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Phlogopite and Hornblende in the Contact Metamorphosed Ultramafic Complex at Yanomine, Sangun Metamorphic Zone, Japan

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Phlogopite and hornblende were found in small amounts in the contact-metamorphosed dunite-harzburgite complex at Yanomine. Phlogopite occurs in interstices of silicate minerals in dunite and harzburgite located near the contact with granite. Some phlogopite grains also occur as inclusions in chromian spinel of chromitite bands. Hornblende is present associated with such metamorphic minerals as talc, olivine and orthopyroxene. Interstitial phlogopite is characterized by lower TiO_2 and higher K/(K+Na) atomic ratio compared to that included in chromian spinel. Hornblende in dunite changes its composition from edenite associated with olivine-talc through edenitic hornblende to Si-poorer magnesio-hastingsitic hornblende and magnesio-hastingsite with olivine or olivine-orthopyroxene.

The interstitial phlogopite is suggested to have been formed intimately connected with fluids generated in relation to the intrusion of granite. On the other hand, included phlogopite is considered to have crystallized from the incompatible elements-enriched hydrous melt resulted from mantle-melt interaction. Hornblende should be a metamorphic mineral formed under high temperature conditions.

Keywords: Phlogopite, Hornblende, Ultramafic complex, Dunite, Harzburgite, Chromitite, Contact metamorphism, Yanomine

I. Introduction

More than fifteen serpentinized Alpine-type dunite-harzburgite complexes are distributed in the Sangun metamorphic zone in the eastern Chugoku district (Fig. 1). Small podiform chromitite bodies are sometimes found in these complexes associated with dunite. Gabbroic rocks have intruded ubiquitously into the complex. During the petrological and mineralogical studies of the Yanomine ultramafic mass, one of the large complexes in the district, phlogopite and hornblende were found in small amounts in the contact-metamorphosed aureoles of the complex. Some phlogopite grains were also found as inclusions in chromian spinel of thin chromitite bands.

Phlogopite and hornblende are known to occur in some Alpine-type ultramafic complexes in the world. For example, phlogopite and hornblende occur in variable amounts in harzburgite and lherzolite from the Horoman complex, Hokkaido, where phlogopite-rich veinlets cut olivine-rich parts of the complex. Interstitial discrete phlogopite is associated with orthopyroxene. Hornblende is disseminated in rocks or sometimes occurs in the phlogopite-rich veinlets. These minerals are interpreted as products of metasomatism by fluids released from evolving alkali basaltic magmas of unspecified origin (Arai and Takahashi, 1989). Phlogopite and hornblende occurring as veinlets and disseminated grains in the peridotite adjacent to hornblendite and pyroxenite dykes in the Lherz complex, southern France, are considered to have been formed by metasomatic interaction between peridotite and melt (Woodland *et al.*, 1996). Similar occurrences of these minerals are known in the Tinaquillo complex, Venezuela (Seyler and Mattson, 1989). Hornblende also occurs in contact-metamorphosed ultramafic complexes in the western Sierra Nevada Foothills, California (Springer, 1974).

Phlogopite and hornblende occurring as inclusions in chromian spinel of chromitite have been reported from some ophiolites and layered intrusions (e.g., Irvine, 1975; Peng *et al.*, 1995). The occurrences of these alkali-bearing minerals are considered to be deeply related with chromitite genesis (e.g., Melcher *et al.*, 1997).

In the ultramafic complexes in the Sangun zone, however, phlogopite and hornblende occur very rarely. Na-phlogopite and pargasite were found as inclusions in chromian spinel of chromitite from the Yanomine complex, of dunite from the Yufune complex, and Na-phlogopite in chromian spinel of troctolite from the Ashidachi complex (Matsumoto *et al.*, 1995a). Pargasite occurs in the contact-metamorphosed chromitite of the Inazumi-yama complex (Tamura, 1996). Discrete interstitial phlogopite has not been reported until now in the Sangun zone.

In this paper, we describe the modes of occurrence and the chemical compositions of phlogopite and hornblende from the Yanomine complex, and discuss the genesis of these minerals in relation to the intrusion of a granitic rock.

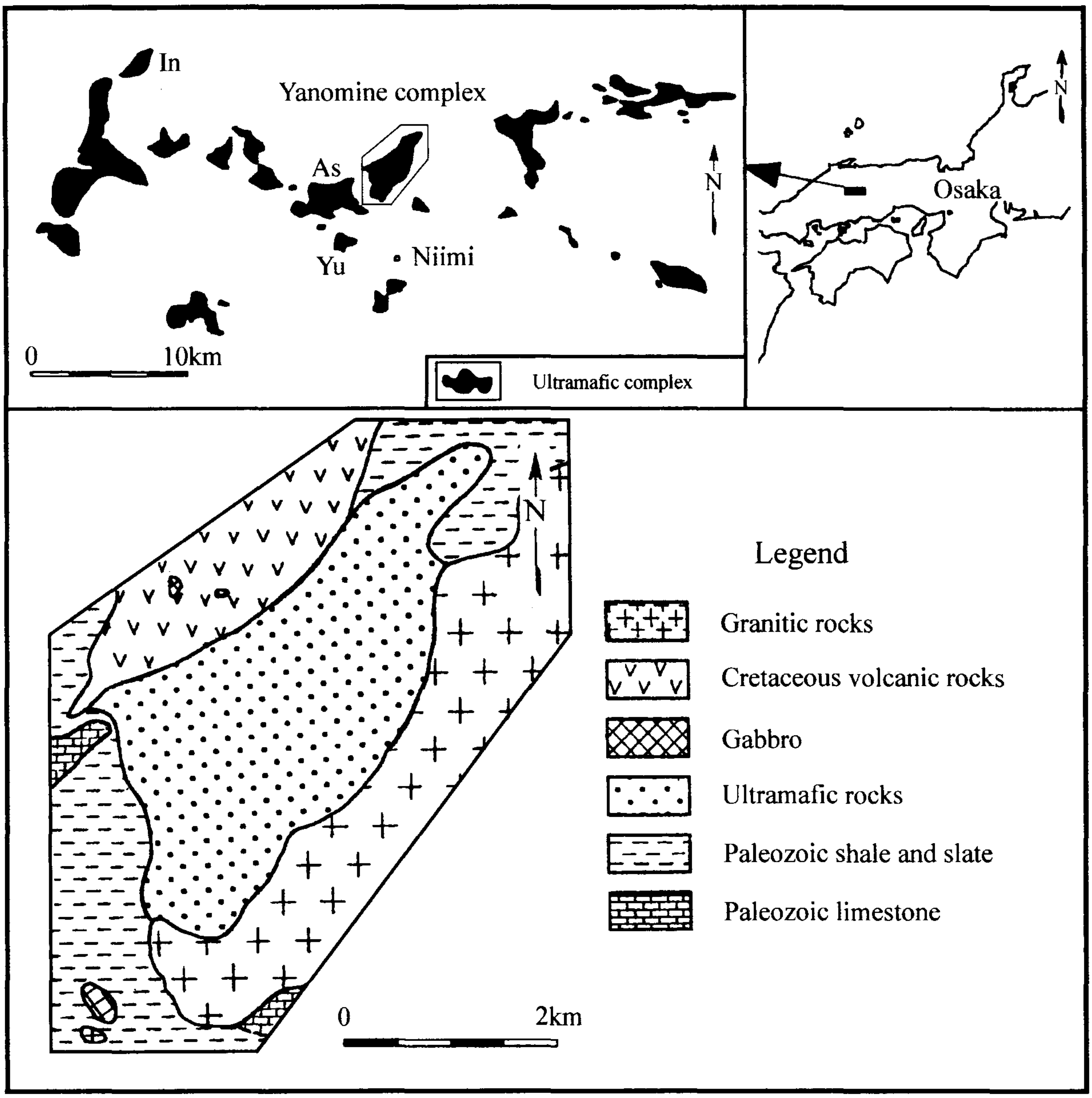

Fig. 1. Geological map of the Yanomine area (modified after MITI, 1993). Inserted is a map showing the distribution of ultramafic complexes in the Sangun zone of the eastern Chugoku district. In: Inazumi-yama complex; As: Ashidachi complex; Yu: Yufune complex.

II. Geological setting

The Yanomine ultramafic complex (5.0km×3.0km) is situated about 7km northwest from Niimi (Fig. 1). The complex is covered with Cretaceous rhyolitic volcanic rocks in the north, in contact with weakly metamorphosed Paleozoic formations both to the northeast and the southwest, and is bounded on the southeast by a Cretaceous granitic rock (Fig. 1). The wholly serpentinized Yanomine complex was intensively contact-metamorphosed by the intrusion of the granitic rock. The complex was classified into chrysotile-lizardite zone, antigorite zone, olivine-talc zone, and olivine-orthopyroxene zone toward the granite contact based on the contact-metamorphic mineral assemblages (Matsumoto *et al.*, 1995b).

The primary lithology of the serpentinized Yanomine complex was estimated from the presence or absence of pseudomorph of primary orthopyroxene and the morphology of chromian spinel, with a result that dunite and harzburgite can be discriminated, and dunite is relatively dominant in the southeastern part of the complex where three layers of dunite are recognized in harzburgite (Fig. 2). The result confirms the lithological division and the distribution by MITI (1994). Many small podiform chromitites are included in the dunite layers. These were worked in the past under the names of Sakamoto, Imohara, Yanomine, Hasebe, and Kano mines (MITI, 1992).

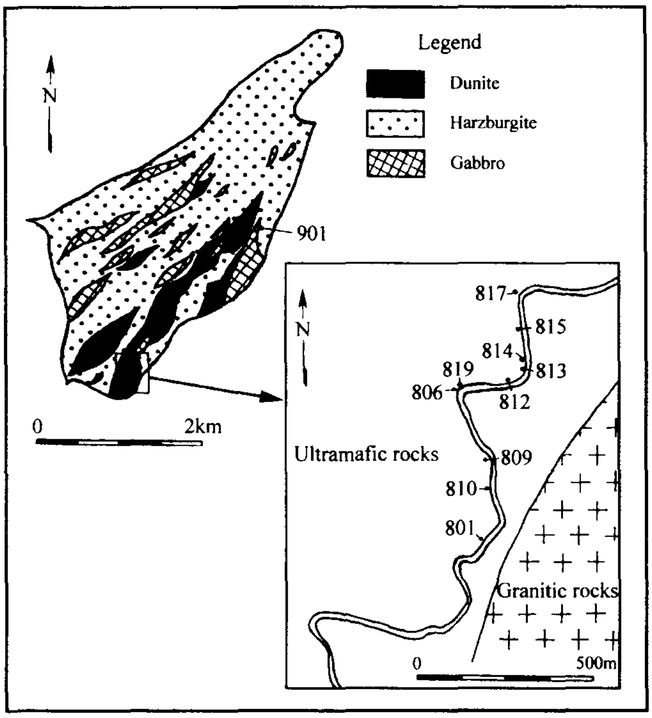

Fig. 2. Map showing the lithology of the Yanomine ultramafic complex (after MITI, 1994) and the sample locations.

III. Mode of occurrence of phlogopite and hornblende

Phlogopite was found in small to extremely small amounts in 4 harzburgite and 6 dunite samples taken from the neighborhood of granite contact in the southern part of the Yanomine complex (Fig. 2). Some dunite samples contain thin chromitite bands, less than 1cm thick. Hornblende was found in 4 dunites of these samples. In Table 1, primary lithology of the samples, mineral assemblages and amounts of phlogopite and hornblende are presented. Despite similar distances from the granite contact (Fig. 2), the metamorphic mineral assemblage is variable in the samples as shown in Table 1. Hornblende was also found in a harzburgite from the eastern part of the complex (Fig. 2), with an assemblage of olivine-orthopyroxene-hornblende.

Phlogopite occurs as tabular and irregular grains, mostly less than 0.2mm long, in interstices of silicate minerals (commonly chlorite, less commonly serpentine, talc, olivine, and rarely orthopyroxene) and chromian spinel (Fig. 3). The mineral is usually colorless, but pleochroic from pale-green to colorless when coexists with olivine and orthopyroxene. Phlogopite sometimes includes fine-grained and needle-like magnetites.

In the sample rich in phlogopite (No. 819), some white veins consisting mainly of chlorite, about 5mm thick, crosscut thin magnetite veinlets formed along with serpentinization (Fig. 4). Phlogopite occurs within and around the chlorite veins. Microscopically, chlorite in the veins is colorless to pale-green, although chlorite from the Yanomine complex is generally colorless. A number of fine-grained chromian spinel grains are dispersed in the chlorite veins.

Several phlogopite grains occur as inclusions in chromian spinel of chromitite bands (Fig. 3). They are colorless and tabular in form, less than 0.1mm long, and often include extremely fine-grained chromian spinel grains. The phlogopite is always associated with serpentine in chromian spinel grains. Such composite inclusions are often connected with the outside of the chromian spinel grains through cracks developed in the chromian spinel grains.

Table 1. Description of phlogopite- and hornblende-containing samples from the Yanomine ultramafic complex

sample number	primary lithology	mineral assemblage*	amount of phlogopite	amount of hornblende
southern part				
801	harzburgite	ser+sp	△	-
806	dunite (containing chromitite band)	ser+ol+hb+chl+sp	△	○
809	harzburgite	ser+talc+sp	+	-
810	dunite	ser+sp	△	-
812	dunite	ser+ol+talc+hb+opx+sp	+	△
813	dunite	ser+ol+talc+opx+sp	+	-
814	harzburgite	ser+ol+opx+sp	+	-
815	dunite?	ser+ol+talc+sp	+	+
817	harzburgite?	ser+ol+opx+sp	+	-
819	dunite (containing chromitite band)	ser+ol+hb+chl+sp	○	○
eastern part				
901	harzburgite	ser+ol+talc+opx+sp	-	+

*abbreviations: ser; serpentine, ol; olivine, hb; hornblende, opx; orthopyroxene, chl; chlorite, sp; chromian spinel.
○: small; △: very small; +: extremely small; -: not present.

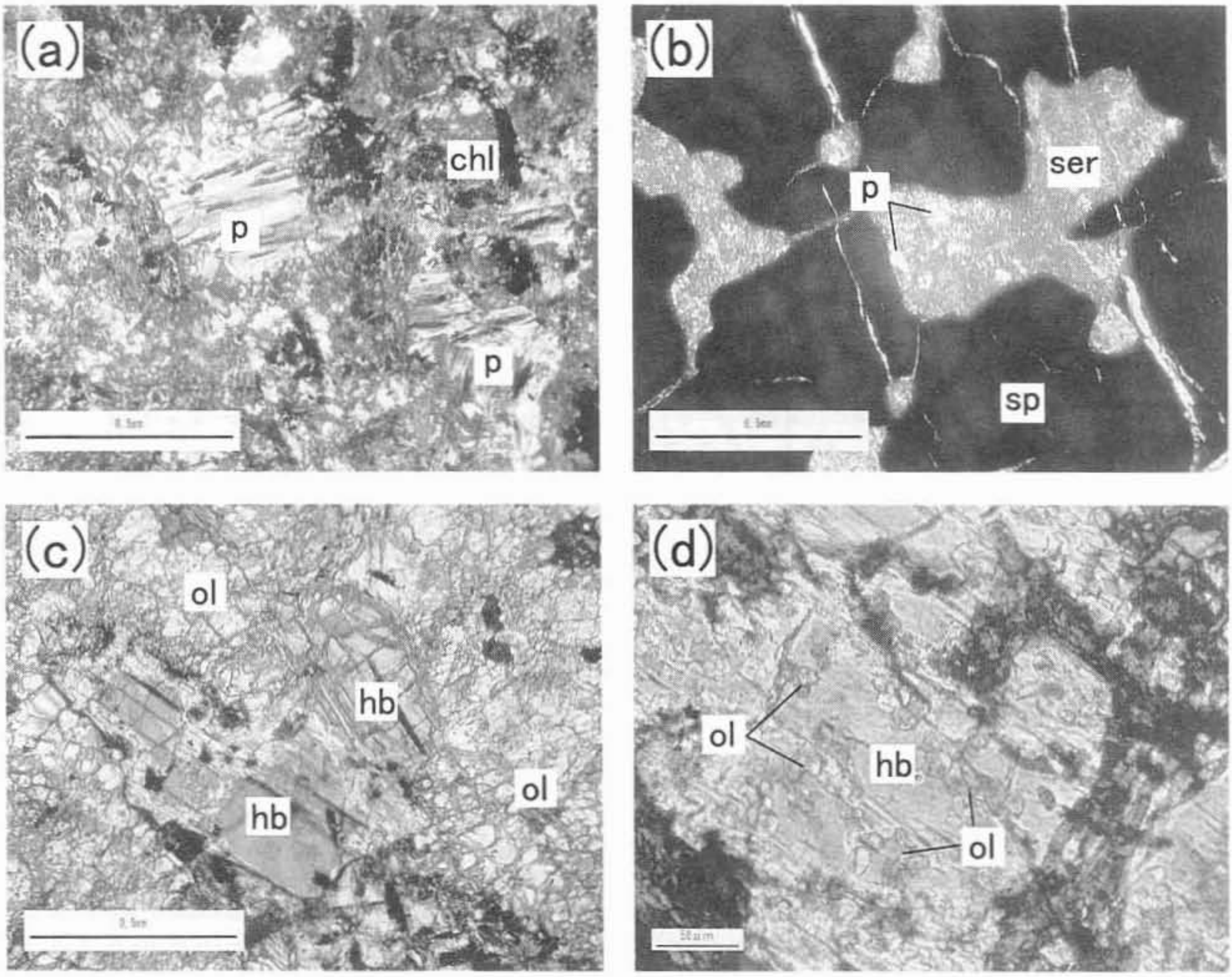

Fig. 3. Photomicrographs of thin sections containing phlogopite and hornblende in the Yanomine ultramafic complex.
(a) Phlogopite (p) associated with chlorite (chl) in chlorite veins in dunite.
(b) Phlogopite (p) and serpentine (ser) included in chromian spinel (sp) in chromitite bands.
(c) Hornblende (hb) associated with olivine (ol) in dunite.
(d) Hornblende (hb) containing olivine inclusions (ol) in chlorite veins in dunite.

To facilitate description, phlogopite occurring in interstices of silicate minerals is called interstitial phlogopite, and phlogopite included in chromian spinel of chromitite bands is called included phlogopite hereafter.

Hornblende occurs in extremely small amounts in harzburgite, extremely small to very small amounts in dunite, and in small amounts in dunite with chromitite band. This mineral is thus contained in larger amounts in dunite just contacted with chromitite band. Hornblende is found in rocks containing metamorphic minerals as olivine, talc, and orthopyroxene, but not in rocks free from these metamorphic minerals. In the southern part of the Yanomine complex, hornblende often occurs as colorless or pale-brown columnar crystals, 0.1-0.8mm long, among serpentine and olivine grains (Fig. 3). Hornblende sometimes includes olivine, chromian spinel, and fine-grained magnetite grains (Fig. 3), and rarely pseudomorphs of olivine. Hornblende occurring in chlorite veins includes fine-

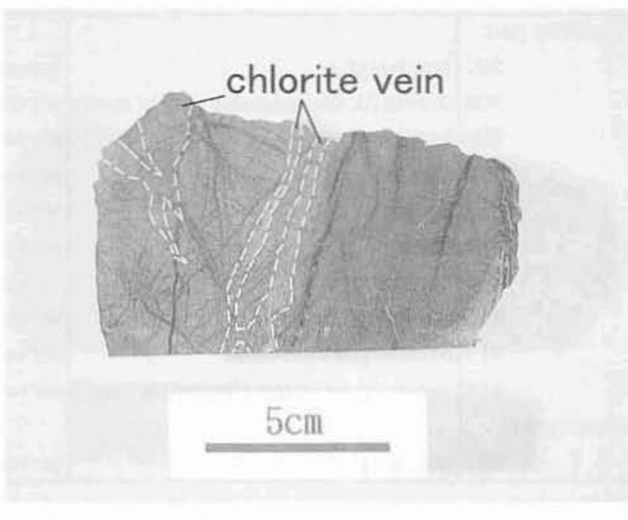

Fig. 4. Photograph showing chlorite veins in dunite (No.819).

grained chromian spinel grains dispersed in the veins. Similar to the occurrence in the southern part, hornblende in a harzburgite from the eastern part occurs as colorless columnar crystals, 0.1-0.2mm long, among serpentine and olivine grains.

IV. Chemical composition of phlogopite and hornblende

Phlogopite and hornblende were analyzed with a JEOL electron probe microanalyzer (model JXA-733), using an accelerating voltage of 15 kV and a beam current of 20nA. Data reduction was carried out according to Bence and Albee (1968) with α factors of Nakamura and Kushiro (1970). Results are shown in Tables 2 and 3. Structural formulae were obtained based on 22 oxygens for phlogopite and 23 oxygens for hornblende. Number of cations in hornblende excluding K, Na and Ca was normalized to be 13 after Robinson *et al.* (1982). Number of the ferric iron of hornblende was calculated by the charge balance.

1. phlogopite

Most interstitial phlogopites contain TiO_2 lower than 0.2 wt.%, whereas TiO_2 contents of included phlogopite are between 0.93 and 1.39 wt.%, clearly higher than those of interstitial phlogopite (Fig. 5). The Cr_2O_3 contents of phlogopite depend on coexisting minerals, and interstitial phlogopite in contact with chromian spinel and included phlogopites are rich in Cr_2O_3. Most interstitial phlogopites associated with olivine and orthopyroxene have higher MnO contents than those from other assemblages (Table 2). Some EPMA analyses of the Yanomine phlogopite acquire total oxide wt.% markedly lower than that calculated

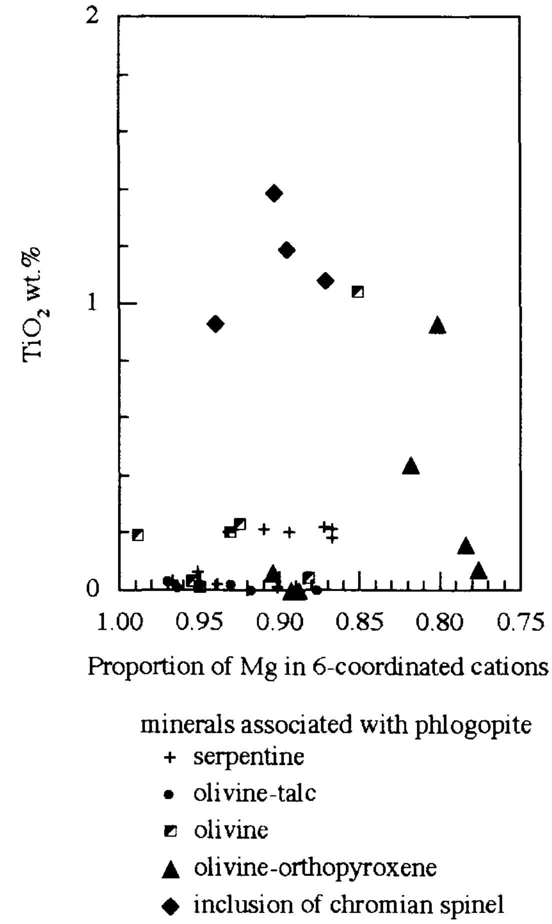

Fig. 5. Relationship between TiO_2 wt.% and proportion of Mg in 6-coordinated cations (atomic ratio) in phlogopite.

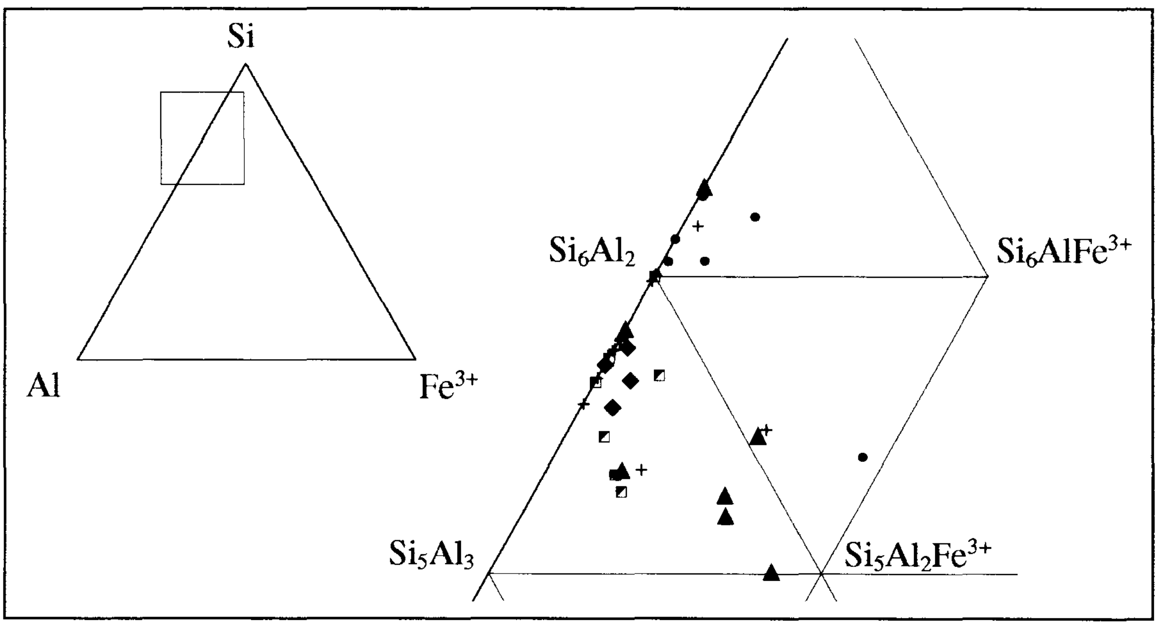

Fig. 6. Proportion of 4-coordinated cations in phlogopite. Symbols as in Fig. 5.

Table 2. Representative microprobe analyses of phlogopite in the Yanomine ultramafic complex

mineral assemblage	serpentine				olivine-talc			olivine		
primary lithology	harzburgite		dunite		dunite			dunite		
sample	801 M-3	801 M-6	810 P-6	810 P-8	815 S-3	815 M-1	815 M-2	806.0 K-1	806.0 P-4	819.1 p-1
SiO_2	43.18	43.62	40.75	41.98	43.07	44.02	44.94	39.91	36.69	39.44
TiO_2	0.00	0.01	0.22	0.18	0.02	0.00	0.00	0.20	0.19	0.01
Al_2O_3	13.10	14.07	15.15	15.67	11.65	12.75	10.44	14.26	14.31	14.82
Cr_2O_3	0.13	0.20	1.46	1.46	0.54	0.98	0.49	0.83	0.96	0.00
FeO*	3.06	2.49	2.81	2.84	3.22	3.55	3.81	2.41	2.33	3.66
MnO	0.00	0.01	0.02	0.01	0.04	0.01	0.03	0.02	0.01	0.00
MgO	28.46	27.49	26.34	26.01	27.94	25.65	27.16	28.47	28.86	31.36
NiO	0.15	0.18	0.20	0.24	0.10	0.12	0.17	0.19	0.19	0.27
CaO	0.01	0.00	0.00	0.00	0.01	0.03	0.15	0.05	0.05	0.01
Na_2O	0.01	0.05	0.04	0.04	0.05	0.07	0.05	0.08	0.07	0.00
K_2O	7.10	7.87	7.73	9.23	6.74	8.12	7.05	6.60	6.36	3.54
total	95.20	95.99	94.72	97.66	93.38	95.30	94.29	93.02	90.02	93.11
Number of atoms for 22 oxygens										
Si	5.983	6.006	5.749	5.756	6.051	6.126	6.271	5.646	5.335	5.462
Al (IV)	2.017	1.994	2.251	2.244	1.930	1.874	1.718	2.354	2.452	2.420
Fe (IV)	0.000	0.000	0.000	0.000	0.019	0.000	0.011	0.000	0.213	0.118
Al (VI)	0.123	0.289	0.269	0.289	0.000	0.217	0.000	0.024	0.001	0.000
Ti	0.000	0.001	0.023	0.019	0.002	0.000	0.000	0.021	0.021	0.001
Cr	0.014	0.022	0.163	0.158	0.060	0.108	0.054	0.093	0.110	0.000
Fe (VI)	0.355	0.287	0.332	0.326	0.360	0.413	0.433	0.285	0.071	0.306
Mn	0.000	0.001	0.002	0.001	0.005	0.001	0.004	0.002	0.001	0.000
Mg	5.879	5.642	5.540	5.316	5.852	5.321	5.649	6.004	6.256	6.474
Ni	0.017	0.020	0.023	0.026	0.011	0.013	0.019	0.022	0.022	0.030
Ca	0.001	0.000	0.000	0.000	0.002	0.004	0.022	0.008	0.008	0.001
Na	0.003	0.013	0.011	0.011	0.014	0.019	0.014	0.022	0.020	0.000
K	1.255	1.382	1.391	1.615	1.208	1.442	1.255	1.191	1.180	0.625
total	15.646	15.658	15.754	15.760	15.513	15.539	15.450	15.671	15.690	15.438
Mg/(Mg+Fe (VI))	0.943	0.952	0.944	0.942	0.942	0.928	0.929	0.955	0.989	0.955
K/(K+Na)	0.998	0.990	0.992	0.993	0.989	0.987	0.989	0.982	0.984	1.000

*: total iron as FeO.

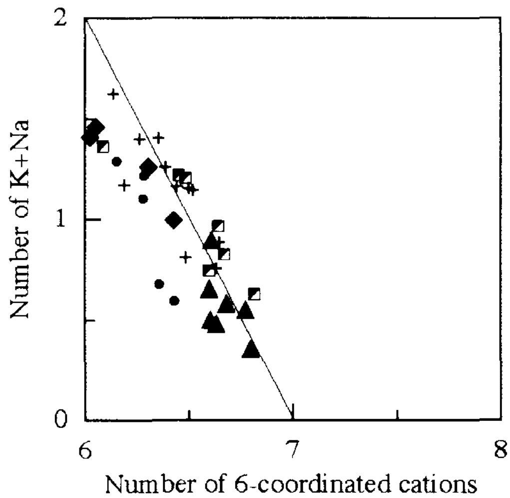

Fig. 7. Relationship between number of Na+K atoms and that of 6-coordinated cations in phlogopite, calculated based on O=22. Straight line represents the relationship between number of Na+K atoms and that of divalent 6-coordinated cations based on balanced charges. Symbols as in Fig. 5.

from the ideal chemical composition (Table 2). As discussed later, this is considered to be an essential nature of these phlogopites.

The structural formula of phlogopite calculated based on 22 oxygens indicates that number of Si+Al is smaller than 8 for most phlogopites. Making up for the lack of 4-coordinated cations by Fe^{3+}, phlogopite associated with olivine and orthopyroxene generally contains larger numbers of tetrahedral Fe^{3+} than that associated with other minerals (Fig. 6).

The K/(K+Na) atomic ratios range from 0.88 to 1.00 for interstitial phlogopite from both dunite and harzburgite, from 0.70 to 0.90 for included phlogopite. The number of Na is larger in the latter (Table 2). The calculated number of (K+Na) widely varies from 0.36 to 1.63. The number for interstitial phlogopite decreases with the variation of associated minerals from serpentine through olivine-talc and olivine to olivine-orthopyroxene. The number is negatively correlated with the number of 6-coordinated cations (Fig. 7), which is larger than 6 (Table 2). The K/(K+Na) atomic ratios of interstitial phlogopite associated with ser-

Table 2 (continued).

olivine-orthopyroxene			inclusion	
dunite	harzburgite		chromitite band	
812 M-2	814 p-1	817 c-2	806.0 S-7	806.0 P-1
46.83	35.85	36.66	41.61	40.75
0.00	0.44	0.16	1.39	1.19
13.24	12.78	14.08	13.45	13.95
0.17	0.05	0.51	1.00	0.75
2.59	13.39	9.67	2.92	3.22
0.01	1.03	0.76	0.03	0.04
29.21	25.27	25.10	26.32	25.97
0.20	0.20	0.16	0.22	0.18
0.02	0.08	0.55	2.06	2.63
0.03	0.24	0.17	1.22	1.10
3.75	2.73	4.11	4.42	4.30
96.05	92.06	91.93	94.64	94.08
6.303	5.200	5.351	5.767	5.706
1.697	2.186	2.422	2.198	2.294
0.000	0.614	0.227	0.035	0.000
0.403	0.000	0.000	0.000	0.009
0.000	0.048	0.018	0.145	0.125
0.018	0.006	0.059	0.110	0.083
0.292	1.011	1.313	0.303	0.392
0.001	0.127	0.094	0.004	0.005
5.861	5.464	5.462	5.438	5.421
0.022	0.023	0.019	0.025	0.020
0.003	0.012	0.086	0.306	0.395
0.008	0.068	0.048	0.328	0.299
0.644	0.505	0.765	0.782	0.768
15.251	15.264	15.863	15.439	15.517
0.953	0.844	0.806	0.947	0.933
0.988	0.882	0.941	0.704	0.720

*: total iron as FeO.

pentine, olivine-talc, and olivine do not vary with decreasing proportion of Mg in 6-coordinated cations, while the K/(K+Na) atomic ratios decrease with decreasing proportion of Mg in 6-coordinated cations for interstitial phlogopite associated with olivine and orthopyroxene (Fig. 8).

2. hornblende

Hornblende in dunite from the Yanomine complex contains higher TiO_2 (0.07-3.17 wt.%), Na_2O (2.28-3.09 wt.%), and Cr_2O_3 (0.50-1.34 wt.%) than that in harzburgite (0.03-0.05 wt.% of TiO_2, 1.89-1.99 wt.% of Na_2O, 0-0.09 wt.% of Cr_2O_3) (Table 3). A negative correlation is present between the number of Ti and that of Fe^{3+} (Fig. 9). Fe^{3+} contents of hornblende associated with olivine-talc and olivine-orthopyroxene are relatively high, whereas those associated with olivine are variable (Fig. 9). Hornblende from both harzburgite and dunite is magnesian, with the $Mg/(Mg+Fe^{2+})$ atomic ratios ranging from 0.84 to 1.00 (Table 3). The number of (K+Na) (mostly Na) of hornblende in dunite increases with decreasing number of Si (Fig. 10). The number of Si appears to be related with

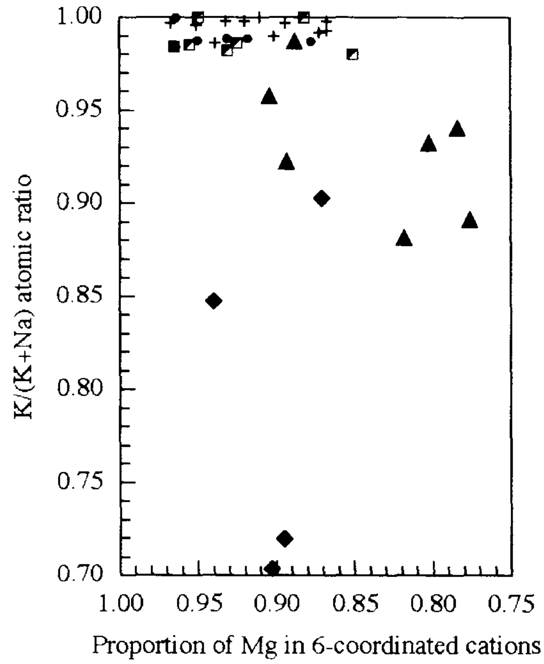

Fig. 8. Relationship between K/(K+Na) and proportion of Mg in 6-coordinated cations (atomic ratio) in phlogopite. Symbols as in Fig. 5.

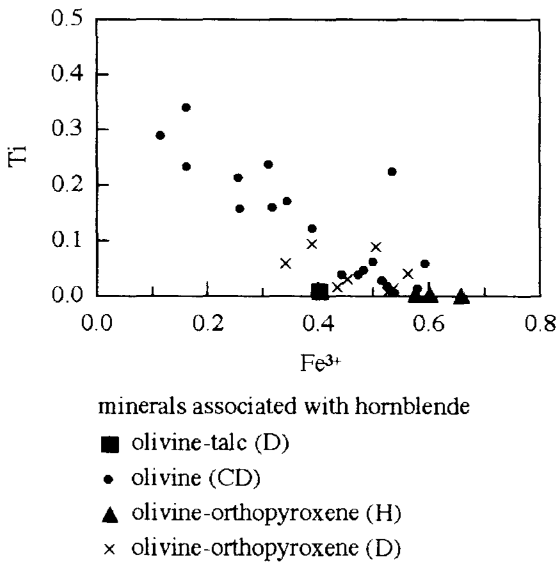

Fig. 9. Relationship between number of Ti and that of Fe^{3+} in hornblende (O=23). H: harzburgite; D: dunite; CD: dunite with chromitite band.

Table 3. Representative microprobe analyses of hornblende in the Yanomine ultramafic complex

mineral assemblage	olivine-talc	olivine				olivine-orthopyroxene			
primary lithology	dunite?	dunite				harzburgite	dunite		
sample	815 A-5	806.0 A-3	819.B A-5	819.B A-1	819.B A-7	901 A-1	812 A-3	812 A-7	812 A-11
SiO_2	48.97	45.85	42.72	42.89	43.06	46.80	46.62	46.93	47.74
TiO_2	0.10	1.62	3.17	2.67	2.13	0.03	0.89	0.57	0.85
Al_2O_3	8.59	10.47	12.39	11.52	12.49	12.48	9.77	9.96	9.17
Cr_2O_3	1.34	0.60	0.56	1.10	0.86	0.09	1.13	0.77	0.85
FeO*	3.49	4.85	5.40	5.59	5.96	5.92	5.05	4.99	5.01
MnO	0.05	0.06	0.04	0.03	0.05	0.06	0.08	0.08	0.07
MgO	20.34	18.63	17.30	17.27	17.65	18.30	19.13	19.23	19.67
NiO	0.11	0.10	0.09	0.12	0.06	0.14	0.11	0.10	0.11
CaO	12.74	12.23	12.50	12.71	12.37	12.80	12.85	13.10	12.67
Na_2O	2.28	2.87	3.09	3.01	2.87	1.99	2.59	2.54	2.44
K_2O	0.08	0.10	0.12	0.13	0.10	0.11	0.11	0.09	0.10
Total	98.09	97.38	97.38	97.04	97.60	98.72	98.33	98.36	98.68
Number of atoms for 23 oxygens									
Si	6.801	6.490	6.132	6.203	6.121	6.473	6.545	6.582	6.636
Al (IV)	1.199	1.510	1.868	1.797	1.879	1.527	1.455	1.418	1.364
Al (VI)	0.207	0.237	0.229	0.167	0.214	0.507	0.162	0.228	0.139
Ti	0.010	0.172	0.342	0.290	0.228	0.003	0.094	0.060	0.089
Cr	0.147	0.067	0.064	0.126	0.097	0.010	0.125	0.085	0.093
Fe^{3+}	0.403	0.346	0.164	0.117	0.536	0.658	0.389	0.341	0.505
Fe^{2+}	0.002	0.228	0.484	0.559	0.173	0.026	0.204	0.244	0.078
Mn	0.006	0.007	0.005	0.004	0.006	0.007	0.010	0.010	0.008
Mg	4.211	3.931	3.702	3.723	3.740	3.773	4.004	4.020	4.076
Ni	0.012	0.011	0.010	0.014	0.007	0.016	0.012	0.011	0.012
Ca	1.896	1.855	1.922	1.969	1.884	1.897	1.933	1.968	1.887
Na	0.614	0.788	0.860	0.844	0.791	0.534	0.705	0.691	0.658
K	0.014	0.018	0.022	0.024	0.018	0.019	0.020	0.016	0.018
Total	15.524	15.660	15.804	15.837	15.693	15.450	15.658	15.675	15.562
$Mg/(Mg+Fe^{2+})$	1.000	0.945	0.884	0.869	0.956	0.993	0.952	0.943	0.981

*: total iron as FeO.

the metamorphic mineral assemblage (Fig. 10).

According to the classification by Leake (1978), the Yanomine hornblendes are divided into those in harzburgite with the number of (K+Na) less than 0.5 and those in dunite with (K+Na) more than 0.5 (Fig. 11). Furthermore, alkali-rich hornblendes in dunite are divided into two groups by the proportion of Fe^{3+} to Al in tetrahedral site, and most hornblendes in dunite are classified into Fe^{3+}-rich group (Fig. 11). In terms of metamorphic mineral assemblage, hornblende in dunite changes its composition from edenite associated with olivine-talc through edenitic hornblende to Si-poorer magnesio-hastingsitic hornblende and magnesio-hastingsite with olivine or olivine-orthopyroxene (Fig. 11).

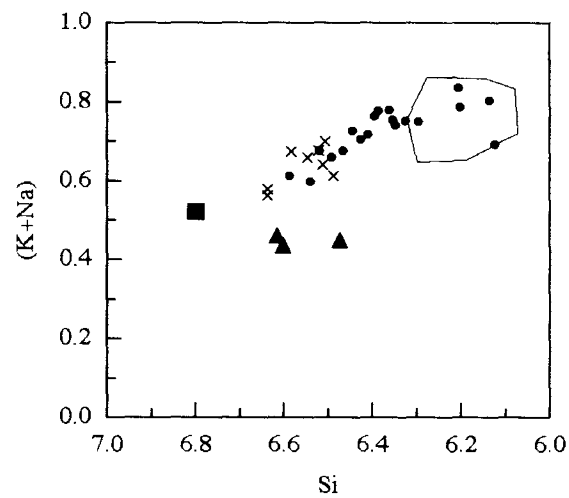

Fig. 10. Relationship between number of Na+K atoms and that of Si in hornblende (O=23). Symbols as in Fig. 9. The area enclosed by solid line is the range for hornblende formed by metasomatism. Data are taken from Arai and Takahashi (1989), Seyler and Mattson (1989) and Woodland *et al.* (1996).

V. Whole-rock chemical composition

The whole-rock major element compositions of harzburgite and dunite from the Yanomine complex were obtained by XRF (Table 4). The serpentinized harzburgite and dunite show depleted and alkali-poor compositions as a whole. Dunite contains slightly higher MgO and CaO

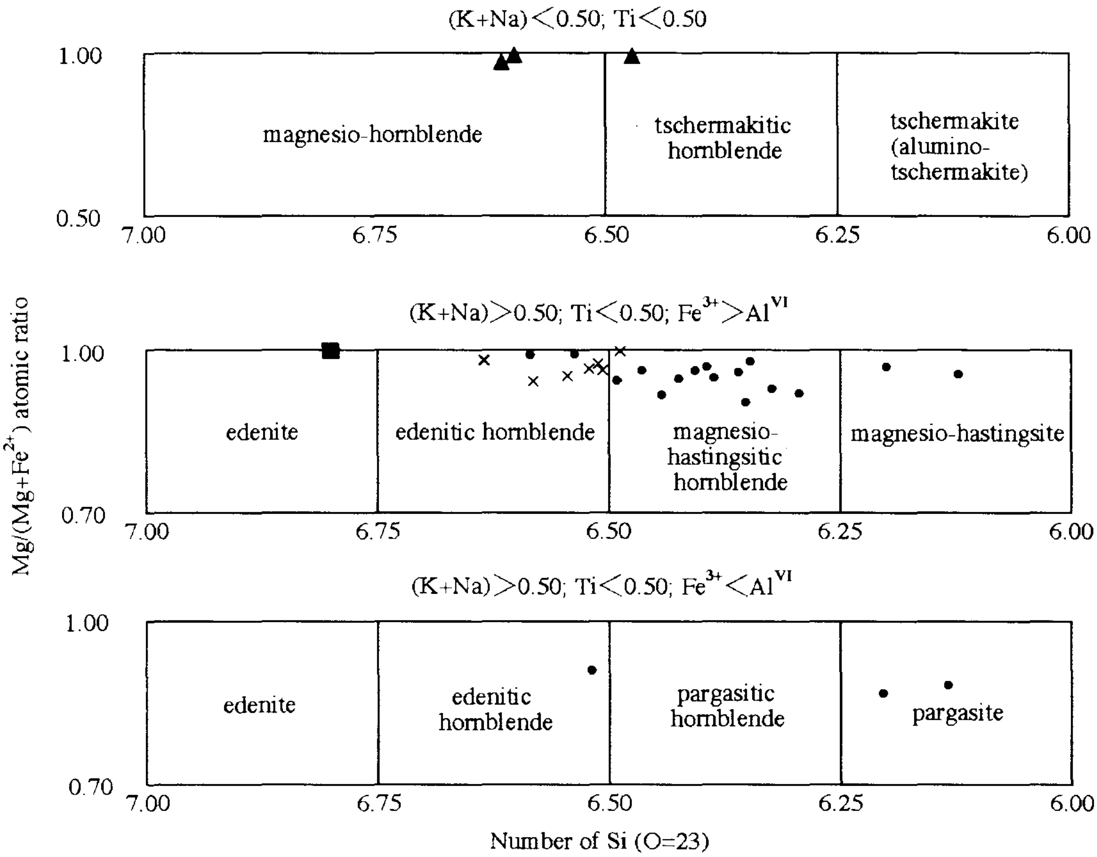

Fig. 11. Chemical composition of hornblende from the Yanomine complex. Classification scheme is after Leake (1978). Symbols as in Fig. 9.

than harzburgite. The dunite sample containing phlogopite and hornblende in and around chlorite veins (No. 819) has the highest Al_2O_3 and K_2O contents in all of the analyzed rocks. The Na_2O content is not different from those of other rocks. The phlogopite- or hornblende-containing harzburgites (Nos. 801 and 901) are similar in major element compositions to harzburgites free from these minerals.

VI. Discussion

1. Interstitial phlogopite

The phlogopite in sample No. 819 occurs in and around chlorite veins crosscutting magnetite veinlets formed at the stage of serpentinization. The mode of occurrence is similar to that of secondary phlogopite which occurs in veinlets of garnet lherzolite xenolith trapped in S. African kimberlite (Delaney *et al.*, 1980). In the chemical composition of whole-rocks, the sample No. 819 has the highest Al_2O_3 and K_2O contents in all of the analyzed rocks (Table 4). The phlogopite should have been formed, together with chlorite veins, influenced by an addition of Al and K.

Phlogopites hitherto reported from the Alpine-type ultramafic complexes are interpreted to have been formed secondarily, for example, by the interactions with melts that brought about hornblendite and pyroxenite dykes in the Lherz complex, southern France (Woodland *et al.*, 1996), and with fluids released from alkali basaltic magmas in the Horoman complex, Hokkaido (Arai and Takahashi, 1989). The locations of the Yanomine interstitial phlogopite are limited to the neighborhood of granite contact in the southern part of the complex. It is likely that the formation of phlogopite is intimately connected with fluids generated in relation to the granitic intrusion. However, it is uncertain whether the fluids were released from the granitic rock or were brought about from dehydration of serpentinite by the contact metamorphism.

Interstitial phlogopite occurring in contact with chromian spinel often tends to be rich in Cr. The chemistry of phlogopite may depend on the composition of rocks in a narrow portion, while the K/(K+Na) atomic ratios, proportion of Mg in the 6-coordinated cations, and the number of tetrahedral Fe^{3+} of interstitial phlogopite appear to be closely related with metamorphic mineral assemblages.

2. Included phlogopite

Inclusions of Na-phlogopite as well as of pargasite were reported in chromian spinel grains of podiform chromitite from the Yanomine complex (Matsumoto *et al.*, 1995a). Podiform chromitites in the Sangun zone are sug-

Table 4. Whole-rock chemical compositions of the Yanomine ultramafic complex*

mineral assemblage**	serpentine					ol-talc		ol		ol-opx
primary lithology	harzburgite	harzburgite	harzburgite	harzburgite	harzburgite	dunite	harzburgite	dunite	dunite	harzburgite
sample number	801 ◆	803	5917	9904	3215	5903	908	5921	819◆■	901■
SiO_2	38.12	37.51	39.29	38.77	38.80	39.11	38.57	35.78	35.17	40.08
TiO_2	0.01	0.01	<0.01	<0.01	0.01	0.02	0.01	0.01	0.02	0.01
Al_2O_3	0.77	0.67	0.82	0.96	0.89	0.81	0.90	1.08	1.84	0.92
Cr_2O_3	0.40	0.40	0.34	0.42	0.44	0.45	0.42	0.36	0.44	0.41
Fe_2O_3***	8.73	8.37	7.15	8.24	8.59	8.38	8.52	7.62	8.52	8.10
MnO	0.08	0.12	0.05	0.09	0.10	0.10	0.11	0.13	0.12	0.09
MgO	37.82	37.91	38.50	37.75	37.47	39.31	37.99	41.21	38.89	37.77
CaO	0.08	0.12	0.10	0.09	0.08	0.34	0.19	0.49	0.34	0.15
Na_2O	0.07	0.13	0.06	0.08	0.05	0.06	0.07	0.10	0.08	0.03
K_2O	0.05	0.04	0.04	0.03	0.03	0.04	0.04	0.03	0.12	0.04
P_2O_5	0.01	<0.01	0.01	<0.01	<0.01	0.01	<0.01	0.01	<0.01	<0.01
LOI	13.11	13.81	12.90	12.91	13.14	10.78	12.70	12.49	13.65	11.45
total	99.25	99.09	99.26	99.34	99.60	99.41	99.52	99.31	99.19	99.05

*obtained by XRF at Chemex Co. Ltd. **abbreviations: ol; olivine, opx; orthopyroxene. ***: total iron as Fe_2O_3.
LOI: loss of ignition. ◆: containing phlogopite. ■: containing hornblende.

gested to have been generated by mixing of relatively SiO_2-rich melts formed by mantle-melt interaction with less-differentiated primary melts (e.g., Arai and Yurimoto, 1994). Na-phlogopite and pargasite included in chromian spinel are considered to reflect the incompatible elements-enriched composition of a hydrous melt resulted from mantle-melt interaction (Matsumoto *et al.*, 1995a).

The composition of included phlogopite found in this study obviously differs from that of interstitial phlogopite in K/(K+Na) atomic ratios and TiO_2 contents. The genesis of included phlogopite may differ from that of interstitial one. Compared with Na-phlogopite described by Matsumoto *et al.* (1995a), present included phlogopite contains clearly higher K_2O and CaO. Na-phlogopite and pargasite of Matsumoto *et al.* (1995a) are enclosed in chromian spinel. The present phlogopite included in chromian spinel, however, constitutes a composite inclusion together with serpentine, and the composite inclusions are connected with the outside of the chromian spinel grains through cracks developed in the chromian spinel grains (Fig. 3).

Peng *et al.* (1995) reported inclusions of phlogopite and phlogopite hydrate in chromite from the Honggulieleng ophiolite, China. From a comparison between compositions of phlogopite and phlogopite hydrate, they showed that relatively Na-poor phlogopite hydrate was formed by the hydration of phlogopite and Na was selectively leached out relative to K during hydration. The Na-poor chemical composition and low total oxide wt.% of EPMA analyses for the present included phlogopite are very similar to those of phlogopite hydrate in the Honggulieleng ophiolite. Thus, it is likely that the present included phlogopite was formed by similar processes to Na-phlogopite reported by Matsumoto *et al.* (1995a), and then hydrated during serpentinization or contact metamorphism. The hydration of phlogopite might have taken place for interstitial one. Some phlogopites with low total oxide wt.% of EPMA analyses and high MgO contents may be due to hydration.

3. Hornblende

The Yanomine hornblende occurs associated with metamorphic minerals as talc, olivine, and orthopyroxene in the southern and eastern parts of the complex near the contact with the granitic rock. Some hornblendes contain olivine and chromian spinel as inclusions (Fig. 3). The mode of occurrence and texture of the hornblende are similar to those of metamorphic hornblende that occurs in contact metamorphosed peridotite of zone I (olivine-orthopyroxene) in the western Sierra Nevada Foothills, California (Springer, 1974).

In the diagram indicating the relationship between the number of (K+Na) and that of Si, the compositional range of hornblendes formed by metasomatism in the Horoman complex, the Lherz complex, and the Tinaquillo complex is plotted (Fig. 10). The composition of these hornblendes falls in a narrow range, and differ from that of the Yanomine hornblendes that show a wider variation on the line with positive slope. Also, K_2O and Al_2O_3 contents of these metasomatic hornblendes are much higher than those of the Yanomine hornblendes. The compositional trend displayed by the Yanomine hornblendes is similar to that indicated by Evans (1982) for calcic amphiboles subjected to the progressive metamorphism. The compositional variation of calcic amphiboles correlates well with the metamorphic grade. According to Evans (1982), the number of Si of the formula unit for amphibole decreases with increasing grade of the metamorphism to which it was subjected, and the variation in the number of Si is a compositional parameter most sensitive to the metamorphic grade.

The number of Si ranges between 6.47 and 6.63 for hornblende associated with olivine-orthopyroxene. The range falls within that of calcic amphiboles (7.9-6.5) subjected to the olivine-orthopyroxene-chlorite/spinel grade metamorphism, the equilibrium temperature of which being estimated to be 600-700℃. The olivine-hornblende and the olivine-orthopyroxene assemblages may have been formed under similar metamorphic conditions in the Yanomine complex because the rocks with respective assemblages locate adjacent to each other. It is considered that the lower Si number of hornblende with a metamorphic olivine reflects the Al-rich peculiar composition of the rock (No. 819).

The whole-rock composition of dunite No. 5921 is similar to that of the hornblende-containing dunite No. 819 (Table 4). The former sample was taken from a location 700m distant from the contact with the granitic rock, and contains tremolite instead of hornblende. This indicates that the occurrence of hornblende is bound up with the metamorphic temperature. The Yanomine hornblende should be a contact metamorphic mineral formed under high temperature conditions.

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