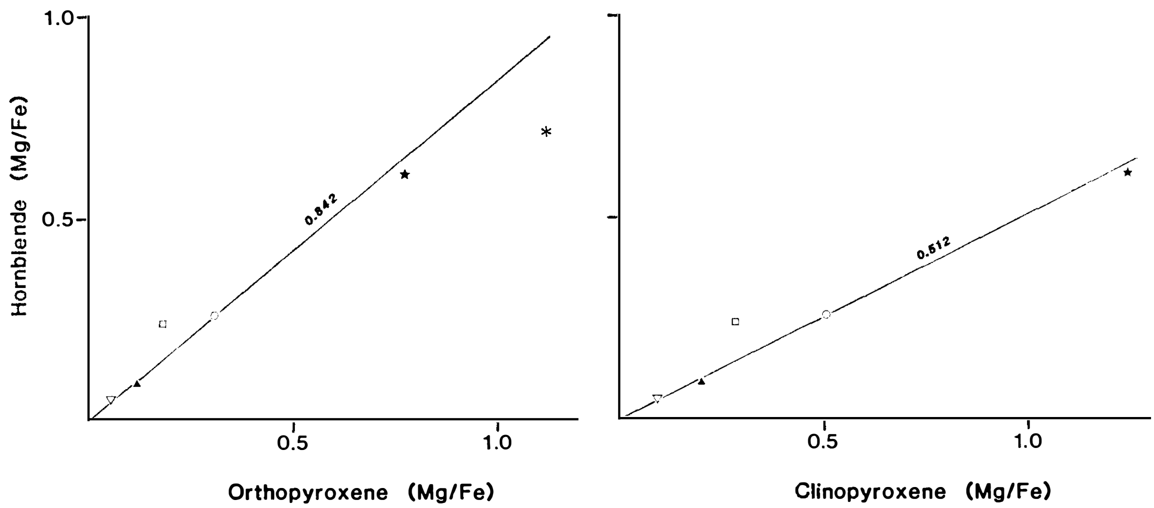

Fig. 6. Mg-Fe distribution between hornblende and coexisting orthopyroxene and clinopyroxene, respectively. Symbols are the same as those in Figs. 3 and 4.

also for the comparable ones from Skallen. Mg-Fe distribution among hornblende and two pyroxenes is shown in Fig. 6. The distribution coefficients are nearly the same in three specimens of pyroxene gneiss but different in the garnet-pyroxene rock of metabasites (SG25). This fact may suggest that the hornblende from specimen SG25 might have been formed by the reaction of garnet and clinopyroxene as described before. Thus, the Fe-Mg distribution relationship among the mineral pairs suggests that orthopyroxene, clinopyroxene, garnet and hornblende in the pyroxene gneisses are in an equilibrium relationship. None of the orthogneisses with the above four-phase parageneses have ever been reported except for only one specimen (70020603) by YOSHIDA (1978).

Next, the compositional relations of the pyroxene gneisses carrying the above four-phase association are discussed. The selected pyroxene gneisses, which contain quartz and potash feldspar as a potash-bearing phase, can be approximately expressed in the system Al_2O_3-FeO-MnO-MgO-CaO-Na_2O. Although MnO is an important component in garnets and pyroxenes, it is excluded from consideration because of its minor amount. For convenience of graphic presentation, Na_2O is excluded from considerations. Therefore, the CaO-FeO-MgO-Al_2O_3 tetrahedron can conveniently be used for consideration of compositional relations among orthopyroxene, clinopyroxene, garnet and hornblende in the pyroxene gneisses. Figure 7 is the projection on the basal plane of CaO-MgO-FeO of the relation in this tetrahedron viewed from the apex of Al_2O_3. This figure shows that Fe/Mg ratios of garnet and/or hornblende are varied with correlation to those of the coexising pyroxenes. In other words, the chemical compositions of all kinds of minerals are varied in terms of bulk chemistry. The above consideration for mineral parageneses, suggests that these minerals have been formed in equilibrium under granulite-facies condition.

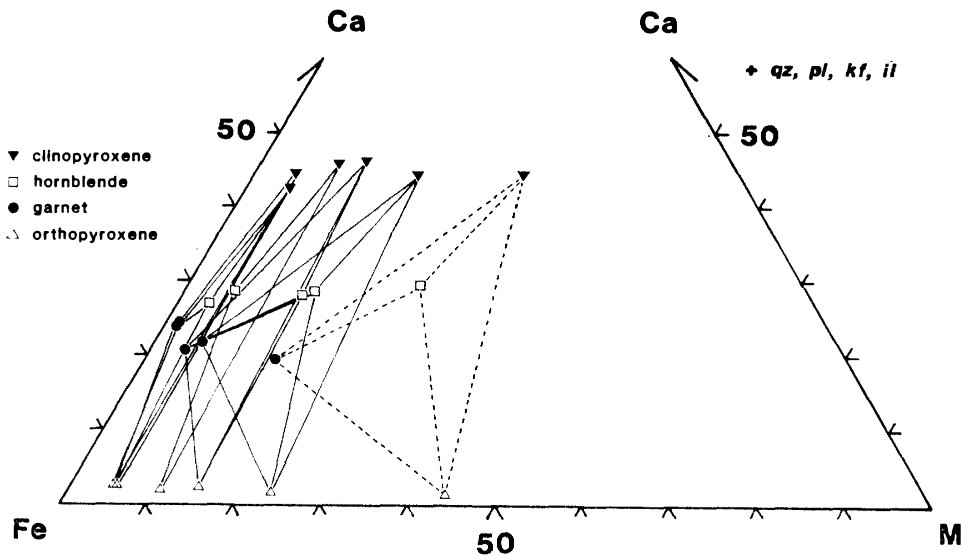

Fig. 7. Ca-Fe-Mg diagram showing compositional relations of the association of orthopyroxene and clinopyroxene with garnet and/or hornblende in pyroxene gneiss and garnet-pyroxene rock. Solid lines show the joins among the minerals in three- or four-phase relations. Broken lines show those of the potash feldspar-free metabasite from Skallen.

6. Physical Condition of Metamorphism

Table 8 shows the calculated results of *P-T* conditions based on various geothermometers and geobarometers for the selected specimens from the present area and for the comparable specimens from the surrounding areas.

Geothermometers of orthopyroxene-clinopyroxene by WELLS (1977), garnet-clinopyroxene by ELLIS and GREEN (1979), garnet-biotite by THOMPSON (1976) and garnet-hornblende by GRAHAM and POWELL (1984) are adopted. Calculations by ELLIS and GREEN's thermometer (1979) is made on pressure of 7 kb. In general, the estimated values by garnet-hornblende geothermometer are relatively lower than others, especially in SG25. These low temperature values suggest that the pair may have been equilibrated at a retrogressive stage. From calculations by WELLS' (1977) or ELLIS and GREEN's (1979) method, the metamorphic temperature in this area is estimated at 750–800°C approximately.

Geobarometers using the association of garnet-orthopyroxene-plagioclase-quartz have been proposed by NEWTON and PARKINS (1982) and BOHLEN *et al.* (1983). Table 8 shows the metamorphic pressures calculated by the methods using the temperature values estimated by WELLS' or THOMPSON's method. Because the geobarometer by BOHLEN *et al.* (1983) is based on the experimental investigation about Fe-orthopyroxene, it may be suitable for the present study. Consequently, the metamorphic pressure in this area is estimated to be 7–8 kb.

The estimated *P-T* values are higher than the values of 725±25°C and 6.3±1.3 kb

Table 8. Estimates of temperature and pressure.

No. of sample		Temperature (°C) Opx-Cpx (1)	Gar-Cpx* (2)	Gar-Bio (3)	Gar-Hor (4)	Pressure (kb) Gar-Opx-Pl** (5)	(6)
West Langhovde	82SY10	811	703		688	6.0	7.5
Islands	82SG01	766	820			9.0	7.1
	82SG07	828	784		765	8.8	8.0
	82SG25	758	766		624	7.1	6.9
	82SG13	740					
	82UG01			679		5.9	6.5
	82YH04			791			
Langhovde	77020603			744		6.0	6.6
Skarvsnes	77012314			697		5.4	6.1
	57110802	908					
	57110505			973			
	57110506			665			
	57111105			854			
Skallen	69020601			735			
	69020613	843	749		750		
	69020615	845	845			7.6	5.8

(1): WELLS (1977), (2): ELLIS and GREEN (1979), (3): THOMPSON (1976), (4): GRAHAM and POWELL (1984), (5): NEWTON and PERKINS (1982), (6): BOHLEN *et al.* (1983).

* at P=7 kb.

** at the temperature based on the method by WELLS (1977) or THOMPSON (1976).

for rocks in the Lützow-Holm Bay region estimated by SUZUKI (1983). Re-examination of the metamorphic conditions throughout the Lützow-Holm Bay region has recently been carried out by MOTOYOSHI *et al.* (1984). They estimated the metamorphic conditions at 750–850°C and 7–8 kb. These values are similar to the present estimation.

By the way, Fe-rich chemical composition of orthopyroxene is significant for the estimation of pressure. BOHLEN *et al.* (1980), in their experimental determination of the effect of manganese on the stability of ferrosilite in relation to fayalite + quartz, assessed its importance to orthopyroxene barometry. In addition, BOHLEN and BOETTCHER (1981) described the effect of magnesium as well. In the present analyses, the Fe/(Fe + Mn + Mg) ratios of the orthopyroxenes from two specimens are higher than 0.9, as described before. The minimum pressure of their stability field is estimated to be about 9 kb at 800°C by these orthopyroxene barometries. This value is slightly higher than the results obtained by other barometers, but the inconsistency remains unsolved at present.

7. Conclusion

1) The four-phase association of orthopyroxene, clinopyroxene, garnet and hornblende is close to equilibrium in the pyroxene gneisses from the West Langhovde Islands.

2) Orthopyroxenes in the rocks carrying the above-association are Fe-rich, and similar to those from Adirondack, Labrador Trough and Loften. According to the experimental data of BOHLEN *et al.* (1980) and BOHLEN and BOETTCHER (1981) their stability field is more than 9 kb at 800°C.

3) The metamorphic condition of the granulite-facies rocks from this area is estimated approximately at 750–800°C and 7–8 kb by various geothermometers and geobarometers. The above estimation is almost consistent with the metamorphic conditions in the surrounding areas estimated by MOTOYOSHI *et al.* (1984).

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