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MODE OF OCCURRENCE, BULK CHEMICAL COMPOSITIONS, AND MINERAL TEXTURES OF ULTRAMAFIC ROCKS IN THE LÜTZOW-HOLM COMPLEX, EAST ANTARCTICA

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Abstract: Available data on the mode of occurrence, bulk chemical compositions, and mineral textures of ultramafic rocks (ultrabasic rocks plus "normatively" ultramafic rocks (normative olivine + pyroxenes + ilmenite > 70%)) in the Late Proterozoic high-grade Lützow-Holm Complex are summarized. The bulk chemical compositions suggest that most of them are derived from various parts of layered gabbro. Some are troctolitic, being composed mainly of normative olivine and plagioclase without pyroxenes. The mode of occurrence in the field suggests that they were tectonically fractured and emplaced in the metasedimentary gneisses. Their occurrence mainly in the western part of the Lützow-Holm Complex suggests that original gabbroid masses were present in the presently missing part (ocean floor?) between the adjacent Lützow-Holm and Yamato-Belgica Complexes. The mineral textures, especially those of garnet and spinel, suggest changing metamorphic conditions within the spinel-amphibole lherzolite facies during prograde recrystallization of the rocks; from earlier relatively high-pressure and low-temperature conditions to later lower-pressure and higher-temperature conditions.

1. Introduction

The occurrence of mafic to ultramafic rocks within metasedimentary sequences poses problems as to their origin, particularly where the rocks are so deformed and recrystallized that any original intrusive or sedimentary relationships have been destroyed. Such is the case with mafic to ultramafic rocks occurring within the upper amphibolite- to granulite-facies metasedimentary gneisses of the Late Proterozoic Lützow-Holm Complex in East Antarctica. The complex is of special interest because it is considered to have been formed as a continental collision zone (HIROI *et al.*, 1984; HIROI and SHIRAISHI, 1986; SHIRAISHI *et al.*, 1986) and therefore can provide information on the processes of crustal development of the East Antarctic shield, a fragment of the Gondwanaland.

The purpose of this paper is to summarize available data on the mode of occurrence, bulk chemical compositions, and mineral textures of the ultramafic rocks in the Lützow-Holm Complex and to discuss their origin and likely tectonic setting which may bear upon the evolution of the Gondwanaland as a whole. More quantitative and comprehensive discussions based on the mineral chemistry and other data will be presented elsewhere.

In this paper, ultramafic rocks include both ultrabasic rocks ($SiO_2 < 45$ wt%) and "normatively" ultramafic rocks (normative olivine+pyroxenes+ilmenite>70%).

2. Geologic and Petrologic Outline of Lützow-Holm Complex

The Late Proterozoic high-grade metamorphic rocks exposed along the Prince Olav Coast and around Lützow-Holm Bay are termed the Lützow-Holm Complex (Fig. 1). This complex is characterized by the medium-pressure type progressive metamorphism from east to west, the prograde recrystallization of the rocks from the kyanite to sillimanite stability fields, and the low initial $^{87}Sr/^{86}Sr$ ratios (Hiroi *et al.*, 1984; Hiroi and Shiraishi, 1986; Shiraishi *et al.*, 1986). The older Rayner and Yamato-Belgica Complexes occur to the east and to the west, respectively, of the Lützow-Holm Complex.

The Lützow-Holm Complex consists largely of well-layered pelitic and intermediate gneisses with some migmatitic rocks. Small amounts of metamorphosed calcareous, basic, and ultrabasic rocks are also present. The pelitic rocks show a wide range of

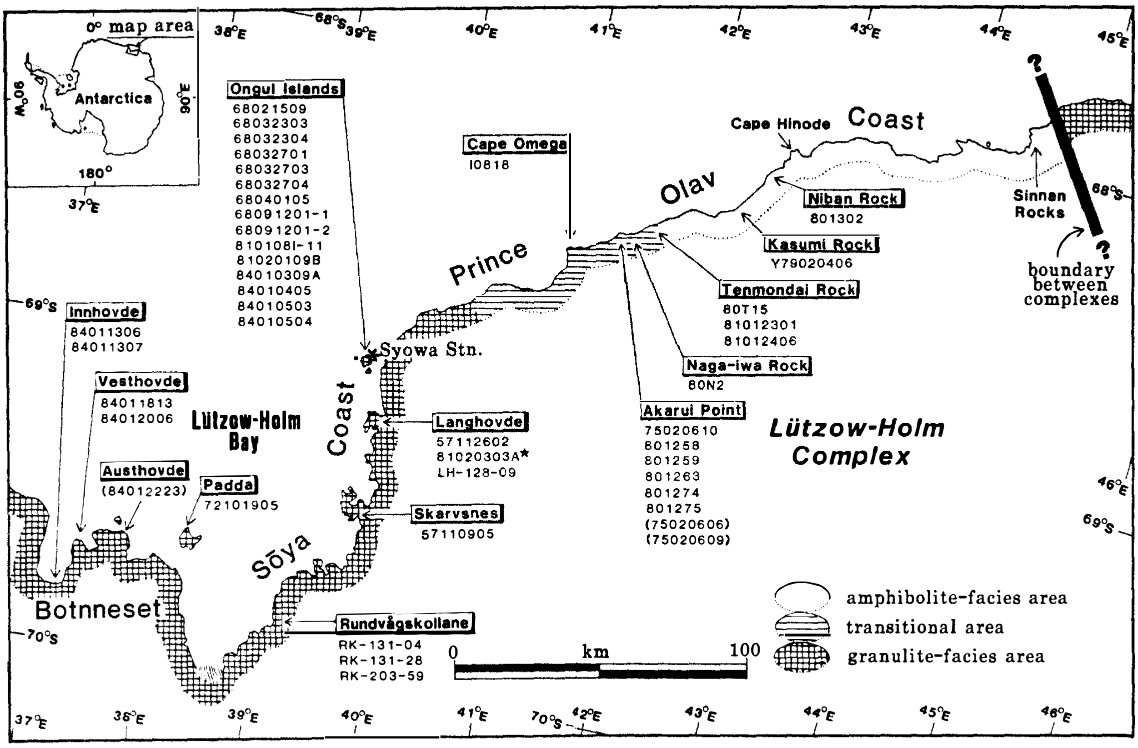


Fig. 1. Map of the Prince Olav Coast and Lützow-Holm Bay region, East Antarctica, showing boundary between complexes, metamorphic facies, and sample localities. Samples in parentheses are those without data on their bulk chemical compositions. Sp. 81020303A from Langhovde is a calc-silicate rock for reference.

bulk chemical composition and are biotite, garnet-biotite, sillimanite-garnet-biotite, and sillimanite-cordierite-biotite gneisses. The intermediate rocks include biotite-hornblende gneiss and pyroxene gneiss. The latter occurs only in the high-grade part of the complex. The migmatitic rocks are granitic to granodioritic in composition and are of anatectic origin (HIROI *et al.*, 1983c). These rocks were folded, at least twice; the earlier isoclinal folds with axial planes trending N-S to NW-SE and later open to close folds with axial planes of an NE-SW trend (SHIRAISHI, 1986; HIROI and SHIRAISHI, 1986). The Lützow-Holm Complex was intruded by the Early Paleozoic granite and pegmatite.

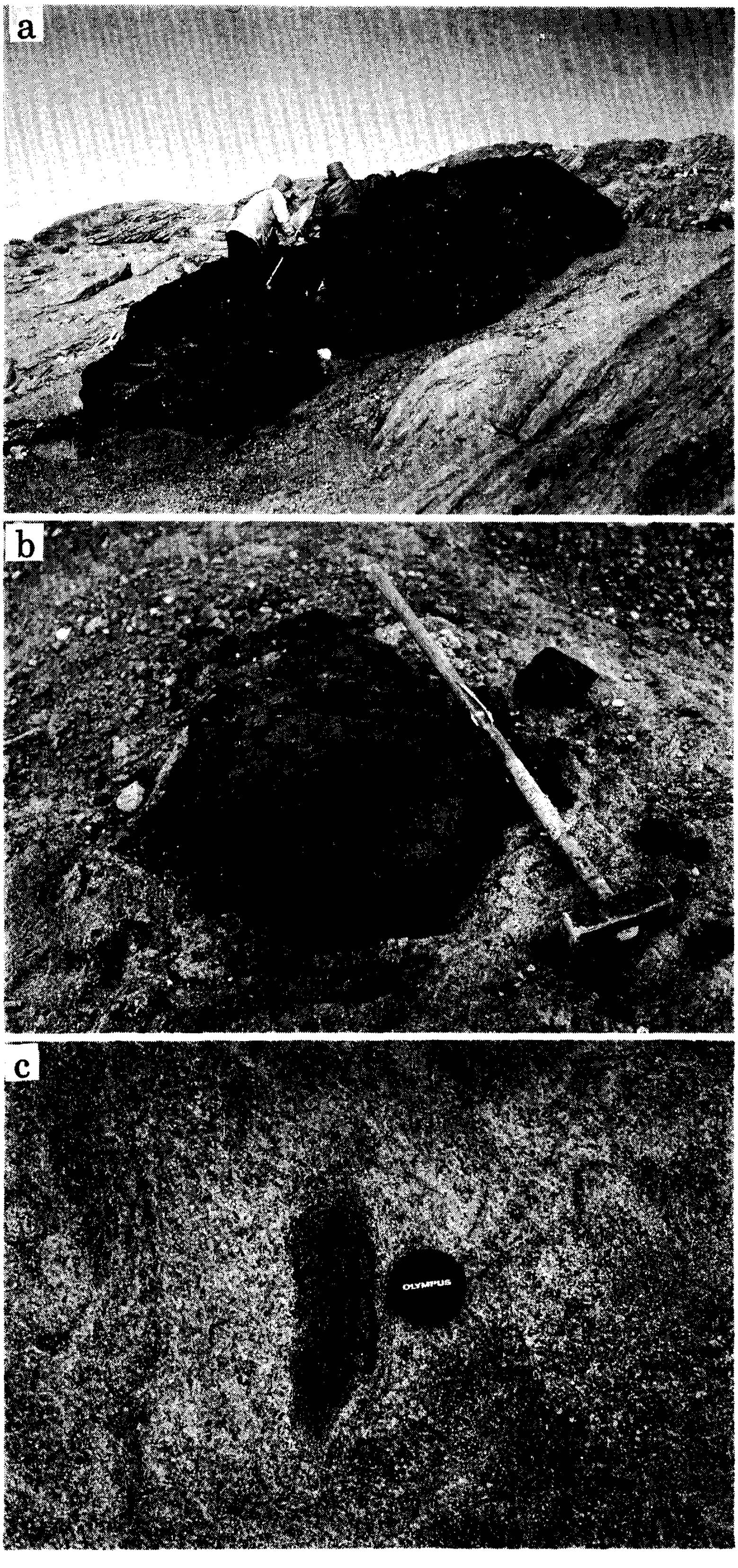
The K-Ar and Rb-Sr ages from total rock and mineral separates concentrate at about 500 Ma, indicating a heating event coeval with the Early Paleozoic granite and pegmatite activity (YANAI and UEDA, 1974; SHIBATA *et al.*, 1985), which is known over a large portion of East Antarctica (GREW, 1982). A few Rb-Sr mineral and whole rock ages, however, range from 1200 to 680 Ma, dating the earlier regional metamorphism of the Lützow-Holm Complex (MAEGOYA *et al.*, 1968; SHIRAHATA, 1983; SHIBATA *et al.*, 1986).

The Prince Olav Coast and the Lützow-Holm Bay region are divided into three areas of different metamorphic facies (Fig. 1). The eastern part of the Prince Olav Coast is an amphibolite-facies area where calcium-poor amphiboles (anthophyllite and cummingtonite) occur and no orthopyroxene has been found (RAVICH and KAMENEV, 1975; HIROI *et al.*, 1983a, c). Its western part is a transitional area from the amphibolite to the granulite facies. In the transitional area, orthopyroxene occurs sporadically, confined to rocks with appropriate bulk chemical compositions (HIROI *et al.*, 1983c; SHIRAISHI *et al.*, 1984). The Lützow-Holm Bay region to the southwest is a granulite-facies area characterized by the common occurrence of orthopyroxene in various rocks (BANNO *et al.*, 1964a; KIZAKI, 1964; SUWA, 1968; YOSHIDA, 1978, 1979a, b; YOSHIDA *et al.*, 1982; SUZUKI, 1982, 1983; MOTOYOSHI, 1986).

Sillimanite + K-feldspar paragenesis is commonly found in aluminous pelitic gneisses throughout the study area (HIROI *et al.*, 1983b, c). A small amount of kyanite occurs as a metastable relic within garnet and plagioclase in most of the sillimanite-bearing rocks regardless of the metamorphic grade, suggesting that the rocks of the Lützow-Holm Complex experienced kyanite-sillimanite type prograde recrystallization (HIROI *et al.*, 1983b, c; MOTOYOSHI *et al.*, 1985). On the other hand, andalusite occasionally occurs in rocks cut extensively by the Early Paleozoic granite and pegmatite, suggesting thermal metamorphism by the granite and pegmatite (HIROI *et al.*, 1983b, c).

3. Mode of Occurrence of Ultramafic Rocks

Ultramafic rocks have been reported sporadically from the western part of the Prince Olav Coast and the Sôya Coast to the southwest (Fig. 1). Recently they have also been found from the Botnneset area including Padda (Fig. 1). However, ultramafic rocks have not been found in the eastern part of the Prince Olav Coast in spite of detailed geologic survey in the area (YANAI and ISHIKAWA, 1978; NAKAI *et al.*, 1980; HIROI *et al.*, 1983a, 1986). These facts suggest that the ultramafic rocks occur in the western part of the Lützow-Holm Complex, that is, in the more high-grade part of the complex (HIROI and SHIRAISHI, 1986; SHIRAISHI *et al.*, 1986).

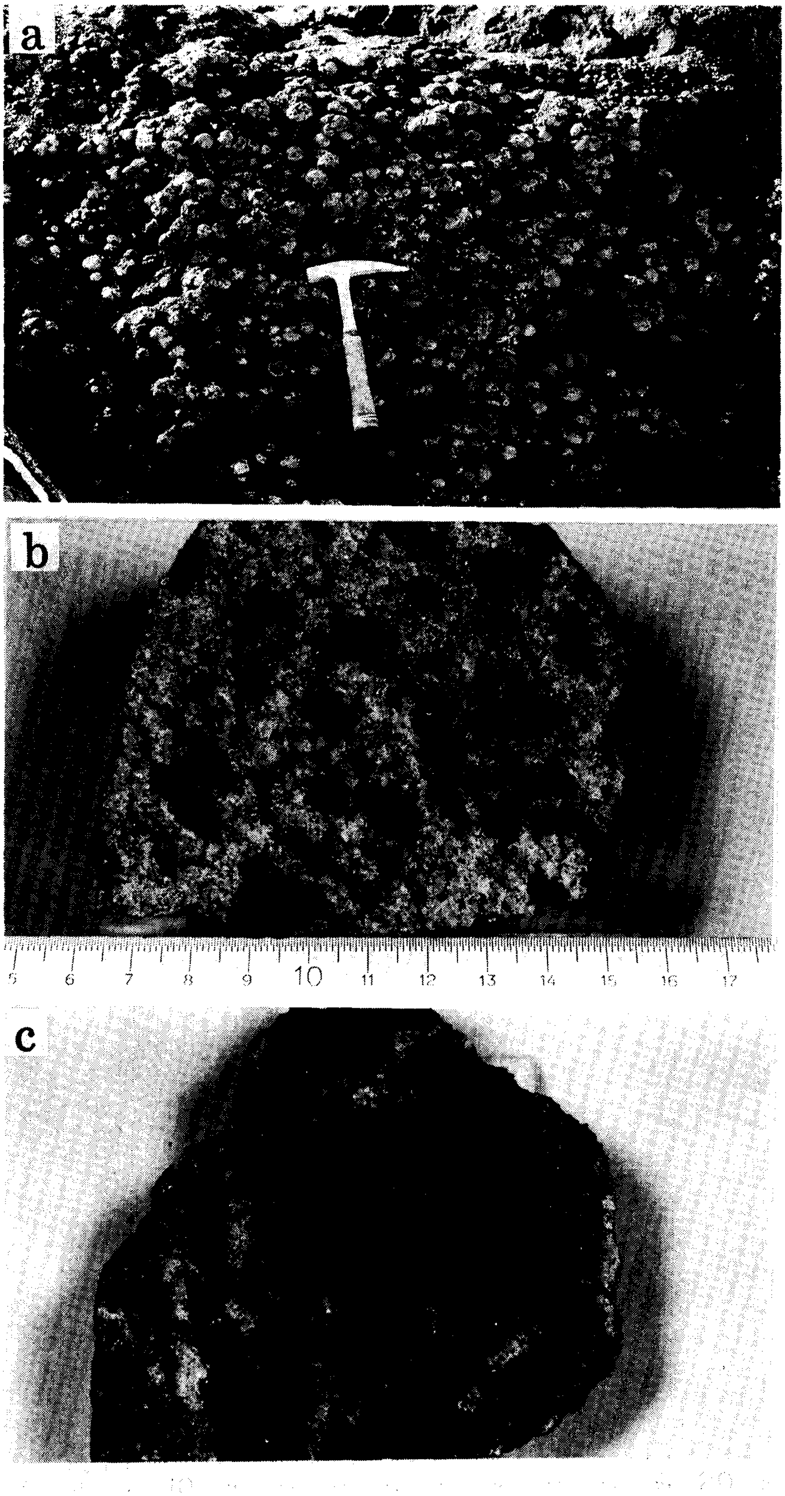


a. Large pyroxenite block (Sp. 81020109B) within well-layered "regional" biotite-hornblende gneiss of HIROI and ONUKI (1985). West Ongul Island.

b. Thick lens-shaped block of hornblende peridotite (Sp. 8101081-11) within pyroxene gneiss. East Ongul Island.

c. Concentrically zoned small block of "ultramafic" rock in pyroxene gneiss. East Ongul Island.

Fig. 2. Photographs showing mode of field occurrence of ultramafic rocks.



a. Sapphirine-bearing garnet hornblendite (Sp. 75020609) from Akarui Point. Note the knobby garnet or its breakdown product of spinel + orthopyroxene + plagioclase symplectite.

b. Plagioclase-rich part of garnet-orthopyroxene amphibolite (Sp. 84010405) from West Ongul Island. The bulk rock composition of Sp. 84010405 in Table 2 is of this part.

c. Plagioclase-poor part of garnet-orthopyroxene amphibolite (Sp. 84010405) from West Ongul Island. Note large prismatic plagioclase crystals, which are now composed of smaller grains containing spinel.

Fig. 3. Photographs showing lithologies of ultramafic rocks of troctolitic compositions.

The ultramafic rocks usually occur as rounded blocks and lensoid masses up to several meters in thickness within metasedimentary and migmatitic rocks (Fig. 2). They also occur as sheet-like masses in some cases. Foliation of the country rock is concordant with the margins of the included blocks. On the other hand, occasional banding and layered structures of the included blocks are not always concordant with their margins. Small blocks sometimes show a concentrically zoned structure (Fig. 2c), suggesting a metasomatic reaction between the included ultramafic rocks and the host rocks rich in quartz and K-feldspar. In addition, phlogopitic biotite is sometimes concentrated at the marginal parts and along the fractures of the ultramafic blocks. Some garnetiferous rocks have a knobby surface due to the differential weathering between porphyroblastic garnets or their breakdown products and the matrix composed mainly of hornblende (Fig. 3a). It is worthy of note that each block of ultramafic rocks is isolated from one another by quartzo-feldspathic rocks free of ultramafic-derived detrital material.

4. Bulk Chemical Compositions of Ultramafic Rocks

The available data on the mineral assemblages and the bulk chemical compositions of the ultramafic rocks in the Lützow-Holm Complex are summarized in Tables 1 and 2, respectively. It is apparent that they are highly variable. In Table 2 and Fig. 4, CIPW normative minerals are calculated and plotted, respectively, to estimate the assemblages and amounts of "igneous" minerals. Some biotite-rich rocks are leucite-normative. Normative plagioclase+pyroxenes+olivine is usually more than 80%. In Figs. 4 and 5, samples are divided into three groups to check the compositional difference in respect to their localities, that is, from the Prince Olav Coast, the Sôya Coast, and the Botnneset area including Padda. As is apparent in the figures, there is no essential difference in bulk chemical compositions among the localities, although there are fewer samples from Botnneset area than from the other areas.

5. Mineral Textures of Ultramafic Rocks

The mineral assemblages of the ultramafic rocks listed in Table 1 show that neither olivine+garnet nor olivine+plagioclase parageneses are found in the rocks, suggesting that these rocks were recrystallized under the spinel-amphibole lherzolite "facies" of JENKINS (1983). The most remarkable textural features are those of garnet and spinel, as follows.

Garnet

(1) It often shows a breakdown texture to the symplectitic intergrowths of spinel+orthopyroxene+plagioclase (anorthite) or orthopyroxene+plagioclase (Figs. 6, 8c, and 9c). The degree of garnet decomposition seems to be correlated with its composition and therefore with the host rock composition, because garnets coexisting with such a Mg-rich mineral as sapphirine show the most advanced breakdown features (Table 1 and Fig. 6).

(2) Garnet contains inclusions of calcic amphibole, spinel, plagioclase, opaque minerals, and sapphirine (Figs. 6 and 8b). Quartz is also included in some cases

Table 1. Constituent minerals of described ultramafic rocks.

Sample number (Locality)	Rock name	Minerals													Data source
		ol	opx	cpx	calcic amph	bi	gar	sp	cor	sap	pl	Ksp	qz	others	
801302 (Niban R.)	Cpx-amph			+	+	+					+	tr		sc, cc, om	B
Y79020406 (Kasumi R.)	Cpx-amph			tr	++	tr					+				C
80T15 (Tenmondai R.)	Cpx-amph			+	+	+					+			sc, om	D
81012301 (*ditto*)	Cpx-amph			+	+	tr					+			sc, sph, om	D
81012406 (*ditto*)	Bi-amph				++	+					tr			om	D
80N2 (Naga-iwa R.)	two px-amph		+	+	+	+					+	tr	tr	cc, po, pent	E
75020610 (Akarui P.)	Sap-opx-amph		+		+	+	(+)*	+	tr	+	+				A
801258 (*ditto*)	Hb-perid	+	+		+	tr		tr						cb, om, ta	E
801259 (*ditto*)	Hb-perid	+	+	+	+	+								cb, om, ta	E
801263 (*ditto*)	Sp-hb-perid	+	+		+	tr		+						om, ta	E
801274 (*ditto*)	Sp-amph				+	+		+			+				E
801275 (*idtto*)	Sp-opx-hbt		+		+			+			tr			cb, om, ta	E
75020606 (*ditto*)	Sp-hb-perid	+	+		+	tr		+						cb, om, ta	A
75020609 (*ditto*)	Sap-gar-hbt		+		+	+	+	+		tr	+			om	A
I0818 (C. Omega)	Cpx-amph			+	+	+					+	?	+	sph, il, mt	F
68021509 (Ongul Is.)	"Hb-eclog"		+	+	+		+				+				H
68032303 (*ditto*)	"Hb-eclog"		+		+		+				+				G
68032304 (*ditto*)	Pxt		+	+											G
68032701 (*ditto*)	Opxt		+	+	+									om	G
68032703 (*ditto*)	Pxt		+	+	+						tr				G
68032704 (*ditto*)	Pxt		+	+		+									G
68040105 (*ditto*)	Gar-opx-amph		+		+		+				+				H
68091201-1 (*ditto*)	"Hb-eclog"		+		+		+				+				G
68091201-2 (*ditto*)	Hbt		+	+	++	+					tr				G
8101081-11 (*ditto*)	Hb-perid	+	+	+	+	+								cb, om	A
81020109B (*ditto*)	Pxt		+	+	tr	tr					tr	tr	tr	om	A
84010309A (*ditto*)	Sp-opx-hbt		+		+	+		+			tr			om	A
84010405 (*ditto*)	Gar-opx-amph		+		+	+	+	+	tr		+			om	A

84010503 (*ditto*)	Gar-opx-amph		+		+	tr	+				+			om	A
84010504 (*ditto*)	Hb-pxt		+	+	+									om	A
57112602 (Langhovde)	Ub. granul		+	+	+						+			om	I
81020303A (*ditto*)**	Cpxt			++							tr			om	A
LH-128-09 (*ditto*)	Sp-hb-perid	+	+		+	+		+						om	A
57110905 (Skarvsnes)	Ub. granul		+		+		+	+						il, py, po	I
RK-131-04 (Rundvågskollane)	Sp-hb-perid	+	+		+	+		+						om	A
RK-131-28 (*ditto*)	Hb-perid	+	+		+	+								om	A
RK-203-59 (*ditto*)	Sp-opx-hbt		+		+			+			tr			om	A
720101905 (Padda)	Sp-hb-perid	+	+	tr	+	+		+						cb, om	A
84012223 (Austhovde)	Opx-eclog		+	+	tr	+	+				+		+***	om	A
84011813 (Vesthovde)	Perid	tr	+	+	tr									om	A
84012006 (*ditto*)	Sp-hb-perid	+	+		+	tr		+						om	A
84011306 (Innhovde)	Hb-pxt		+	+	+	+								om	A
84011307 (*ditto*)	Hb-perid	+	+	+	+									om	A

Rock name abbreviations
amph—amphibolite ub. granul—ultrabasic granulite eclog—eclogite hbt—hornblendite perid—peridotite pxt—pyroxenite

Mineral abbreviations
bi—biotite including phlogopite calcic amph—calcic amphiboles (mostly hornblende) cb—carbonate minerals cc—calcite chl—chlorite cor—corundum cpx—clinopyroxene gar—garnet il—ilmenite Ksp—K-feldspar mt—magnetite ol—olivine om—opaque minerals opx—orthopyroxene pent—pentlandite pl—plagioclase po—pyrrhotite py—pyrite qz—quartz sap—sapphirine sc—scapolite sp—spinel sph—sphene ta—talc

Data sources
A—this study B—Kizaki *et al.* (1983) C—Nishida *et al.* (1984) D—Shiraishi *et al.* (1985) E—Yanai *et al.* (1984)
F—Suzuki (1985) G—Yanai *et al.* (1974a) H—Yanai *et al.* (1974b) I—Banno *et al.* (1964b)

++; abundant (>50 modal %), +; common, tr; minor (<5 modal %).
* Only pseudomorph composed of spinel+orthopyroxene+plagioclase symplectitic intergrowth.
** Calc-silicate rock for reference.
*** Only as inclusions in garnet.

Table 2. Chemical compositions and CIPW norms of ultramafic rocks.

	Prince Olav Coast							
	Niban	Kasumi	Tenmondai Rock			Naga-iwa	Akarui Point	
	801302	Y79020406	80T15	81012301	81012406	80N2	75020610	801258
SiO_2	49.25	44.58	41.09	41.17	40.06	51.34	41.82	41.98
TiO_2	0.29	1.83	0.65	1.70	2.40	0.31	0.19	1.58
Al_2O_3	6.02	14.36	20.15	17.02	15.18	4.79	23.05	9.46
Fe_2O_3	0.87	3.48	3.76	4.36	3.95	2.31	2.41	2.92
FeO	2.78	9.54	6.81	10.89	11.76	7.81	3.00	4.39
MnO	0.29	0.19	0.18	0.18	0.10	0.26	0.04	0.11
MgO	15.87	8.65	9.10	6.54	9.12	19.98	15.10	21.72
CaO	19.48	11.02	14.56	14.18	11.60	9.42	10.63	10.25
Na_2O	0.58	2.60	1.48	1.34	2.01	0.63	1.80	1.69
K_2O	1.66	1.54	0.39	0.36	1.52	0.70	0.21	0.31
H_2O (+)	2.46	2.03	1.75	1.29	1.59	1.88	1.03	3.67
H_2O (−)	0.04	0.03	0.04	0.10	0.08	0.21	0.14	0.06
P_2O_5	0.12	0.11	0.05	0.60	0.38	tr.	0.02	1.23
Total	99.71	99.96	100.01	99.73	99.75	99.64	99.44	99.32
Normative minerals								
Q	—	—	—	—	—	—	—	—
C	—	—	—	—	—	—	0.59	—
Or	—	9.33	—	2.17	—	4.25	1.27	1.92
Ab	—	5.70	—	2.05	—	5.48	3.21	7.32
An	9.18	23.54	48.23	40.21	28.54	8.40	53.66	18.16
Lc	7.92	—	1.85	—	7.20	—	—	—
Ne	2.74	9.13	6.93	5.16	9.42	—	6.68	4.16
Di wo	34.48	13.26	6.52	11.54	9.99	16.54	—	11.17
Di en	26.44	6.64	3.51	4.63	4.76	11.19	—	8.41
Di fs	4.41	6.34	2.79	7.03	5.10	4.08	—	1.63
Hy en	—	—	—	—	—	26.76	—	—
Hy fs	—	—	—	—	—	9.75	—	—
Ol fo	10.00	10.83	13.77	8.42	12.95	9.24	26.89	33.87
Ol fa	1.84	11.41	12.03	14.08	15.30	3.71	7.29	7.23
Cs	2.15	—	2.99	—	1.19	—	—	—
Il	0.57	3.56	1.26	3.30	4.66	0.61	0.37	3.15
Ap	0.29	0.26	0.12	1.42	0.90	tr.	0.05	2.99
MgO/(MgO+FeO*)	0.887	0.550	0.614	0.440	0.515	0.782	0.839	0.846

* Total Fe as FeO.
Norms calculated on conversion of all Fe_2O_3 to FeO, deletion of H_2O and normalizing.
Data sources in Table 1.
Analysts of this paper:
H. ONUKI for Sp. 81020109B. (conventional wet chemical analysis)
S. KANISAWA for the others. (XRF analysis except for FeO, alkalis, and H_2O)

Table 2 (continued).

	Prince Olav Coast					Sôya Coast		
	Akarui Point				C. Omega	Ongul Islands		
	80125 9	80126 3	80127 4	80127 5	10818	680215 09	680323 03	680323 04
SiO_2	43.67	40.02	40.78	41.43	43.05	40.15	44.20	52.41
TiO_2	0.21	0.19	0.09	0.18	0.91	0.78	0.42	0.25
Al_2O_3	7.20	8.09	21.86	19.58	17.06	16.85	15.38	0.76
Fe_2O_3	2.81	3.20	2.36	2.69	4.36	1.35	4.53	1.12
FeO	4.97	7.85	2.99	3.80	10.20	17.06	15.48	22.14
MnO	0.14	0.17	0.09	0.11	0.42	0.31	0.48	0.26
MgO	25.72	32.25	14.27	19.26	7.49	9.65	8.65	22.10
CaO	8.46	3.70	8.00	8.67	15.24	9.34	6.96	0.18
Na_2O	1.19	0.78	1.45	1.45	1.08	1.48	1.93	0.53
K_2O	0.59	0.15	4.10	0.25	0.90	0.87	0.30	1.13
H_2O (+)	4.39	3.44	3.38	1.86	—	1.85	1.27	—
H_2O (−)	0.17	0.13	0.22	0.08	—	0.12	0.20	0.19
P_2O_5	0.06	0.04	0.06	0.05	—	0.14	0.09	0.07
Total	99.58	100.01	99.65	99.41	100.71	99.95	99.89	100.12
Normative minerals								
Q	—	—	—	—	—	—	—	—
C	—	0.01	0.66	1.32	—	—	—	—
Or	3.68	0.92	—	1.52	—	5.24	1.81	0.77
Ab	4.59	3.62	—	5.14	—	1.32	16.67	3.19
An	13.26	18.83	41.01	43.92	38.94	37.57	33.09	—
Lc	—	—	11.33	—	4.16	—	—	—
Ne	3.27	1.76	6.94	4.06	4.94	6.22	—	ns=0.30
Di wo	12.79	—	—	—	12.58	3.69	0.65	0.18
Di en	9.51	—	—	—	5.36	1.57	0.25	0.10
Di fs	2.03	—	—	—	7.24	2.14	0.41	0.08
Hy en	—	—	—	—	—	—	3.99	49.06
Hy fs	—	—	—	—	—	—	6.68	37.91
Ol fo	40.72	58.56	26.00	34.58	9.28	16.12	12.45	4.20
Ol fa	9.59	15.83	7.58	9.00	13.82	24.28	22.99	3.58
Cs	—	—	—	—	1.96	—	—	—
Il	0.41	0.38	0.18	0.35	1.72	1.51	0.81	0.48
Ap	0.15	0.10	0.15	0.12	—	0.33	0.21	0.16
MgO/(MgO +FeO*)	0.860	0.843	0.833	0.846	0.486	0.485	0.441	0.638

(Table 1), but orthopyroxene is never so.

Spinel

(1) It is associated with various minerals; olivine, sapphirine, corundum, garnet, orthopyroxene, clinopyroxene, calcic amphibole, and plagioclase.

(2) Spinel shows variable textures; as inclusions in garnet, plagioclase, olivine, and sapphirine (Figs. 6c, 7a, 7c, and 8b) and as symplectitic intergrowths with orthopyroxene and plagioclase fringing garnet (Figs. 6b and 8c) and with orthopyroxene and calcic amphibole with or without sapphirine and plagioclase (Figs. 7b and 8a).

Table 2 (continued).

	Sôya Coast							
	Ongul Islands							
	680327 01	680327 03	680327 04	680401 05	680912 01-1	680912 01-2	810108 I-11	810201 09B
SiO_2	51.53	44.99	53.20	44.20	40.14	44.49	46.88	53.41
TiO_2	0.08	1.19	0.22	0.59	0.56	0.24	0.29	0.26
Al_2O_3	4.48	12.26	2.70	26.26	20.79	13.69	2.82	0.77
Fe_2O_3	1.29	1.94	1.03	0.77	0.46	1.19	1.53	2.37
FeO	18.80	5.65	8.74	6.58	19.42	11.36	7.78	7.60
MnO	0.22	0.16	0.28	0.09	0.49	0.14	0.19	0.14
MgO	22.35	11.82	24.16	6.02	10.82	14.17	22.79	15.71
CaO	1.27	17.31	6.78	11.19	6.00	9.38	13.20	17.83
Na_2O	0.34	1.42	0.33	2.47	0.56	1.87	0.72	0.87
K_2O	0.08	0.99	0.34	0.63	0.24	1.25	0.57	0.06
H_2O (+)	—	1.54	2.03	0.89	0.34	1.85	3.17	0.47
H_2O (−)	0.06	0.42	0.10	0.08	0.11	0.16	0.04	0.19
P_2O_5	0.05	0.03	0.12	0.17	0.11	0.11	0.01	tr.
Total	100.55	99.72	100.03	99.94	100.04	99.90	99.99	99.68
Normative minerals								
Q	—	—	—	—	—	—	—	—
C	1.64	—	—	1.59	9.01	—	—	—
Or	0.47	—	2.05	3.77	1.43	7.56	3.49	0.36
Ab	2.87	—	2.86	13.59	4.76	6.21	2.31	3.67
An	5.95	24.26	4.99	55.01	29.18	25.85	2.88	—
Lc	—	4.61	—	—	—	—	—	—
Ne	—	6.54	—	4.09	—	—	2.17	ns=0.88
Di wo	—	23.03	11.94	—	—	8.78	27.07	37.39
Di en	—	16.28	8.41	—	—	5.09	19.11	24.04
Di fs	—	4.76	2.50	—	—	3.27	5.62	10.87
Hy en	47.79	—	46.58	—	11.70	—	—	14.76
Hy fs	31.70	—	13.87	—	15.79	—	—	6.68
Ol fo	5.38	9.31	4.58	10.63	10.78	21.73	27.77	0.57
Ol fa	3.94	3.00	1.50	9.79	16.04	15.39	9.00	0.29
Cs	—	2.05	—	—	—	—	—	—
Il	0.15	6.09	0.23	1.13	1.07	0.47	0.57	0.50
Ap	0.12	0.07	0.28	0.40	0.26	0.26	0.02	—
MgO/(MgO+FeO*)	0.666	0.740	0.816	0.596	0.493	0.670	0.816	0.743

6. Discussion

Mafic to ultramafic metamorphics may have been derived from mafic to ultramafic igneous rocks and from calcareous or dolomitic shales (*e.g.* LEAKE, 1964), or may have developed as a metasomatic reaction zone between adjacent pelitic and carbonate rocks (*e.g.* ORVILLE, 1969). In the study area, some calcareous rocks show the same mode of field occurrence as the ultramafic rocks. However, calcareous rocks in the study area are easily identified by field and microscopic observations (*e.g.* MATSUEDA *et al.*, 1983).

Table 2 (continued).

	Sôya Coast							
	Ongul Islands				Langhovde			Skarvsnes
	840103 09A	840104 05	840105 03	840105 04	571126 02	810203 03A	LH-128 -09	571109 05
SiO_2	42. 12	44. 37	46. 81	46. 34	42. 57	52. 11	43. 35	40. 47
TiO_2	0. 12	0. 08	0. 19	2. 18	1. 60	0. 48	0. 95	1. 29
Al_2O_3	15. 79	26. 96	9. 49	4. 37	16. 95	2. 15	8. 71	11. 50
Fe_2O_3	5. 79	1. 23	5. 75	3. 91	2. 37	0. 80	5. 31	5. 87
FeO	5. 50	3. 87	13. 49	13. 73	11. 67	6. 82	8. 38	15. 26
MnO	0. 15	0. 07	0. 27	0. 27	0. 23	0. 20	0. 22	0. 24
MgO	20. 82	6. 69	16. 78	12. 83	8. 71	11. 83	23. 10	16. 64
CaO	6. 82	13. 71	5. 06	12. 62	9. 88	22. 51	6. 10	5. 86
Na_2O	1. 37	1. 64	0. 46	0. 94	1. 75	0. 54	1. 31	1. 29
K_2O	0. 88	0. 31	0. 62	0. 61	1. 59	0. 04	0. 90	0. 30
H_2O (+)	0. 60	0. 86	1. 03	1. 49	1. 84	2. 32	1. 59	1. 27
H_2O (−)	0. 02	0. 20	0. 04	0. 28	0. 20	0. 19	0. 04	0. 17
P_2O_5	—	—	—	0. 42	0. 18	—	0. 21	0. 16
Total	99. 98	99. 99	99. 99	99. 99	99. 54	99. 99	99. 99	100. 32
Normative minerals								
Q	—	—	—	—	—	0. 24	—	—
C	0. 19	—	—	—	—	—	—	—
Or	5. 27	1. 85	3. 73	3. 69	9. 66	0. 24	5. 44	1. 80
Ab	3. 24	8. 51	3. 96	8. 13	4. 93	4. 69	8. 86	9. 92
An	34. 25	66. 07	22. 32	6. 03	34. 65	3. 41	15. 56	25. 13
Lc	—	—	—	—	—	—	—	—
Ne	4. 60	3. 00	—	—	5. 58	—	1. 34	0. 65
Di wo	—	1. 15	1. 34	23. 03	6. 07	46. 45	5. 83	1. 41
Di en	—	0. 70	0. 71	11. 84	2. 90	29. 81	3. 88	0. 73
Di fs	—	0. 39	0. 59	10. 59	3. 09	13. 58	1. 53	0. 64
Hy en	—	—	22. 77	4. 95	—	0. 45	—	—
Hy fs	—	—	18. 77	4. 43	—	0. 20	—	—
Ol fo	36. 79	11. 32	13. 33	11. 12	13. 60	—	38. 49	29. 03
Ol fa	15. 44	6. 85	12. 12	10. 96	15. 98	—	16. 74	27. 82
Cs	—	—	—	—	—	—	—	—
Il	0. 23	0. 15	0. 37	4. 23	3. 12	0. 94	1. 84	2. 49
Ap	—	—	—	1. 00	0. 43	—	0. 50	0. 38
MgO/(MgO +FeO*)	0. 776	0. 706	0. 615	0. 570	0. 529	0. 736	0. 760	0. 591

For example, Sp. 81020303A (clinopyroxenite) from Langhovde may have originated from a calcareous rock. It is highly Ca-rich, as shown in Fig. 5b. Moreover, most of the ultramafic rocks in the study area occur as isolated blocks within quartzo-feldspathic rocks. Some small blocks are concentrically zoned (Fig. 2c), suggesting chemical exchange with the surrounding quartzo-feldspathic rocks. In this connection, extremely biotite-rich Sp. 801274 from Akarui Point may have been enriched with K_2O by such chemical exchange (see Fig. 5a). Therefore, we may assume that the inner parts of the large ultramafic blocks have essentially the same compositions as their protoliths.

Table 2 (continued).

	Sôya Coast			Padda and Botnneset				
	Rundvågskollane			Padda	Vesthovde		Innhovde	
	RK-131 -04	RK-131 -28	RK-203 -59	721019 05	840118 13	840120 06	840113 06	840113 07
SiO_2	41.21	47.75	43.21	41.74	47.95	39.58	47.68	49.21
TiO_2	0.51	0.52	0.20	0.36	1.43	0.73	0.62	0.40
Al_2O_3	4.88	5.35	16.52	6.12	7.03	7.15	4.74	7.24
Fe_2O_3	6.08	5.69	5.15	5.32	2.69	10.57	8.83	2.35
FeO	9.79	7.87	6.19	10.93	9.80	11.89	6.53	3.17
MnO	0.18	0.17	0.13	0.20	0.16	0.31	0.21	0.11
MgO	31.33	23.88	17.14	27.15	18.59	23.50	25.47	19.40
CaO	2.95	5.87	8.67	4.23	9.20	4.09	2.35	15.42
Na_2O	0.56	1.09	1.26	0.84	1.21	1.18	0.27	1.12
K_2O	0.64	0.69	0.42	0.35	0.74	0.19	1.94	0.74
H_2O (+)	1.78	0.86	0.98	2.64	0.97	0.59	1.00	0.77
H_2O (−)	0.01	0.19	0.10	0.09	0.09	0.14	0.10	0.06
P_2O_5	0.06	0.06	0.02	0.04	0.14	0.07	0.27	—
Total	99.98	99.99	99.99	99.99	100.00	99.99	100.01	99.99
Normative minerals								
Q	—	—	—	—	—	—	—	—
C	—	—	—	—	—	—	—	—
Or	3.88	4.15	2.52	2.14	4.43	1.14	11.70	4.43
Ab	4.86	9.38	8.56	7.35	10.38	5.21	2.33	3.48
An	9.13	7.79	38.80	12.24	11.72	13.90	6.11	12.70
Lc	—	—	—	—	—	—	—	—
Ne	—	—	1.23	—	—	2.69	—	3.32
Di wo	2.28	8.94	2.00	3.84	14.03	2.63	1.66	27.04
Di en	1.55	5.95	1.27	2.51	9.09	1.51	1.10	20.48
Di fs	0.55	2.33	0.59	1.06	4.00	1.00	0.45	3.79
Hy en	0.83	14.46	—	1.99	9.76	—	25.83	—
Hy fs	0.29	5.67	—	0.84	4.29	—	10.57	—
Ol fo	54.37	28.07	29.51	45.84	19.68	40.71	26.48	19.93
Ol fa	21.12	12.12	15.08	21.40	9.54	29.64	11.94	4.07
Cs	—	—	—	—	—	—	—	—
Il	0.99	1.00	0.39	0.71	2.75	1.41	1.20	0.77
Ap	0.14	0.14	0.05	0.10	0.33	0.17	0.64	—
MgO/(MgO +FeO*)	0.786	0.766	0.720	0.754	0.731	0.666	0.758	0.867

Normative minerals listed in Table 2 and plotted in Fig. 4a suggest that most of the ultramafic rocks in the Lützow-Holm Complex are gabbroids in composition and probably in origin. Some are troctolitic, being composed mainly of normative olivine and plagioclase without pyroxenes. The variable amounts of normative olivine, pyroxenes, and plagioclase suggest that they were derived from different parts of layered gabbro. Although most of the ultramafic blocks show no original "cumulate" or layered structures, some large block show a variation in modal amounts of plagioclase and mafic minerals and occasionally a cumulate-like structure (Figs. 3b and 3c). The AFM and

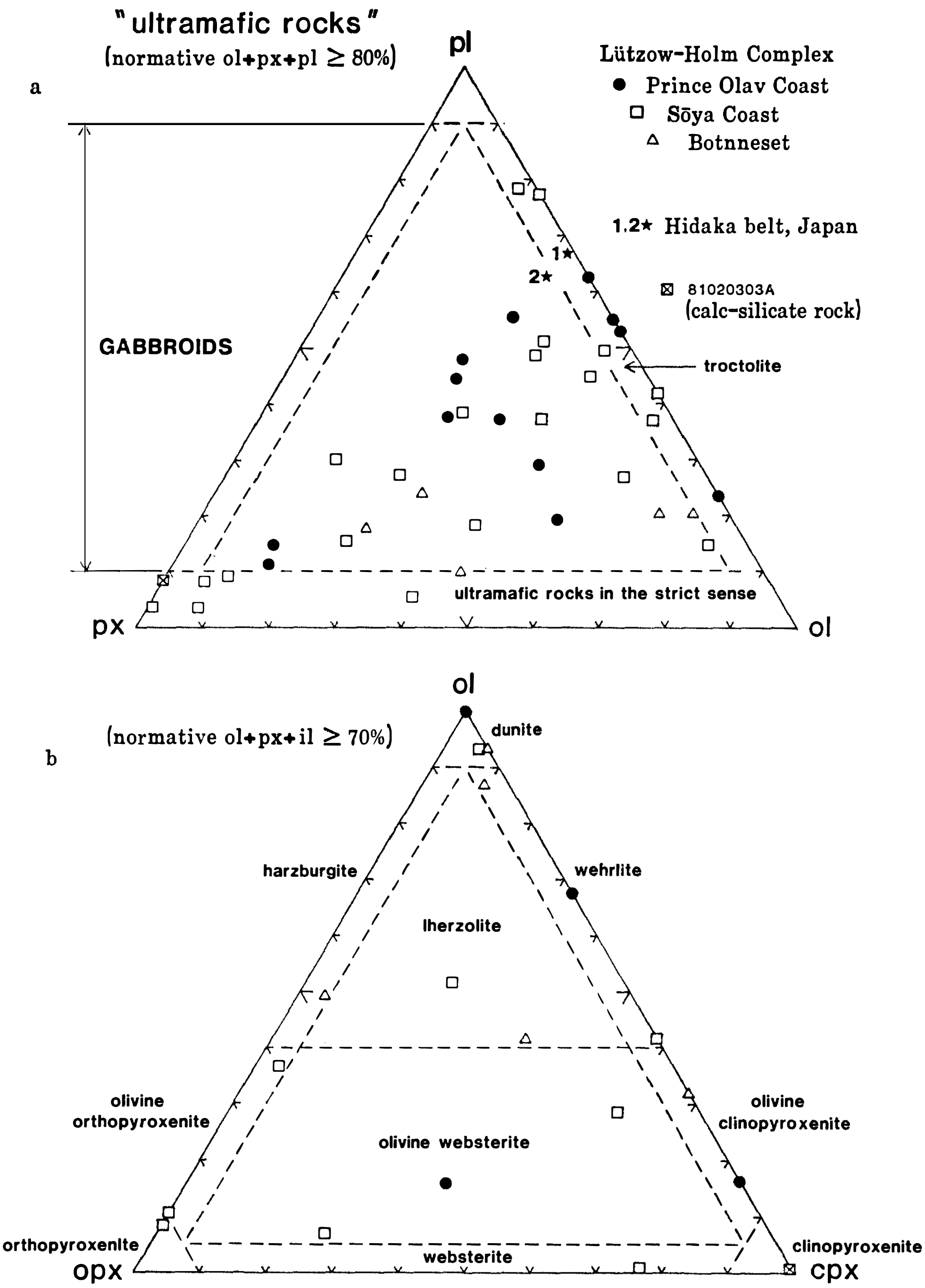


Fig. 4. Normative amounts of olivine, pyroxenes, and plagioclase of ultramafic rocks in Lützow-Holm Complex. See text for detailed discussion on Sp. 81020303A. Troctolite (1) and its metamorphosed equivalent carrying sapphirine (2) from the ophiolite complex of the Hidaka belt, Japan (MIYASHITA et al., 1980), are also plotted for comparison.

a. Normative olivine, pyroxenes, and plagioclase.

b. Normative olivine, orthopyroxene, and clinopyroxene.

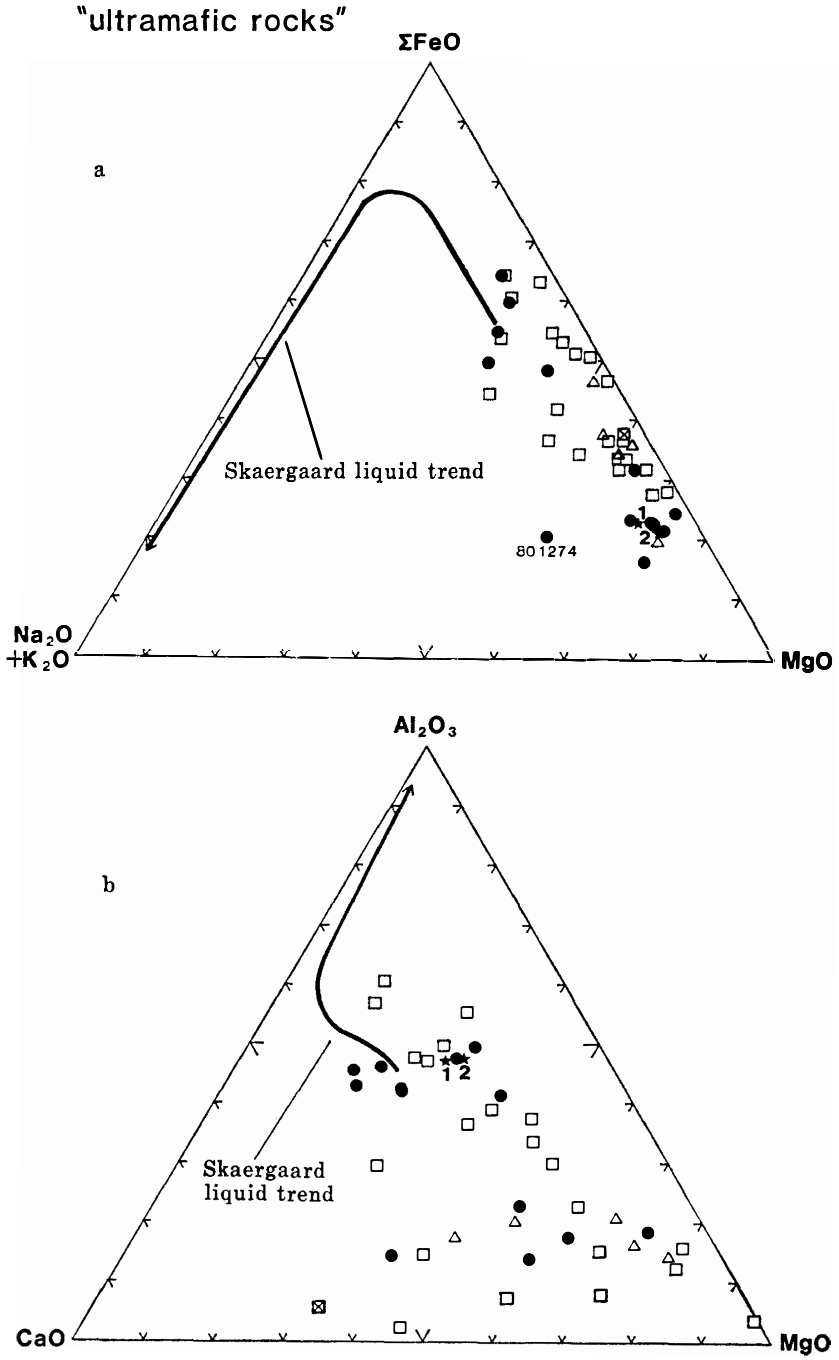
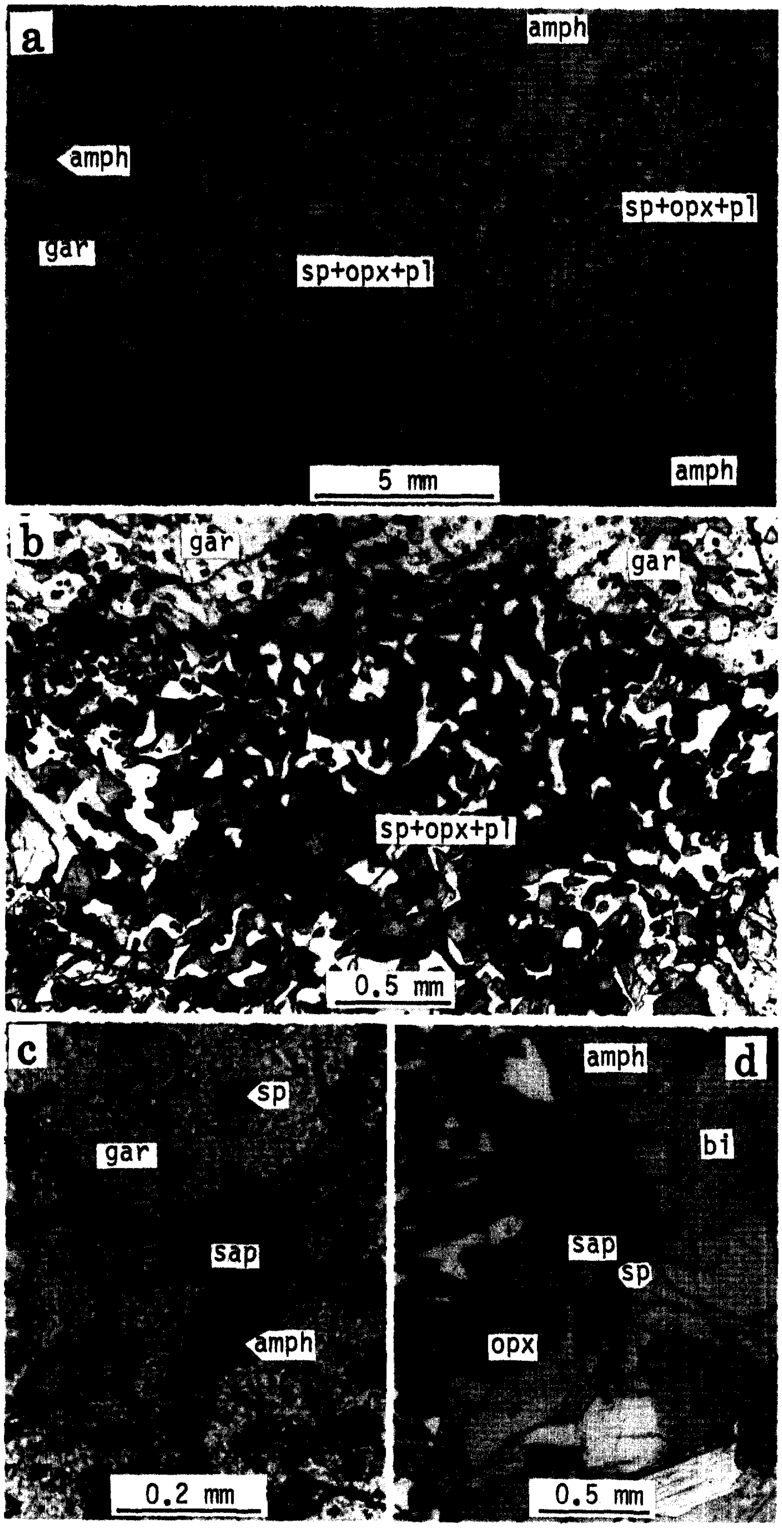


Fig. 5. Triangular diagrams for ultramafic rocks in Lützow-Holm Complex in weight percent. Troctolite and its metamorphosed equivalent from the Hidaka belt, Japan (MIYASHITA et al., 1980), are also plotted for comparison. Skaergaard liquid trend is after WAGER and DEER (1939) and WAGER and BROWN (1967). Symbols as in Fig. 4. See text for detailed discussion on Sp. 801274 and Sp. 81020303A.

a. AFM diagram.

b. Al_2O_3-CaO-MgO diagram.



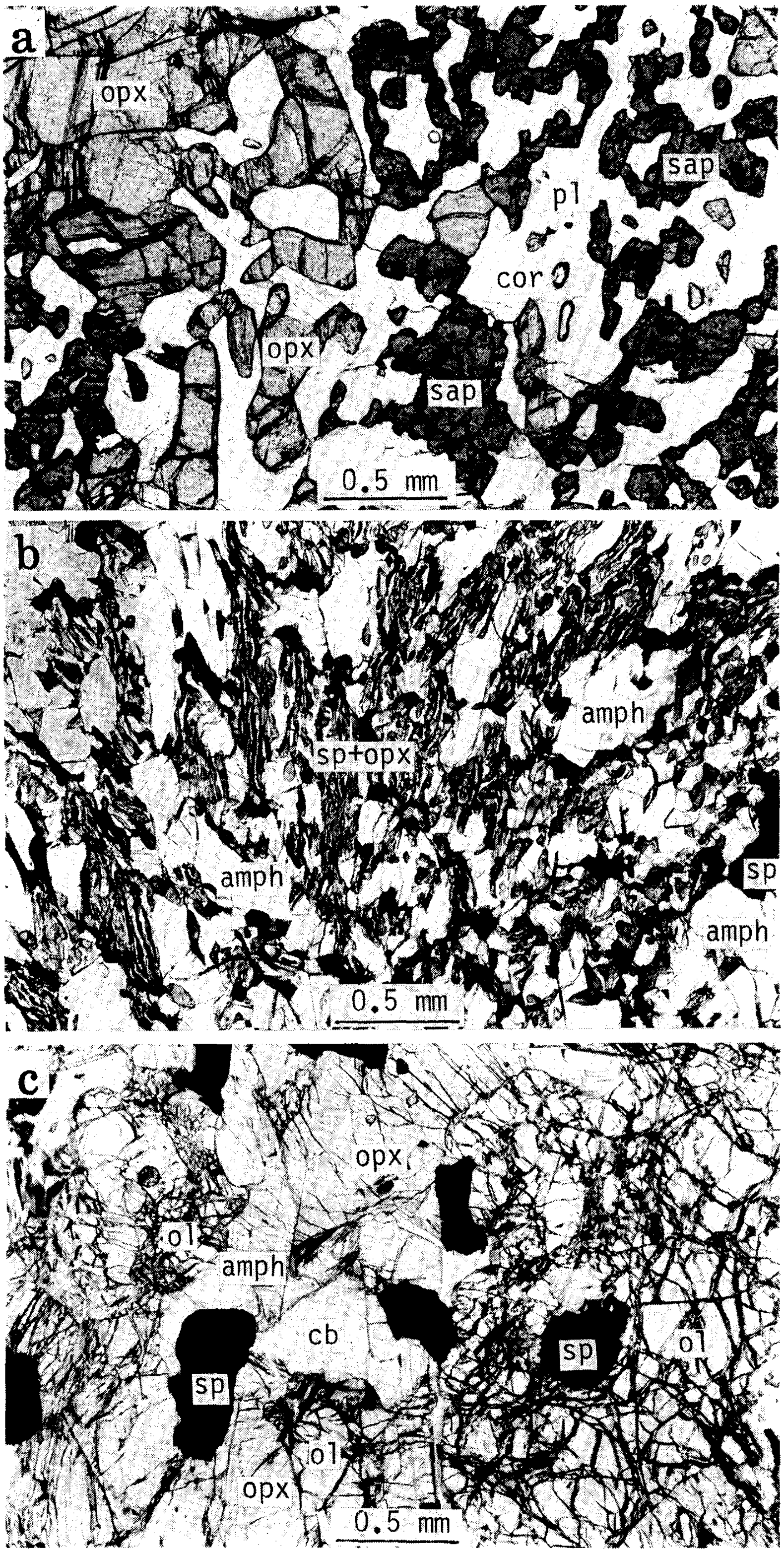
a. Garnet and its breakdown product of spinel + orthopyroxene + plagioclase symplectitic intergrowth in hornblende matrix.

b. Enlarged photograph of spinel + orthopyroxene + plagioclase symplectitic-intergrowth around garnet in a. Hornblende is also present.

c. Enlarged photograph of garnet in a, showing inclusions of sapphirine, spinel and hornblende. Note orthopyroxene is entirely absent within garnet.

d. Enlarged photograph of boundary between hornblende matrix and spinel + orthopyroxene + plagioclase symplectitic intergrowth in a. Note sapphirine is in direct contact with spinel, hornblende, biotite, and orthopyroxene. It is also in direct contact with plagioclase elsewhere.

Fig. 6. Photomicrographs of sapphirine-bearing garnet hornblendite (Sp. 75020609) from Akarui Point. Plane polarized light.

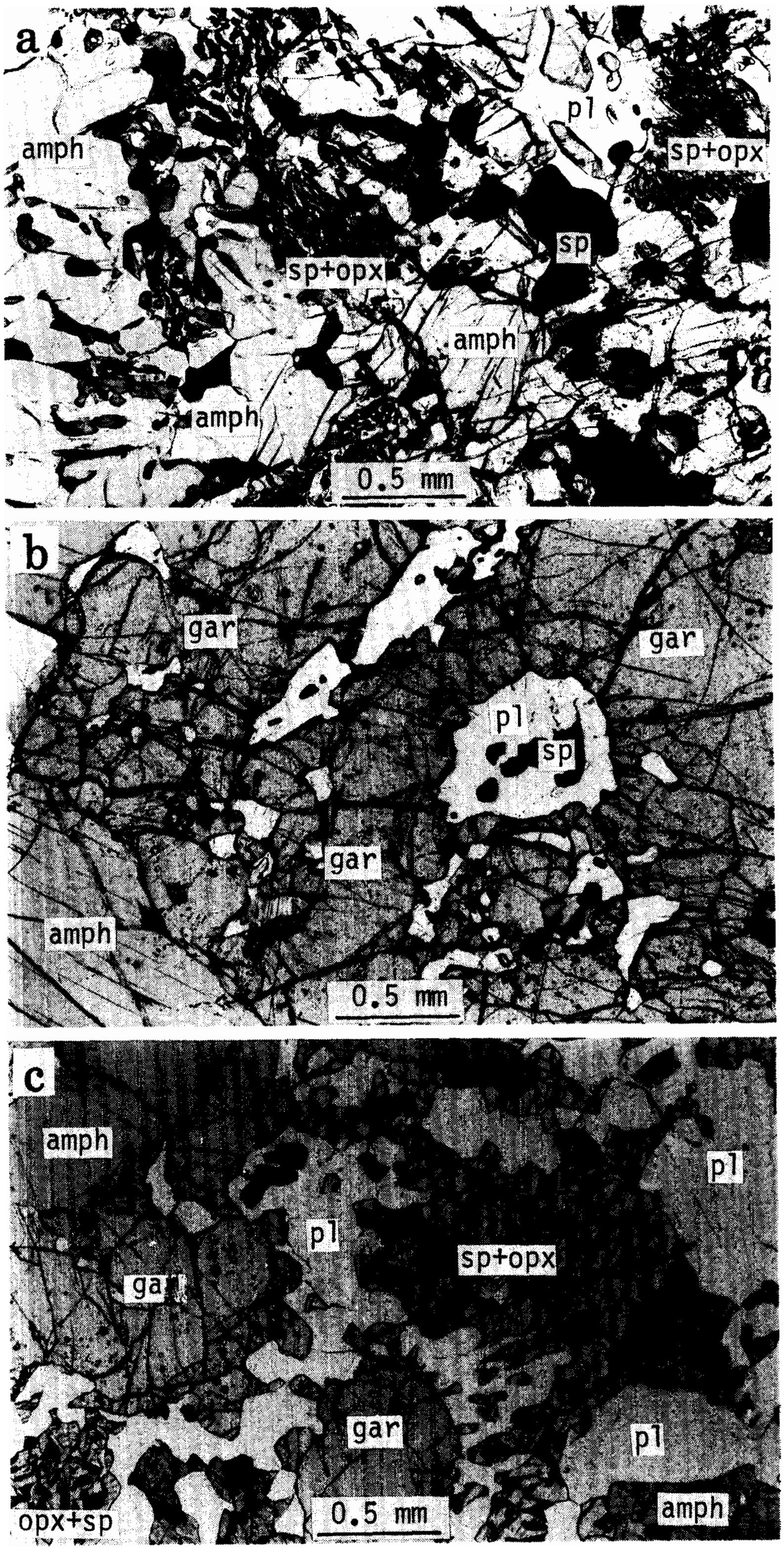


a. Sapphirine + spinel + corundum + orthopyroxene + plagioclase paragenesis in sapphirine-orthopyroxene amphibolite (Sp. 75020610). Spinel often occurs as inclusions in sapphirine.

b. Spinel + orthopyroxene + hornblende intergrowth in spinel-orthopyroxene hornblendite (Sp. 801275).

c. Spinel + olivine + orthopyroxene + hornblende paragenesis in spinel-hornblende peridotite (Sp. 75020606).

Fig. 7. Photomicrographs of ultramafic rocks from Akarui Point. Plane polarized light.

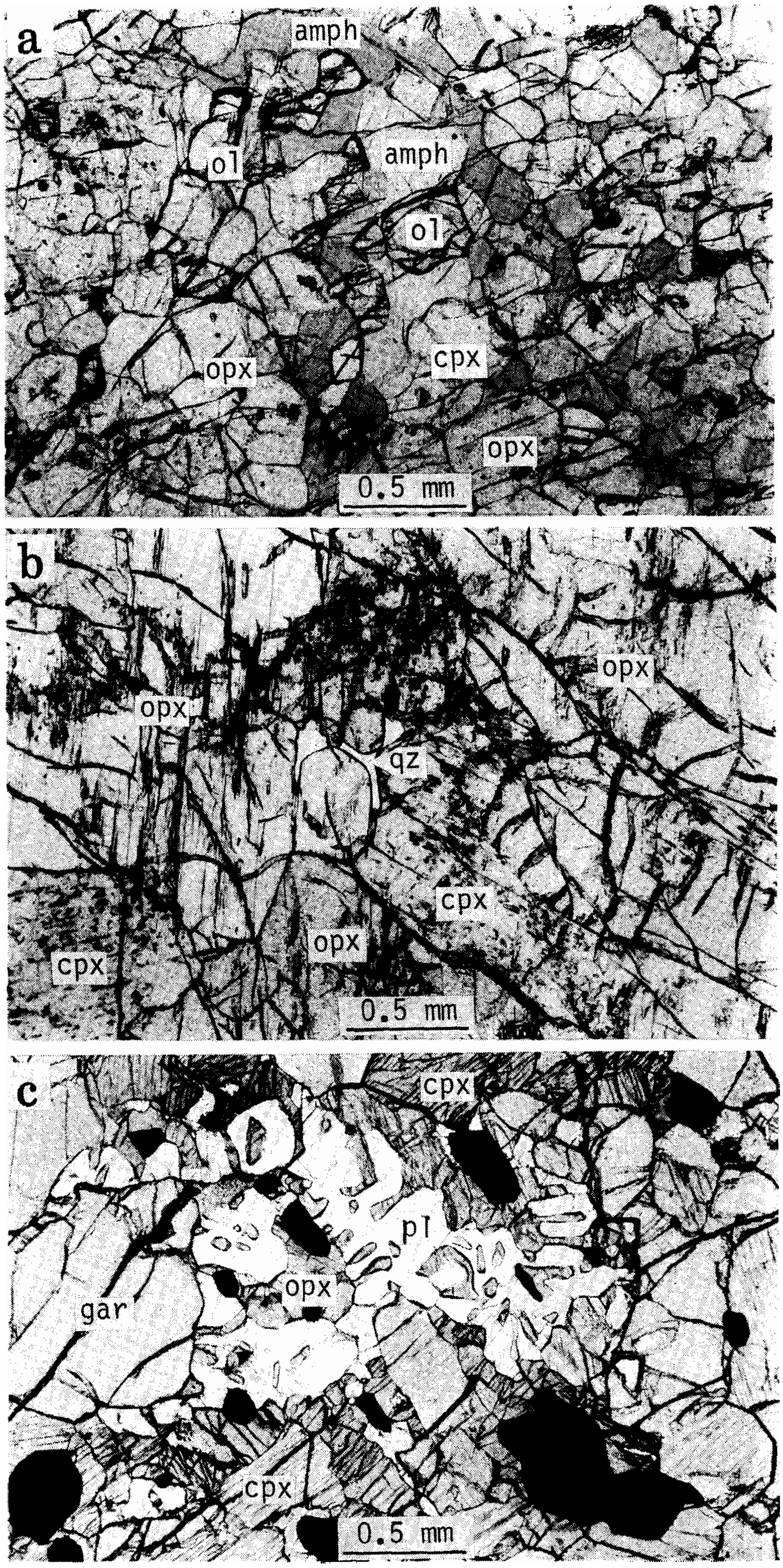


a. Spinel + orthopyroxene + hornblende intergrowth in spinel-orthopyroxene hornblendite (Sp. 84010309A). Note a small amount of plagioclase is also present.

b. Inclusions of spinel and plagioclase within garnet in garnet-orthopyroxene amphibolite (Sp. 84010405). Note garnet does not show a decomposition texture.

c. Garnet and intergrowth of spinel + orthopyroxene within plagioclase in garnet-orthopyroxene amphibolite (Sp. 84010405).

Fig. 8. Photomicrographs of ultramafic rocks from Ongul Islands. Plane polarized light.



a. Olivine + orthopyroxene + clinopyroxene + hornblende paragenesis in hornblende peridotite (Sp. 8101081-11) from East Ongul Island.

b. Orthopyroxene + clinopyroxene in pyroxenite (Sp. 81020109B) from West Ongul Island. Note a small amount of quartz is also present.

c. Garnet, clinopyroxene, and intergrowth of orthopyroxene + plagioclase in orthopyroxene eclogite (Sp. 84012224) from Austhovde.

Fig. 9. Photomicrographs of ultramafic rocks from Ongul Islands and Austhovde. Plane polarized light.

Al_2O_3-CaO-MgO diagrams in Fig. 5 suggest that the protoliths were formed by fractional crystallization of basic magma. Such chemical features of the ultramafic rocks in the Lützow-Holm Complex are similar to those of cumulate complexes in ophiolitic sequences (COLEMAN, 1977). In this connection, it is noteworthy that a plagiogranite-like rock ("anorthositic gneiss" of YANAI and ISHIKAWA (1978)) occurs in the Cape Hinode area in the eastern part of the Prince Olav Coast (*e.g.* KANISAWA *et al.*, 1979). On the other hand, it may be pointed out that ultramafic rocks in the strict sense (especially harzburgite) are rare in the study area (Fig. 4).

The mode of occurrence of the ultramafic rocks of the Lützow-Holm Complex in the field suggests that they were emplaced in the metasedimentary gneisses through a sedimentary or tectonic process. The concordant foliations of the country gneisses and the absence of ultramafic detrital material around the isolated ultramafic blocks suggest that a tectonic process is more likely. The occurrence of the ultramafic rocks in the western part of the Lützow-Holm Complex suggests that the original gabbroid masses were present to the west of the original sedimentary piles of the Lützow-Holm Complex. However, ultramafic rocks have not been found in the Yamato-Belgica Complex which is located immediately to the west of the Lützow-Holm Complex (HIROI *et al.*, 1984; HIROI and SHIRAISHI, 1986; SHIRAISHI *et al.*, 1986). It may follow that the original gabbroid masses were situated in the presently missing part (ocean floor?) between the Lützow-Holm and Yamato-Belgica Complexes.

The most notable textural features of the minerals in the ultramafic rocks are those of garnet and spinel, as mentioned above. The textural features of these minerals, together with the bulk chemical compositions of the rocks, are interpreted as the results of their crystallization and recrystallization history, as follows.

(1) Fractional crystallization of basic magma to produce a sequence of ultramafic to leucocratic rocks under a relatively low-pressure condition (because of the formation of the olivine+plagioclase association).

(2) Regional metamorphic recrystallization to produce garnet free of orthopyroxene inclusions under relatively high-pressure and low-temperature conditions (high-pressure and low-temperature part of the spinel-amphibole lherzolite "facies" of JENKINS (1983)).

(3) Subsequent metamorphic recrystallization under lower-pressure and higher-temperature conditions to form the symplectitic intergrowth of orthopyroxene+plagioclase+spinel from garnet (low-pressure and high-temperature part of the spinel-amphibole lherzolite "facies" of JENKINS (1983)). Other mineral textures may be well explained by the following dehydration reactions:

$$\text{chl} + \text{pl} = \text{opx} + \text{sp} + \text{calcic amph} + H_2O,$$
$$\text{chl} + \text{cor} + \text{sp} = \text{sap} + H_2O,$$
$$\text{chl} = \text{ol} + \text{opx} + \text{sp} + H_2O,$$
$$\text{calcic amph} + \text{ol} = \text{opx} + \text{cpx} + \text{sp} + H_2O \quad \text{etc.}$$

The sequence of regional metamorphic recrystallization of the ultramafic rocks is interpreted as prograde metamorphism and is in good agreement with that of adjacent sillimanite-bearing pelitic gneisses as revealed by the ubiquitous occurrence of metastable kyanite (HIROI *et al.*, 1984; HIROI and SHIRAISHI, 1986; SHIRAISHI *et al.*, 1986).

7. Conclusion

The mode of field occurrence and bulk chemical compositions of the ultramafic rocks in the Late Proterozoic high-grade Lützow-Holm Complex suggest that most of them were derived from various parts of layered gabbro and were tectonically fractured and emplaced in the metasedimentary rocks. Their occurrence in the western part of the complex suggests that original gabbroid masses were situated in the presently missing part (ocean floor?) between the adjacent Lützow-Holm and Yamato-Belgica Complexes. The mineral textures, especially those of garnet and spinel, suggest changing metamorphic conditions during prograde recrystallization; from earlier relatively high-pressure and low-temperature conditions to later lower-pressure and higher-temperature conditions. This change in metamorphic conditions with time is in good agreement with those revealed in adjacent pelitic gneisses.

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