Mineral paragenesis in thermally metamorphosed serpentinites, Ohsa-yama, Okayama Prefecture

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The Ohsa-yama ultramafic body, which consists of several types of serpentinized peridotites, underwent contact metamorphism caused by a Cretaceous granite intrusion; this metamorphism resulted in the formation of contact aureole, 1.5-2.0 km wide, around the granite intrusion, and produced progressive mineral changes in metaserpentinites toward the contact between the Ohsa-yama body and the granite intrusion. On the basis of analysis of mineral paragenetic relations, the Ohsa-yama ultramafic body can be divided into three zones with progressive changes in mineral assemblages as follows:

Zone I: serpentine ± chlorite ± brucite

Zone II: olivine + talc ± tremolite ± chlorite

Zone III: olivine + orthopyroxene ± tremolite ± spinel

Zone I corresponds to the parts unaffected by the thermal event, and Zones II and III correspond to the thermally metamorphosed parts of the Ohsa-yama body. The results obtained in this study are generally consistent with those of the previous studies on metamorphic peridotites from the Sangun and Mizuru zones.

Keywords: peridotite, serpentinite, thermal metamorphism, contact metamorphism

I. Introduction

The serpentinized peridotites that occur in the Sangun and Maizuru zones are in many cases thermally metamorphosed by Cretaceous granitic intrusions. Arai (1975) and Uda (1984) showed that mineral paragenesis changes progressively in the metaserpentinites which occur in the contact aureoles at the Tari-Misaka and Oye-yama area, respectively, and defined possible metamorphic reactions to generate these mineral changes. Recently, Matsumoto *et al.* (1995) conducted a regional study on the ultramafic bodies of the Sangun zone in an attempt to reveal regional variations in petrographic characters of these peridotites.

The Ohsa-yama ultramafic body is located 2 km west of the town of Ohsa, Okayama Prefecture, and is one of these ultramafic bodies of the Sangun zone. Our field and petrographic observations indicated that the Ohsa-yama ultramafic

body is originally composed of dunite and harzburgite, and lacks layered structures (Nozaka and Shibata, 1994). The Ohsa-yama body also underwent contact metamorphism caused by a Cretaceous granitic intrusion, around which serpentinites are converted to hard, compact peridotites. A cursory study on the Ohsa-yama body was included in the regional study of Matsumoto *et al.* (1995), but so far a detailed account of the metamorphic peridotites of the Ohsa-yama body has not been given. In this short report, we describe petrography and mineral chemistry of the Ohsa-yama metamorphic peridotites and present metamorphic mineral changes in the contact aureole.

II. Petrography

The minerals that constitute the Ohsa-yama ultramafic body are olivine, orthopyroxene,
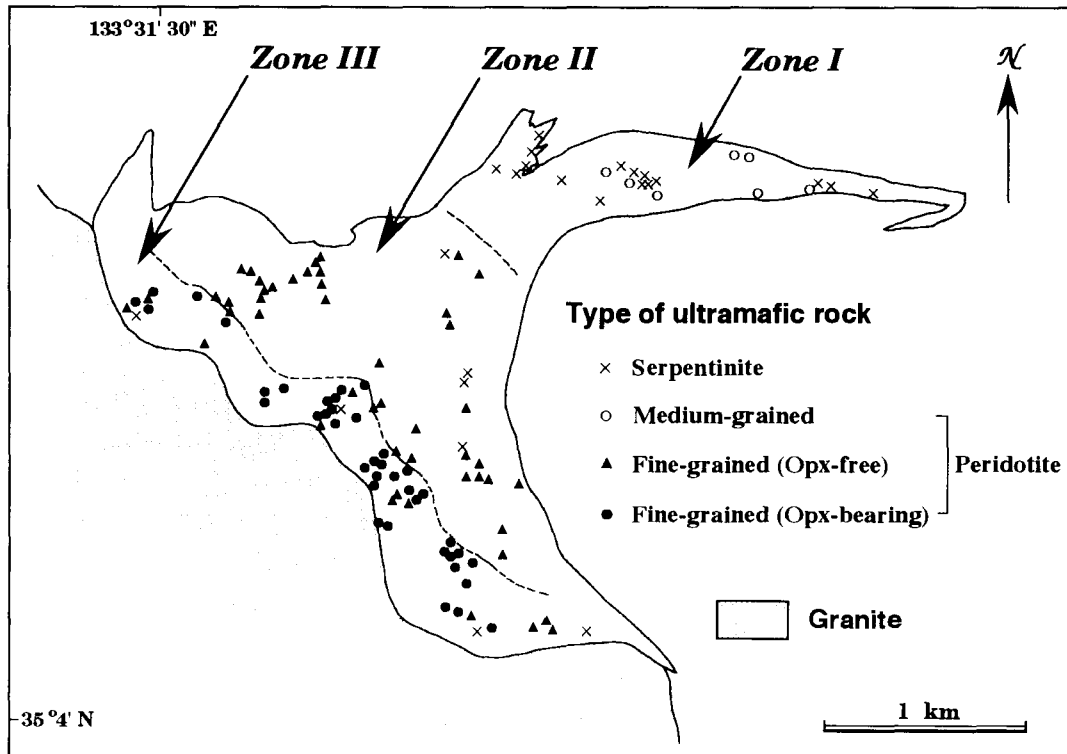
Fig. 1   Petrographical zonal map of the Ohsa-yama ultramafic body showing distribution of each rock type. Serpentinite is defined here as containing no olivine due to intense serpentinization.

clinopyroxene, spinel, amphibole, talc, serpentine, chlorite, brucite, and opaque minerals such as magnetite, nickel sulfide, and awaruite. Textural relations show that serpentine and opaque minerals, locally together with chlorite and brucite, replace olivine, orthopyroxene, clinopyroxene, and spinel to various degrees. Serpentine and opaque minerals occur throughout the Ohsa-yama body, but their modal proportions tend to decrease toward its contact with the granite intrusion.

The parts of the Ohsa-yama body that did not undergo intense serpentinization show various textures and mineral assemblages. On the basis of size of olivine grains, we divided the Ohsa-yama peridotites into medium-grained (commonly >1 mm) and fine-grained (commonly 0.1-0.2 mm) rocks. We further subdivided the fine-grained peridotites into two groups, i.e. orthopyroxene-bearing and orthopyroxene-free peridotites. These three types of peridotite occur in each of well-defined, restricted areas, delineating three zones (Zones I, II, and III) in the Ohsa-yama body (Fig. 1).

Zone I

This zone is characterized by presence of the medium-grained serpentinized peridotites and absence of the fine-grained peridotites. The medium-grained peridotites are composed mainly of olivine and orthopyroxene with small amounts of clinopyroxene and brown spinel. Nozaka and Shibata (1994) reported petrography of this type of peridotite, and so we give only a brief description concerning its difference from the fine-grained rocks in this report. Relict crystals of olivine found in the medium-grained, serpentinized peridotites are commonly equidimensional in shape and 1.0 - 1.5 mm in diameter. Opaque minerals occur in close association with serpentine along partings and fractures of olivine, but never occur as inclusions within olivine grains (Fig. 2-A). Orthopyroxene grains are prismatic in shape, up to 6.0 mm in length, and possess significant amounts of clinopyroxene as thin lamellae (Fig. 2-B). Similarly, discrete clinopyroxene grains have orthopyroxene lamellae. Brown spinel grains have equidimensional or vermicular shapes. Serpentinized peridotites
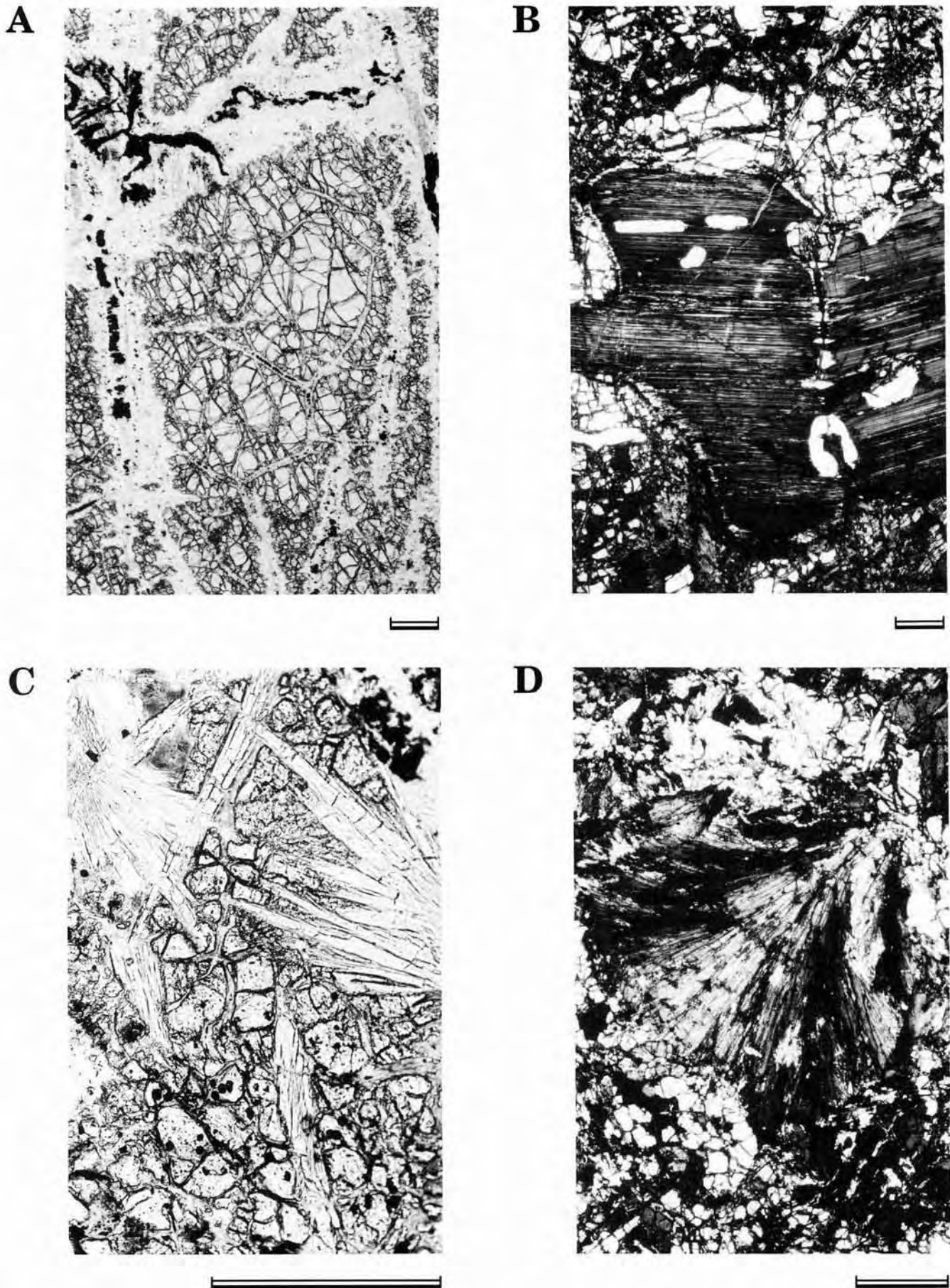
Fig. 2 Photomicrographs of the Ohsa-yama ultramafic rocks. Scale bars indicate 0.3 mm. A: olivine in Zone I (plane polarized light). B: lamellae-rich orthopyroxene in Zone I (crossed polars). C: inclusion-rich olivine and tremolite in Zone II (plane polarized light). D: lamella-free orthopyroxene in Zone III (crossed polars).

with the mesh and bastite textures are much more common in Zone I than in Zones II and III.

Zone II

The fine-grained peridotites occur extensively in this zone. The mineral assemblage found most commonly in these peridotites is olivine + talc + tremolite. Most of the olivine grains in this zone differ from those in Zone I in that the former are smaller in size (0.1 - 0.2 mm) and include minute grains (< 3 μm) of opaque minerals (Fig.2-C). In rare cases, some Zone II olivines reach up to 1.5 mm in size. Tremolite occurs as acicular crystals of 0.1 - 0.5 mm in length, and together with olivine, it locally forms granoblastic texture. Talc occurs commonly as fine-grained aggregates in the matrix surrounding olivine and tremolite grains. Some of the Zone II peridotites contain a minor amount of brown spinel, which is similar in color, size and shape to the Zone I spinel.

Zone III

Orthopyroxene occurs extensively in Zone III. The orthopyroxene crystals in this zone are free from clinopyroxene lamellae; this is a diagnostic feature when compared with those of Zone I. In some cases, orthopyroxene crystals form radial or fan-shaped aggregates (Fig. 2-D). The olivine crystals found in the Zone III peridotites show a mode of occurrence similar to those of the Zone II peridotites. In addition to olivine and orthopyroxene, tremolite and green spinel occur locally in Zone III. Most of the tremolite grains are prismatic in shape and have extinction angles (≤ 23°) larger than those of the tremolites from Zone II (≤ 18°). The green spinel occurs commonly as inclusions(< 0.02 mm in diameter) within orthopyroxene crystals. It appears that clinopyroxene occurs very sparsely in Zone III; clinopyroxene was found only in one specimen taken from a peridotite boulder. This clinopyroxene is associated with olivine and green spinel and, unlike the clinopyroxene in Zone I, it is free from exsolution lamellae.

Nozaka and Shibata (1994) indicated that the medium-grained serpentinized peridotites of Zone I represent those unaffected by later thermal events and thus still retain primary mineral assemblages. On the other hand, the fine-grained peridotites of Zones II and III are distributed parallel to the boundary between the Ohsayama body and the granite intrusion; thus, there is no doubt that these peridotites are affected to various degrees by the contact metamorphism due to the granite intrusion. In metamorphosed ultramafic rocks, however, it is difficult to distinguish newly recrystallized minerals from relict, primary minerals by means of microscopic analysis alone; this is because newly formed assemblages commonly include recrystallized olivine and pyroxenes, and these phases occur along with relict olivine and pyroxenes. In the following section, therefore, we examine chemical compositions of minerals obtained from the three zones in order to understand mineral paragenetic relations in the contact aureole of the Ohsayama body.

III. Mineral Chemistry

All mineral analyses were carried out by using a JEOL electron probe microanalyzer (Model JXA-733) at Okayama University. The correction procedure was that of Bence and Albee (1968) with alpha factors of Nakamura and Kushiro (1970). Representative analyses are listed in Tables 1 to 6.

Olivine compositions are relatively homogeneous within a single grain as well as from grain to grain throughout Zone I, whereas olivines from Zones II and III show significant compositional variations; i.e., Fo contents range from 90.8 to 92.6 mol % in Zone I, whereas they range from 87.6 to 97.3 mol % in Zone II and 89.7 to 95.8 mol % in Zone III, respectively (Table 1 and Fig. 3). The minute grains of opaque minerals occur as inclusions commonly within the relatively magnesian olivine crystals (≥ Fo 93) in Zone II, though we found some in relatively ferrous olivine crystals (< Fo 93).
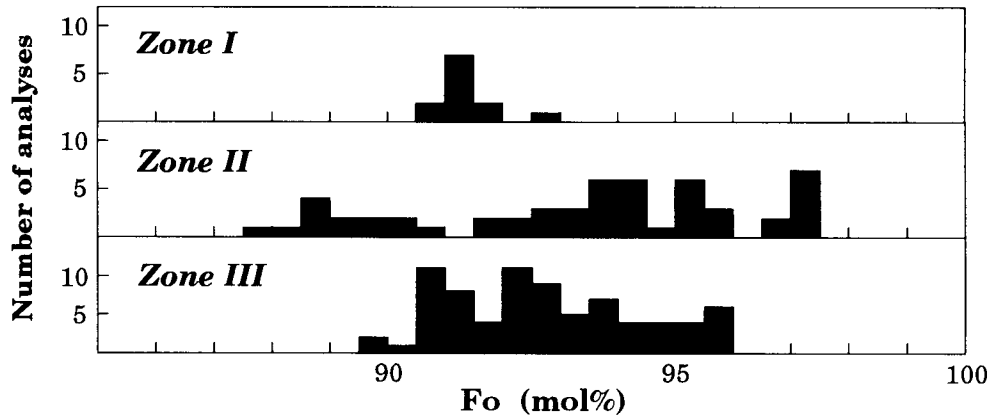
Fig. 3   Frequency distribution of Fo contents for olivines from Zones I, II and III.
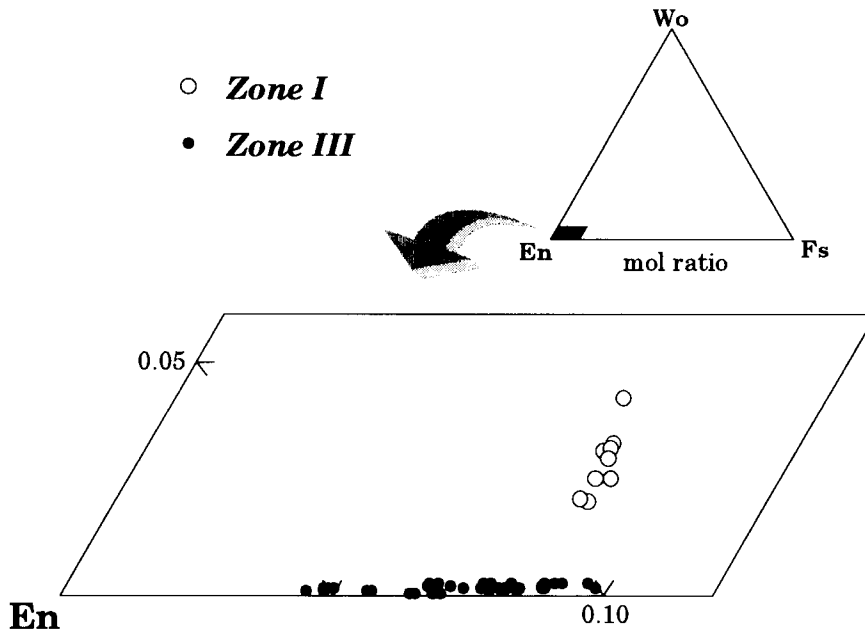
Fig. 4   Compositions of orthopyroxene plotted in the pyroxene quadrilateral.   The Zone I orthopyroxenes were analyzed along with several thin lamellae of clinopyroxene with a broad electron beam of 30 μm in diameter.

As for the Zone I orthopyroxene with thin exsolution lamellae of clinopyroxene, we obtained analyses by using a broad electron beam of $ca.$ 30 μm in diameter.   The chemical compositions so obtained may be regarded as bulk analyses including both host and lamella crystals.   The host orthopyroxene crystals, therefore, should have CaO contents lower than the CaO values listed in Table 2.   We attempted to obtain analyses for the host orthopyroxene crystals with due caution of avoiding nearby clinopyroxene lamellae by using a focused electron beam of $ca.$ 2

μm in diameter.   All the CaO contents obtained in this way are higher than 0.5 wt.%.   In contrast, the Zone III orthopyroxenes, which have no clinopyroxene lamella, are extremely poor in CaO, and most of them are richer in Mg than the Zone I orthopyroxenes.

Tremolite crystals from the Zone II peridotites are highly magnesian; this is consistent with the magnesian nature of the coexisting olivines in Zone II.   The colorless amphiboles from Zone III are richer in Na, Fe, and Al than the tremolites from Zone II, and some of them fall in

Table 1   Microprobe analyses of olivine.

Sample no.	Zone I								Zone II					
	02231183-1	02231183-2	03141083-1	03141083-2	03141083-3	03141083-4	03141083-5	03141083-6	0703H84-2	0703H84-4	0409H84-1	0409H84-5c	1509H84-5	1509H84-8c
SiO_2	40.80	40.79	40.56	40.46	40.42	40.54	40.67	40.53	41.15	40.70	41.02	40.46	40.10	40.77
FeO*	8.99	9.03	8.39	8.40	7.36	8.56	8.56	8.72	4.84	6.01	4.82	6.53	7.96	4.23
MnO	0.10	0.13	0.11	0.12	0.07	0.11	0.11	0.11	0.26	0.14	0.03	1.62	0.14	0.28
NiO	0.36	0.38	0.44	0.40	0.49	0.39	0.43	0.42	0.45	0.47	0.30	0.44	0.33	0.33
MgO	50.24	49.98	50.93	50.53	51.76	50.42	50.25	50.67	53.83	52.85	54.64	51.43	50.51	53.93
CaO	0.00	0.01	0.00	0.02	0.00	0.03	0.02	0.03	0.01	0.02	0.01	0.01	0.01	0.02
Total	100.49	100.32	100.43	99.93	100.10	100.05	100.04	100.48	100.54	100.19	100.82	100.49	99.05	99.56
Cations/O=4														
Si	0.992	0.994	0.986	0.989	0.982	0.990	0.993	0.986	0.985	0.982	0.978	0.982	0.987	0.982
Fe	0.183	0.184	0.171	0.172	0.150	0.175	0.175	0.177	0.097	0.121	0.096	0.133	0.164	0.085
Mn	0.002	0.003	0.002	0.002	0.001	0.002	0.002	0.002	0.005	0.003	0.001	0.033	0.003	0.006
Ni	0.007	0.007	0.009	0.008	0.010	0.008	0.008	0.008	0.009	0.009	0.006	0.009	0.007	0.006
Mg	1.822	1.816	1.846	1.840	1.875	1.835	1.829	1.838	1.920	1.902	1.942	1.861	1.853	1.937
Ca	0.000	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.001	0.000	0.000	0.000	0.001
Total	3.006	3.004	3.014	3.011	3.018	3.010	3.007	3.014	3.015	3.018	3.022	3.018	3.013	3.018
Fo	90.87	90.80	91.54	91.47	92.61	91.30	91.28	91.20	95.20	94.00	95.28	93.35	91.88	95.79

* Total iron as FeO.

Table 1   (continued)

Sample no.	Zone II				Zone III									
	0318H84-1b	0318H84-2	0419H84-6	0419H84-9	02210883-1	02210883-4	0803H84-25	0803H84-33	0507H84-3	0507H84-7	0607H84-1	0607H84-2	0508H84-2	0508H84-8c
SiO_2	39.69	40.91	39.49	40.46	40.85	40.79	40.98	40.33	40.61	41.19	40.86	40.56	40.53	40.10
FeO*	11.00	2.70	11.94	4.90	6.10	8.02	4.65	9.85	5.12	4.19	5.82	6.23	7.18	8.97
MnO	0.16	0.24	0.41	0.05	0.15	0.14	0.21	0.08	0.09	0.04	0.15	0.16	0.05	0.12
NiO	0.38	0.19	0.45	0.37	0.38	0.46	0.19	0.45	0.42	0.38	0.39	0.40	0.32	0.36
MgO	48.71	55.74	47.56	53.75	51.97	50.50	53.13	48.50	53.04	54.11	52.85	52.90	51.37	49.46
CaO	0.01	0.03	0.02	0.00	0.01	0.04	0.01	0.02	0.01	0.01	0.00	0.00	0.01	0.02
Total	99.95	99.81	99.87	99.53	99.46	99.95	99.17	99.23	99.29	99.92	100.07	100.25	99.46	99.03
Cations/O=4														
Si	0.982	0.977	0.984	0.978	0.992	0.994	0.991	0.998	0.985	0.987	0.986	0.979	0.989	0.991
Fe	0.228	0.054	0.249	0.099	0.124	0.163	0.094	0.204	0.104	0.084	0.117	0.126	0.146	0.185
Mn	0.003	0.005	0.009	0.001	0.003	0.003	0.004	0.002	0.002	0.001	0.003	0.003	0.001	0.003
Ni	0.008	0.004	0.009	0.007	0.007	0.009	0.004	0.009	0.008	0.007	0.008	0.008	0.006	0.007
Mg	1.797	1.984	1.766	1.937	1.881	1.835	1.916	1.789	1.917	1.933	1.901	1.904	1.868	1.822
Ca	0.000	0.001	0.001	0.000	0.000	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.001
Total	3.018	3.023	3.016	3.022	3.008	3.006	3.009	3.002	3.015	3.013	3.014	3.021	3.011	3.009
Fo	88.76	97.35	87.66	95.13	93.82	91.82	95.32	89.77	94.86	95.84	94.18	93.80	92.73	90.77

* Total iron as FeO.

Table 2 Microprobe analyses of orthopyroxene.

Sample no.	Zone I **			Zone III				
	02231183-1b	02231183-2a	02231183-4a	02210883-5	0803H84-1	0507H84-1	0607H84-1a	0508H84-2c
SiO_2	55.34	55.72	55.62	58.35	57.56	57.85	56.12	52.57
TiO_2	0.02	0.00	0.02	0.03	0.01	0.00	0.00	0.00
Al_2O_3	2.75	2.54	2.73	0.51	0.27	0.33	2.66	7.12
Cr_2O_3	0.87	0.83	0.79	0.02	0.00	0.03	0.27	0.38
FeO*	5.57	5.86	5.79	4.65	5.58	3.16	4.89	6.36
MnO	0.15	0.14	0.15	0.15	0.06	0.06	0.12	0.12
NiO	0.10	0.10	0.07	0.13	0.09	0.09	0.08	0.06
MgO	33.10	33.80	33.66	36.76	35.80	38.14	36.53	32.92
CaO	2.23	1.06	1.31	0.13	0.06	0.05	0.02	0.07
Total	100.13	100.05	100.14	100.73	99.43	99.71	100.69	99.60
Cations/O=6								
Si	1.917	1.926	1.922	1.981	1.987	1.972	1.913	1.825
Ti	0.001	0.000	0.001	0.001	0.000	0.000	0.000	0.000
Al	0.112	0.104	0.111	0.020	0.011	0.013	0.107	0.291
Cr	0.024	0.023	0.022	0.001	0.000	0.001	0.007	0.010
Fe	0.161	0.169	0.167	0.132	0.161	0.090	0.139	0.185
Mn	0.004	0.004	0.004	0.004	0.002	0.002	0.003	0.004
Ni	0.003	0.003	0.002	0.004	0.002	0.002	0.002	0.002
Mg	1.709	1.742	1.734	1.860	1.842	1.938	1.857	1.704
Ca	0.083	0.039	0.048	0.005	0.002	0.002	0.001	0.003
Total	4.014	4.010	4.011	4.008	4.008	4.021	4.030	4.024
Mg/(Mg+Fe)	0.914	0.911	0.912	0.934	0.920	0.956	0.930	0.902
Wo	4.2	2.0	2.5	0.2	0.1	0.1	0.0	0.1
En	87.5	89.3	88.9	93.2	91.9	95.5	93.0	90.1
Fs	8.3	8.7	8.6	6.6	8.0	4.4	7.0	9.8

* Total iron as FeO.　　** Beam diameter: 30 μm

Table 3 Microprobe analyses of clinopyroxene.

Sample no.	Zone I		Zone III	
	02231183-p2	02231183-p4	05030883-1c	05030883-3
SiO_2	53.62	52.59	50.16	49.88
TiO_2	0.01	0.01	0.01	0.01
Al_2O_3	2.46	2.90	5.22	4.97
Cr_2O_3	0.88	1.17	0.00	0.00
FeO*	1.75	1.85	2.35	2.85
MnO	0.08	0.09	0.05	0.03
NiO	0.00	0.04	0.03	0.00
MgO	17.01	16.51	16.01	15.44
CaO	24.99	24.97	25.60	25.73
Total	100.80	100.13	99.43	98.91
Cations/O=6				
Si	1.934	1.915	1.847	1.852
Ti	0.000	0.000	0.000	0.000
Al	0.105	0.124	0.227	0.218
Cr	0.025	0.034	0.000	0.000
Fe	0.053	0.056	0.072	0.089
Mn	0.002	0.003	0.002	0.001
Ni	0.000	0.001	0.001	0.000
Mg	0.915	0.896	0.879	0.855
Ca	0.966	0.974	1.010	1.024
Total	4.000	4.003	4.038	4.039
Mg/(Mg+Fe)	0.945	0.941	0.924	0.906
Wo	49.9	50.6	51.5	52.0
En	47.3	46.5	44.8	43.4
Fs	2.7	2.9	3.7	4.5

* Total iron as FeO.

Table 4 Microprobe analyses of tremolite.

| Sample no. | Zone II | | Zone III | |
	0703H84-1	1509H84-1c	0803H84-1	0508H84-4
SiO_2	58.65	58.19	57.74	53.52
TiO_2	0.02	0.00	0.00	0.07
Al_2O_3	0.10	0.32	0.64	4.68
Cr_2O_3	0.04	0.03	0.01	0.22
FeO^*	0.88	1.31	2.02	3.26
MnO	0.02	0.00	0.00	0.04
NiO	0.10	0.00	0.04	0.10
MgO	24.39	23.95	23.90	21.55
CaO	13.72	13.86	13.07	13.31
Na_2O	0.00	0.02	0.08	0.50
K_2O	0.01	0.03	0.03	0.02
Total	97.93	97.71	97.53	97.27
Cations/O=23				
Si	7.961	7.935	7.901	7.442
Ti	0.002	0.000	0.000	0.007
Al	0.016	0.051	0.103	0.767
Cr	0.004	0.003	0.001	0.024
Fe	0.100	0.149	0.231	0.379
Mn	0.002	0.000	0.000	0.005
Ni	0.011	0.000	0.004	0.011
Mg	4.935	4.869	4.876	4.467
Ca	1.995	2.025	1.916	1.983
Na	0.000	0.005	0.021	0.135
K	0.002	0.005	0.005	0.004
Total	15.028	15.042	15.058	15.224
Mg/(Mg+Fe)	0.980	0.970	0.955	0.922

* Total iron as FeO.

Table 5 Microprobe analyses of spinel.

| Sample no. | Zone I | | Zone III | |
	02231183-1	03141083-3a	05030883-1	0508H84-2
SiO_2	0.03	0.04	0.02	0.05
TiO_2	0.02	0.05	0.00	0.02
Al_2O_3	27.45	28.85	65.58	60.79
Cr_2O_3	40.03	38.64	0.06	4.63
FeO^*	21.00	21.94	10.81	12.27
MnO	0.42	0.55	0.07	0.12
NiO	0.11	0.06	0.24	0.68
MgO	10.94	9.58	22.20	21.04
CaO	0.02	0.00	0.03	0.03
Total	100.02	99.71	99.01	99.63
Cations/O=32				
Si	0.007	0.010	0.004	0.010
Ti	0.004	0.009	0.000	0.003
Al	7.937	8.362	15.608	14.754
Cr	7.765	7.513	0.010	0.754
Fe	4.309	4.512	1.826	2.113
Mn	0.087	0.115	0.012	0.021
Ni	0.022	0.012	0.039	0.113
Mg	4.001	3.512	6.683	6.459
Ca	0.005	0.000	0.006	0.007
Total	24.138	24.044	24.187	24.233
Mg/(Mg+Fe)	0.482	0.438	0.785	0.753
Al^{**}	0.494	0.523	0.968	0.915
Cr^{**}	0.483	0.470	0.001	0.047
Fe^{3+} **	0.023	0.007	0.031	0.039

* Total iron as FeO.   ** Al-Cr-Fe^{3+} atomic ratio calculated from structural formula.

Table 6 Microprobe analyses of serpentine.

| Sample no. | Zone I | |
	02231183-4b	02231183-6c
SiO_2	40.98	39.23
TiO_2	0.00	0.00
Al_2O_3	0.69	1.29
Cr_2O_3	0.00	1.04
FeO^*	1.54	3.29
MnO	0.06	0.07
NiO	0.00	0.00
MgO	41.65	39.88
CaO	0.20	0.64
Na_2O	0.00	0.00
Total	85.12	85.44
Cations/O=7		
Si	1.954	1.895
Ti	0.000	0.000
Al	0.039	0.073
Cr	0.000	0.040
Fe	0.061	0.133
Mn	0.002	0.003
Ni	0.000	0.000
Mg	2.960	2.872
Ca	0.010	0.033
Na	0.000	0.000
Total	5.026	5.049
Mg/(Mg+Fe)	0.980	0.956

* Total iron as FeO.
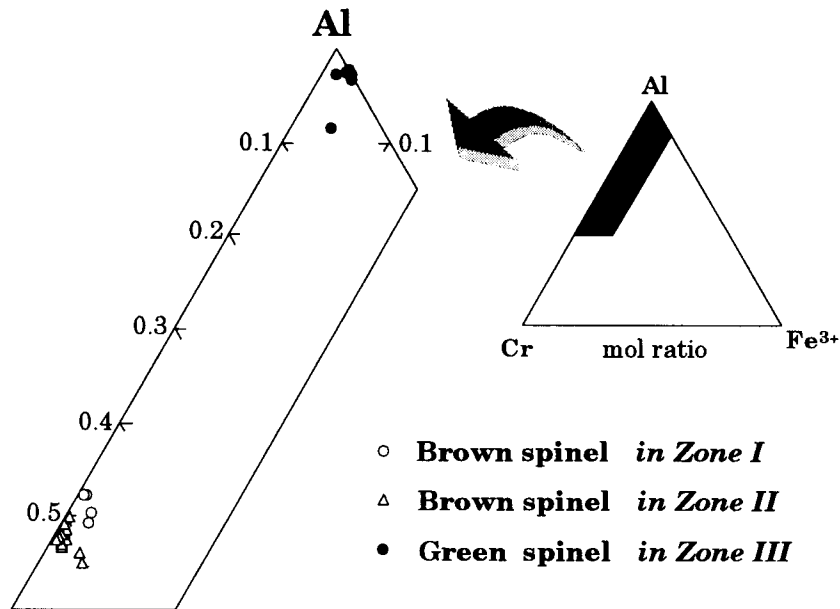
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Fig. 5 Al-Cr-Fe^{3+} atomic ratios of spinels.

the composition range of hornblende, *sensu stricto*. The colorless amphiboles from Zone III, however, are collectively referred to as tremolite for simplicity in this report, because their departures from the tremolite-actinolite compositions are not large.

In addition to tremolite, Mg-Fe amphiboles (*i.e.*, anthophyllite and magnesio-cummingtonite) are common recrystallized amphibole phases generally found in metamorphic peridotites (*e.g.*, Arai, 1975; Uda, 1984). It would be worth noting that the Mg-Fe amphiboles are not found in the Ohsa-yama ultramafic rocks.

As described in the previous section, the spinels from Zones I and II are brown, and that from Zone III is green, suggesting compositional differences between these two types of spinel. Compositions of the brown spinel are plotted nearly halfway between the Al and Cr apices in the Al-Cr-Fe^{3+} triangular diagram (Fig. 5), and the brown spinels from both of Zone I and II are similar in composition. The similarities in composition and mode of occurrence between the Zone I and II brown spinels imply that, like the Zone I brown spinel, the Zone II brown spinel is a relict, primary phase. In contrast to these brown spinels, the green spinel from Zone III is highly

aluminous and extremely poor in chromium (Fig. 5).

IV. Discussion

As we described previously, the medium-grained peridotites of Zone I are similar in petrographic characters to other primary massive peridotites of the Sangun zone (Nozaka and Shibata, 1994). We have no evidence that the serpentinized peridotites of Zone I underwent contact metamorphism. Thus, Zone I corresponds to the parts of the Ohsa-yama body that remained unaffected during the contact metamorphism.

The remaining parts of the Ohsa-yama body, Zones II and III, are likely to be affected by the thermal metamorphism and form a part of the contact aureole generated around the granite intrusion. We found the green spinel and lamella-free orthopyroxene only in the fine-grained peridotites of Zone III. The chemical compositions of these two minerals are distinctly different from those of the primary orthopyroxene and brown spinel of Zone I, respectively. Also, the lamella-free orthopyroxene of Zone III is characterized by extremely low CaO contents, a feature shared in common with recrystallized

orthopyroxenes of other thermally metamor-
phosed serpentinites (*e.g.*, Arai, 1974). These
lines of evidence suggest that the green spinel
and lamella-free orthopyroxene of Zone III are
recrystallized phases formed during the contact
metamorphism.

Occurrences of tremolite and talc are re-
stricted to Zones II and III, suggesting their
metamorphic origin as well.   In Zone III, how-
ever, talc, serpentine and chlorite locally replace
the metamorphic orthopyroxene discussed
above.   Thus, it seems clear that some hydrous
minerals including talc were formed at later
stages after the thermal peak of the contact
metamorphism.   As for the brown spinel grains
of Zone II, it is likely that they are relict crystals
of the primary spinel, as noted in the previous
section.

We found wide composition ranges in Fo
contents for the Zone II and III olivines.   The
wide ranges in olivine compositions were also
noted for the olivines found in the metaserpenti-
nites of the Tari-Misaka and Oye-yama bodies
(Arai, 1973; Uda, 1984).   Furthermore, these au-
thors showed there is a bimodal distribution in
Fo contents of these olivines, and they contended
that the magnesian group of olivine represents
the olivine derived through recrystallization of

serpentine whereas the less magnesian group of
olivine corresponds to relict crystals of the pri-
mary olivine.   This is based on the observation
that serpentinization of peridotites generally re-
sults in the formation of iron oxide (and/or sul-
fide) plus serpentine; the serpentine so formed
must be more magnesian in terms of $Mg/(Mg+Fe)$
ratios than original olivine and pyroxenes.   The
magnesian group of olivine are thus regarded as
those derived from dehydration of such serpen-
tine minerals.   Their interpretation may be ap-
plied to the Ohsa-yama olivines from Zones II
and III as well.   In fact, serpentine is closely as-
sociated with opaque minerals in the Zone I ser-
pentinized peridotites, and this serpentine is
more magnesian $(Mg/(Mg+Fe) = 0.95\text{-}0.98)$ than
the primary olivine (Table 6).   Also, the magne-
sian olivine grains (Fo mol% $\geq$ 95) of the Zone II
and III peridotites tend to contain numerous,
minute grains of opaque minerals as inclusions.
All these facts are consistent with the view that
the magnesian olivine is a recrystallized phase.
We, however, found in the Zone II peridotites
that some of the relatively ferrous olivine grains
also include numerous grains of opaque miner-
als, and these olivine grains are unlikely to be
relict crystals of the primary olivine.   So, all the
compositional variations observed for the Ohsa-

Zone	I	II	III
Serpentine			
Brucite			
Chlorite			
Olivine			
Talc			
Tremolite			
Orthopyroxene			
Spinel			

Fig. 6   Progressive mineralogical changes of the Ohsa-yama ultramafic rocks.   Dashed line indicates
the mineral is not ubiquitous.   Retrogressive serpentine, chlorite and talc in Zones II and III,
and relics of primary minerals are omitted from this diagram.

yama olivines may not be accounted for in terms of the simple scheme presented by Arai (1973) and Uda (1984).

Figure 6 summarizes progressive mineral changes in the thermally metamorphosed serpentinites of the Ohsa-yama body. The clinopyroxene found in the peridotite boulder of Zone III is probably a metamorphic phase, but it is not included in this figure because it is found only in one specimen that appears to have a peculiar bulk composition. The results obtained in this study are virtually consistent with those of the previous studies on thermally metamorphosed serpentinites (Arai, 1975; Uda, 1984). Our results, however, have some remarkable differences from those of the previous studies in the following respects: 1) the aluminous spinel occurs in the highest-grade zone (Zone III), 2) Mg-Fe amphiboles are not found in any of the peridotite samples examined, and 3) the less-magnesian group of olivine grains from the Zone II and III peridotites have inclusions of opaque minerals. These differences imply that the metamorphic conditions of the Ohsa-yama body might be slightly different from those of the Tari-Misaka and Oye-yama bodies. The reasons for these differences will be discussed in detail elsewhere.

V. Conclusions

The Ohsa-yama ultramafic body underwent contact metamorphism; as a result, the thermally metamorphosed serpentinites show progressive mineral changes toward its contact with the granite intrusion. On the basis of metamorphic mineral paragenesis, the Ohsa-yama ultramafic body can be divided, in order of increasing metamorphic grade, into the three zones as follows:

Zone I: serpentine ± chlorite ± brucite

Zone II: olivine + talc ± tremolite ± chlorite

Zone III: olivine + orthopyroxene ± tremolite
          ± spinel

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