ULTRAMAFIC NODULE AND MEGACRYST PYROXENE IN ALKALINE
BASALT FROM KIBI PLATEAU, SOUTHWEST JAPAN

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Introduction

The occurrences of megacryst pyroxenes and ultramafic nodules in alkaline basalts from the Inner zone of Southwest Japan have been reported by several authors (KUNO 1964, ISHIBASHI 1964, 1970, YAMAGUCHI 1964, KUSHIRO and KUNO 1963, AOKI 1968).

High contents of Tschermak's molecule of the megacryst pyroxene may suggest their formation at a deeper level of the crust or the upper mantle.

For the fractionation of some representative basaltic magmas, substantial control of crystallization of aluminous pyroxenes at high pressures under anhydrous condition has been stressed by GREEN and RINGWOOD (1967a). In this connection, KUSHIRO (1969a, b) has advocated that the crystallization of aluminous pyroxenes without forsteritic olivine as the liquidus mineral at high pressure is not plausible except in the presence of water vapor.

Although megacryst pyroxenes and ultramafic

nodules occur concomitantly, it is concluded that their petrogenesis are different to each other on the basis of mineralogic analyses.

This paper describes new occurrence of megacryst pyroxenes and ultramafic nodules from the Kibi plateau, Southwest Japan and discusses their origins.

Occurrence

In the Kibi plateau located in the Chugoku mountainous land, the west margin of Okayama prefecture, the basement complex is composed of the geosynclinal sediments of the Permo-Carboniferous which are unconformably overlain by the molasse type sediments composed mainly of lime-

Table 1. Chemical composition and norm of the host rocks.

	A	B
SiO ₂	44.64	44.38
TiO ₂	1.74	2.09
Al ₂ O ₃	13.73	15.35
Fe ₂ O ₃	2.40	1.89
FeO	9.22	8.24
MnO	0.14	0.12
MgO	10.24	11.19
CaO	12.42	10.73
Na ₂ O	2.70	2.35
K ₂ O	1.50	1.35
H ₂ O ⁺	0.65	1.52
H ₂ O ⁻	0.34	0.40
	99.72	99.61
il	3.34	3.95
mag	3.48	2.78
Or	8.90	7.78
Ab	2.10	8.38
Neph	11.36	6.25
An	20.57	27.52
Wo	17.05	10.67
En	10.70	7.20
Fs	5.28	2.64
Fo	10.36	14.56
Fa	5.51	5.71
	33.03	20.51
	15.87	20.27

A : Basanite from Aratoyama, in the western margin of Okayama Prefecture (new analysis K. TAZAKI).

B : Trachy basalt from Aratoyama (OJI and OJI, 1964).

Fig. 1. The locality of Aratoyama is shown by arrow.

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stones and conglomerates of the Triassic, as well as by the thin sediments of the Neogene. Late Mesozoic acid and intermediate igneous rocks such as rhyolite, porphyrite and granitic rocks are emplaced into the former sediments. Small serpentinite bodies are also found there.

Small alkaline basalt domes bearing numerous ultramafic nodules and megacrystic pyroxenes lie on the Tertiary sediments mentioned above. According to Oji and Oji (1964), the alkaline basalts from the Kibi plateau are divided into three groups such as

- 1) Aratoyama type
- 2) Yatomiya type
- 3) Ni-iyama type

on the basis of the petrographical and geographical characteristics. Of these, ultramafic nodules and megacrysts investigated by the present writer are found in the basalts of the Aratoyama type.

Petrography

Host basalts

The alkaline basalts from Aratoyama carrying ultramafic nodules and megacryst pyroxenes show dense and fine aphyric features. Under the microscope, minute olivine grains, lath-shaped plagioclases and corroded clinopyroxene xenocrysts are observed.

Chemical composition and norm of the host rocks listed in Table 1 show that these rocks are rather rich in CaO and MgO, and poor in SiO₂ comparing with the alkaline olivine basalts from Takashima or Iki Island (Kuno 1964, Aoki 1968).

The contents of normative nepheline surpassing 11% suggests that these alkaline basalts from Aratoyama are rather of trachy basalt or basanite.

Ultramafic nodules

Ultramafic nodules and megacryst pyroxenes enclosed in the basaltic rocks from Aratoyama are composed mainly of such rock types as peridotite, pyroxenite, megacryst of orthopyroxene and clinopyroxene. Gabbroic nodules reported from Takashima and Iki Island have not been found from Aratoyama.

Ultramafic nodules from Aratoyama have rounded or subangular forms, and most of them are 1 to 2 cm in diameter, occasionally ranging up to 5 cm in diameter.

Nodules and megacrysts are divided into five groups, based on their mineral assemblages and petrographic characteristics, such as follows:

Type A: These rock types are granular and vary from greenish yellow to yellow in hand specimens. They comprise olivine, orthopyroxene and clinopyroxene with minor amounts of chro-

mian spinel and are further classified into three subtypes, dunite, lherzolite and harzburgite based on their mineral ratios. The lherzolite consists approximately of 60% olivine, 30% orthopyroxene and 10% clinopyroxene.

In thin section, xenomorphic olivine and orthopyroxene make, in one case, an equigranular mosaic texture in which the grain size of these minerals ranges from 0.3 to 0.5 mm in diameter. In another case, rather fine-grained and granular aggregates of minerals are surrounded by larger xenomorphic crystals which range from 1.5 to 3.0 mm in length. The larger granules of olivine and orthopyroxene exhibit translation lamella.

Olivine bears cleavages imperfectly parallel to (100) and (010) plane. Grass-green clinopyroxene is scattered sporadically. No exsolution lamella are observable in both of the ortho- and clinopyroxenes.

Type B: This rock type classified as olivine pyroxenite comprises large amount of orthopyroxene, small amount of dark green clinopyroxene and minor amount of olivine.

In thin section, hypidiomorphic coarse-grained orthopyroxenes which range from 2 to 4 mm in length are predominant. Bronzitic orthopyroxene shows faint pleochroism, such as

Z=pale green, X,Y=pale purplish.

Exsolution lamella of clinopyroxene are observable in orthopyroxene. Clinopyroxene rarely occurring as poikiloblast encloses olivine and orthopyroxene. Exsolution lamella of orthopyroxene in poikiloblastic clinopyroxene are also observed. This type of nodule has an extensive white marginal rim which ranges 2 to 4 mm in thickness. This marginal rim comprises fine-grained graphic intergrowth of olivine and clinopyroxene.

Type C: This type classified as olivine bearing two pyroxenite is composed approximately of two parts of bronzitic orthopyroxene, one part of diopsidic clinopyroxene and trace of olivine. In thin section, they show equigranular xenomorphic mosaic texture and range up to 2 mm in width. Exsolution lamella are common in both of the orthopyroxene and clinopyroxenes.

Type D: Single huge clinopyroxene ranges from 1 to 3 cm in length and 1 to 1.5 cm in width. Exsolution lamella are also present. Fused clinopyroxene megacrysts are rarely observed, which are now converted into olivine, clinopyroxene and plagioclase.

Type E: Single huge orthopyroxenes ranging from 1 to 2 cm in length and 0.5 to 1 cm in width which are enclosed, by white marginal rim

ranging from 2 to 3 cm in thickness.

Mineralogy of ultramafic nodules and megacrysts

Three olivines, five orthopyroxenes, and three clinopyroxenes from various nodules and a white marginal rim of type B nodules are separated and are chemically analyzed.

Chemical analyses are substantially carried out by the rapid methods revised by MATSUI (1963) except for NiO and Cr₂O₃. SiO₂ percent is calculated by mean of subtraction of analyzed oxides from 100%, because of limited amount of samples. Total iron oxides is allotted as FeO for olivine and orthopyroxene.

Olivine: Chemical composition and structure formula of three olivines listed in Table 2 show that the Fo content of olivines from type A nodules vary from 83 to 90%.

The most Fa rich one is obtained from dunite. Optically determined Fo content of the host basalt ranges from 77 to 87% (OJI and OJI, 1964).

Chemical compositions of olivines in peridotite nodules from Hawaii (WHITE, 1966) and various localities (ROSS *et al.*, 1954) illustrated in Fig. 2 show that olivines of lherzolite nodules are generally rich in Fo molecule than those of other ultramafic rocks. The same tendency is obtained in the peridotite nodules from Aratoyama.

Orthopyroxene: Chemical composition and structure formula of orthopyroxene in the ultramafic nodules and megacrysts are listed in Tables

Table 2. Chemical composition of olivine in ultramafic nodule from Aratoyama.

	A001	A002	A003
SiO ₂	39.78	41.22	40.55
TiO ₂	0.03	0.014	0.03
Al ₂ O ₃	tr.	tr.	tr.
FeO	15.75	9.22	10.56
MnO	0.18	0.13	0.15
MgO	43.71	48.73	47.77
NiO	0.34	0.49	0.41
CaO	0.21	0.20	0.53
Si	1.004 1.004	1.009 1.009	1.003 1.003
Ti	0.001	0.000	0.001
Al	—	—	—
Fe	0.332	0.189	0.218
Mn	0.004 1.993	0.003 1.983	0.003 1.999
Mg	1.643	1.776	1.755
Ni	0.007	0.010	0.008
Ca	0.006	0.005	0.014
Fo (%)	83.0	90.5	88.8

A001 : Olivine in dunite nodule.

A002 : Olivine in lherzolite nodule.

A003 : Olivine in harzburgite nodule.

Fig. 2. Fo content of olivine in peridotite nodule.

I : Phenocrysts of host basalt (OJI and OJI, 1964).

II : Arato nodules.

III : Dunite. IV : Wehrlite. V : Lherzolite.

(III-V : Hawaiian nodules, WHITE R., 1966).

VI : Peridotite nodule (ROSS *et al.*, 1954).

Table 3. Chemical composition of orthopyroxene in ultramafic nodule from Aratoyama

	A002	A003	B002	C001	E001	MY1
SiO ₂	56.09	54.67	53.54	53.96	53.36	51.26
TiO ₂	0.03	0.23	0.28	0.10	0.46	0.38
Al ₂ O ₃	2.22	2.61	5.17	4.01	6.17	6.36
Fe ₂ O ₃	—	—	—	—	—	2.48
FeO	5.75	6.80	10.81	12.25	9.43	8.12
MnO	0.13	0.16	0.14	0.24	0.34	0.18
MgO	34.14	33.62	28.11	27.32	27.64	27.88
CaO	0.91	1.07	1.57	1.83	2.22	3.49
Na ₂ O	0.07	0.19	0.20	0.02	0.21	0.26
K ₂ O	n. d	n. d	n. d	n. d	n. d	tr.
Cr ₂ O ₃	0.53	0.52	0.18	0.27	0.17	n. d
NiO	0.13	0.13	n. d	n. d	n. d	n. d
H ₂ O ⁺	n. d	n. d	n. d	n. d	n. d	0.15
H ₂ O ⁻	n. d	n. d	n. d	n. d	n. d	0.00

A002 : Orthopyroxene in lherzolite nodule.

A003 : Orthopyroxene in harzburgite nodule.

B002 : Orthopyroxene in olivine pyroxenite nodule.

C001 : Orthopyroxene in olivine bearing two pyroxenite nodule.

E001 : Orthopyroxene megacryst.

MY1 : Orthopyroxene in websterite nodule from Nochi (YAMAGUCHI, 1964).

3 and 4. FeO and CaO increase, whereas MgO decreases successively from type A to type C nodules. Al₂O₃ is high in type B, C and E, in comparison with type A nodules. Al₂ ranges from 3 to 5% in ultramafic nodules in our case, meanwhile, it is reported by Yamaguchi to be 9.3% in the websterite from Nochi (YAMAGUCHI, 1964) which belongs to the Aratoyama type. A megacryst orthopyroxene of type E bears 6.1% Al₂.

Molecular proportions of analyzed orthopyro-

Table 4. Formulas of orthopyroxene on the basis of 6 oxygens.

	A002	A003	B002	C001	E001	MY1
Si	1.938	1.904	1.892	1.920	1.878	1.814
Al	0.062	0.096	0.108	0.080	0.122	0.186
Al	0.028	0.012	0.108	0.088	0.134	0.079
Ti	0.001	0.006	0.007	0.003	0.012	0.010
Fe ³⁺	—	—	—	—	—	0.066
Fe ²⁺	0.166	0.198	0.319	0.364	0.277	0.240
Mn	0.004	0.005	0.004	0.007	0.010	0.005
Mg	1.757	1.744	1.480	1.448	1.449	1.469
Ca	0.034	0.040	0.059	0.070	0.084	0.132
Na	0.005	0.013	0.014	0.001	0.014	0.018
Cr	0.014	0.014	0.005	0.008	0.005	—
Ni	0.004	0.004	—	—	—	—
Alz	3.1%	4.8%	5.2%	4.0%	6.1%	9.3%

Table 5. Molecular proportion of orthopyroxene

	A002	A003	B002	C001	E001	MY1
NaFe ³⁺ Si ₂ O ₆	—	—	—	—	—	1.8
NaCrSi ₂ O ₆	0.5	1.3	0.5	0.1	0.5	—
NaAlSi ₂ O ₆	—	—	0.9	—	0.9	—
CaTiAl ₂ O ₆	0.1	0.6	0.7	0.3	1.2	1.0
CaAl ₂ SiO ₆	0.1	0.1	1.2	0.4	0.5	1.0
MgAl ₂ SiO ₆	4.6	4.7	8.5	8.1	10.8	11.5
CaSiO ₃	1.6	1.6	2.0	3.2	3.4	5.1
MgSiO ₃	85.2	83.5	69.9	69.1	68.1	67.3
FeSiO ₃	8.4	9.9	16.2	18.7	14.6	12.2
Wo	1.7	1.7	2.3	3.6	3.9	6.0
En	89.5	87.9	79.3	75.9	79.1	79.6
Fs	8.8	10.4	18.4	20.5	17.0	14.4
Ca(Mg, Fe)Si ₂ O ₆ (wt%)	3.56	3.54	4.80	7.60	8.15	12.55
(Mg, Fe) ₂ Si ₂ O ₆ (wt%)	96.43	96.45	95.20	92.40	91.85	87.45

xenes are listed in Table 5. Calculations are substantially based on the method after KUSHIRO (1962) and ONUKI and TIBA (1965), however, a few points are revised as follows: At first, Cr is allotted to NaCrSi₂O₆ molecule. When excess Cr remain, it is assigned to Al. After CaTiAl₂O₆ molecule is prepared, Ca-Tschermak's molecule is calculated, based on the ratio between Mg and Ca of the rest.

CaTiAl₂O₆ molecule is less than 1% in type A~ type C nodules, however, it is 1.0 and 1.2% in megacryst and websterite nodule from Nochi respectively. Mg-Tschermak's molecule is less than 5.0% in type A nodule. In type B and C nodules, this molecule ranges from 8.1 to 8.5% and it increases up to 10.8 and 11.5% in megacryst (type E) and websterite nodule, respectively.

Plots of the orthopyroxenes from the Aratoyama nodules, together with those of peridotite nodules (Ross *et al.*, 1954) on pyroxene quadrilateral are illustrated in Fig. 3, which show continuous variation from enstatite to bronzite and simultane-

Fig. 3. Chemical composition of orthopyroxene.

○ : Arato nodule. △ : Arato megacryst.
 × : Nochi websterite (YAMAGUCHI, 1964).
 ● : Peridotite nodule (Ross *et al.*, 1954).

ous increase of wollastonite component from type A to type B and C nodules. Those of the websterite from Nochi and megacrysts are plotted, however, on Wo rich side deviated from the trend mentioned above.

Clinopyroxene: Chemical compositions of

Table 6. Chemical composition of clinopyroxene in ultramafic nodule from Aratoyama.

	A002	C001	D001	MY2
SiO ₂	51.75	51.43	48.87	48.66
TiO ₂	0.19	0.40	0.80	0.83
Al ₂ O ₃	3.40	5.69	8.37	8.84
Fe ₂ O ₃	0.61	0.25	2.21	2.74
FeO	2.50	5.58	4.98	5.32
MnO	0.07	0.16	0.15	0.14
MgO	17.12	14.32	15.93	15.77
CaO	22.34	21.16	17.38	16.85
Na ₂ O	1.00	0.64	1.10	1.13
K ₂ O	n. d	n. d	n. d	tr.
Cr ₂ O ₃	1.02	0.37	0.21	n. d
NiO	n. d	n. d	n. d	n. d
H ₂ O ⁺	n. d	n. d	n. d	0.29
H ₂ O ⁻	n. d	n. d	n. d	0.00

A002 : Clinopyroxene in Iherzolite nodule.

C001 : Clinopyroxene in olivine bearing two pyroxenite nodule.

D001 : Clinopyroxene megacryst.

MY2 : Clinopyroxene in websterite nodule from Nochi (YAMAGUCHI, 1964).

clinopyroxene in ultramafic nodules and megacryst are listed in Table 6.

Clinopyroxene in Iherzolite (type A) is green diopside, whereas one from the olivine bearing pyroxenite (type C) is dark brown salite. Megacryst is black augite. The chemistry of clinopyroxene megacryst (type D) and one from the Nochi websterite is similar to that of huge phenocrystic or megacrystic clinopyroxene in alkaline basalt from Armidale, N.S.W., and northern Kyushu, which are low in CaO and high in Al₂O₃, Na₂O and TiO₂ (ISHIBASHI 1964, KUNO 1964, BINNS 1969).

Structure formula and molecular proportion of clinopyroxenes listed in Tables 7 and 8 show that Al₂ are 5.5 and 5.7% in type A and type C nodules respectively, whereas they are larger than 10% in megacryst and in the websterite from Nochi.

Jadeite molecule is 2.4 and 2.7% in the Iherzolite (type A) and in the olivine bearing pyroxenite (type C) respectively, whereas it is 1.0% in megacryst.

Table 8. Molecular proportion of clinopyroxene.

	A002	C001	D001	MY2
NaCrSi ₂ O ₆	2.8	1.1	0.6	—
NaFe ³⁺ Si ₂ O ₆	1.7	0.7	6.1	7.4
NaAlSi ₂ O ₆	2.4	2.7	1.0	0.5
CaTiAl ₂ O ₆	0.5	1.0	2.2	2.3
CaFe ³⁺ AlSiO ₆	—	—	—	—
CaAl ₂ SiO ₆	1.6	10.0	13.4	13.8
CaSiO ₃	41.4	36.6	26.0	25.6
MgSiO ₃	45.7	39.1	43.0	42.3
FeSiO ₃	3.8	8.9	7.8	8.2
Wo	45.5	43.3	33.9	33.6
En	50.3	46.2	56.0	55.6
Fs	4.2	10.5	10.1	10.7
Ca(Mg,Fe)Si ₂ O ₆	91.48	87.33	68.89	63.39
(Mg,Fe) ₂ Si ₂ O ₆	8.52	12.67	31.10	31.61

Fig. 4. Chemical composition of clinopyroxene.

- : Arato nodule. △ : Arato megacryst.
- : Arato phenocryst (OJI and OJI, 1964).
- × : Nochi websterite (YAMAGUCHI, 1964).
- : Ultramafic nodules from northern Kyushu ((ISHIBASHI, 1964).
- ⊕ : Large phenocrystic clinopyroxene from northern Kyushu (ISHIBASHI, 1964).
- : Peridotite nodule (Ross *et al.*, 1954).

Table 7. Formulas of clinopyroxene on the basis of 6 oxygens.

	A002	C001	D001	MY2
Si	1.890	1.886	1.786	1.775
Al	0.110	0.114	0.214	0.225
Al	0.037	0.132	0.146	0.155
Ti	0.005	0.010	0.022	0.023
Fe ³⁺	0.017	0.007	0.061	0.075
Fe ²⁺	0.076	0.171	0.152	0.162
Mn	0.002	0.005	0.005	0.004
Mg	0.934	0.782	0.867	0.857
Ca	0.874	0.831	0.680	0.658
Na	0.071	0.045	0.078	0.080
Cr	0.029	0.011	0.006	—
Alz(%)	5.5	5.7	10.7	11.3

Fig. 5. Trend of coexisting pairs of pyroxene from the Aratoyama ultramafic nodules.

○ : Aratoyama pyroxenes.
x.....x : Skaergaard pyroxenes.

Table 9. Chemical composition and reduction to pyroxene formula of marginal rim (Type B).

SiO ₂	49.97	Si	1.791	} 2.000
TiO ₂	0.35	Al	0.209	
Al ₂ O ₃	5.96	Al	0.043	
Fe ₂ O ₃	1.57	Ti	0.010	
FeO	8.84	Fe ³⁺	0.042	} 2.062
MnO	0.24	Fe ²⁺	0.265	
MgO	27.74	Mn	0.007	
CaO	5.03	Mg	1.481	
Na ₂ O	0.30	Ca	0.193	} 2.062
Cr ₂ O ₃	—	Na	0.021	

Ca : Mg : Fe²⁺ = 10.0 : 76.0 : 14.0

Ca-Tschermak's molecule is 1.6% in the lherzolite, however, it ranges from 10 to 14% in the other type of nodules and megacryst. CaTiAl₂O₆ molecule is 2.2 and 2.3% and NaFe³⁺Si₂O₆ is 6.1 and 7.4% respectively in the megacryst and the Nochi websterite. In contrast, CaTiAl₂O₆ is less than 1.0% and NaFe³⁺Si₂O₆ is also less than 1.7% in type A and type C nodules.

The compositions of the clinopyroxenes of type A and type C nodules are represented by Wo_{45.5}-En_{50.3}Fs_{4.2} and Wo_{43.3}En_{46.2}Fs_{10.5} respectively. Plotting of these compositions on quadrilateral illustrated in Fig. 4 demonstrates that they are in good agreement with those of peridotite nodules from northern Kyushu and other localities (ISHIBASHI 1964, ROSS *et al.*, 1954).

Fractionation trends of coexisting pyroxene pairs from the Aratoyama nodules are plotted in Fig. 5 together with those from the Skaergaard intrusion. The trends suggest that pyroxene pairs of type A, B and C nodules vary successively except their aluminian component, and finally they reach the composition similar to the pyroxene pair from the marginal gabbro of the Skaergaard intrusion.

Marginal rim: The marginal rim consisting of spongy augite around clinopyroxene and bronzite rim at the margin of olivine and orthopyroxene aggregate are reported from several localities

(ISHIBASHI 1964, KUNO 1964, YAMAGUCHI 1964, AOKI 1968). The ultramafic nodules from Aratoyama carry also the marginal rims at their peripheries. In general, they consist of mineral aggregates of white tint and sporadic glassy part that has now been altered into clay minerals. The white marginal rims looking like corona 2—3 mm in thickness are predominant in type B nodules and orthopyroxene megacrysts. They occur usually in type B nodule but rather poor in other type nodules.

The marginal rim of type B nodules always consist of domains of crystalline aggregate, each of them shows micrographic intergrowth of olivine and clinopyroxene. These domains are observed to have textural relations to the host nodules indicating that each of them is converted from the orthopyroxene crystal at the periphery of the nodules.

The chemical composition of collected sample of the representative marginal rim from type B nodule is listed in Table 9. It has a composition rich in CaO and low in SiO₂ in comparison with that of bronzite from type B nodule.

Mg, Fe²⁺ distribution between coexisting olivine and Ca-poor pyroxene and coexisting Ca-poor and Ca rich pyroxenes.

Apparent distribution coefficients defined as $K_{Mg-Fe}^{Ol-Opx} = X_1(1-X_2)/X_2(1-X_1)$, where, $X_1 = Mg/(Mg + Fe^{2+})$ in olivine, $X_2 = Mg/(Mg + Fe^{2+})$ in orthopyroxene, are 0.90 and 0.89 for the lherzolite and harzburgite from Aratoyama, respectively.

The apparent distribution coefficients K_{Mg-Fe}^{Ol-Opx} between coexisting olivine and orthopyroxene, in peridotite nodules from various localities range from 0.95 to 1.16 (ROSS *et al.*, 1954). In the case of Hawaiian ultramafic nodules, these values of lherzolite nodule are concentrated in about 1.00 and those of the other type ultramafic nodules are slightly smaller than 1.00 (WHITE, 1966). These results suggest that the pressure and temperature conditions for solidification of ultramafic nodules are not uniform but rather variable.

Apparent distribution coefficients $K_{Mg-Fe}^{Opx-Cpx}$ between coexisting pyroxene pairs in the lherzolite and the olivine clinopyroxenite from Aratoyama are 0.86 and 0.87 respectively, and there are no obvious differences between these rock types. The $K_{Mg-Fe}^{Opx-Cpx}$ values range from 0.76 to 0.86 in pyroxene pairs of various peridotite nodules (ROSS *et al.*, 1954).

$K_{Mg-Fe}^{Opx-Cpx}$ values mentioned above are generally higher than 0.73 which is conceived by KRETZ (1963) as representative value for igneous rocks. The average of seven $K_{Mg-Fe}^{Opx-Cpx}$ in pyroxene pairs of peridotite nodules from various locali-

ties is 0.8 (Ross *et al.*, 1954). The higher $K_{\text{Mg-Fe}}^{\text{Opx-Cpx}}$ of peridotite nodules may suggest their formation at temperature higher than those of igneous rocks.

Petrogenesis

Since the nodules of type A~type C of the Aratoyama dome are characterized by olivine and aluminous pyroxenes without plagioclase, it is highly probable that they have been formed at the P-T conditions higher than 10Kb. and 1200°C, if we assume anhydrous condition (GREEN and RINGWOOD, 1967b).

Distribution coefficient: There are no significant differences in the apparent distribution coefficient values among the coexisting minerals in the ultramafic nodules from Aratoyama, and therefore the P-T conditions, at which these nodules were formed, may not be much different.

The orthopyroxenes in type A~type C nodules show continuous chemical variation from enstatite to bronzite.

This variation will suggest the successive crystallization from certain basaltic source magma at high pressures.

Pyroxene megacryst: The megacryst of orthopyroxene is characterized by high CaTi-Al₂O₆ molecule in comparison with type A~type C nodules. The clinopyroxene megacryst is rich in CaTiAl₂O₆ and aegirine molecules. These facts suggest the origin of these megacryst cognates to the host alkaline basalt.

KUNO (1964) revealed that the megacrysts in alkaline olivine basalt from Takashima, Japan are rich in Tschermak's molecules and they are probably formed under high pressure conditions.

The liquidus minerals of alkaline olivine basalt at 10–15 Kb. under anhydrous condition are clinopyroxene and aluminous orthopyroxene just below the liquidus (GREEN and RINGWOOD, 1967a). It is expected that these liquidus minerals occur as megacryst pyroxenes in early crystallization of alkaline olivine basalt at deep seated stage.

Partial melting: Provided that the partial melting of peridotitic source materials give rise to basaltic magmas, the liquidus which is yielded at the invariant point will precipitate forsteritic olivine succeeded by crystallization of pyroxenes even under high pressure conditions ranging up to 20 Kb. (KUSHIRO, 1969a, b).

As far as the Aratoyama nodules are concerned, it is most likely that the pyroxene megacryst as primary liquidus phase without forsteritic olivine would possibly precipitate under such conditions as

1) temporal pressure increase or 2) temporal

decrease in water vapour pressure.

In the system Fo-Di-Q-H₂O at 20 Kb. P_{H₂O}, the forsterite-pyroxene liquidus boundary shifts to SiO₂ rich side of the join Fo-Q at 1 atm (KUSHIRO, 1969b). From this experiment, it is expected that the phase relation of Fo-Di-En-Q at 1 atm will persist substantially to 20 Kb. P_{H₂O}; in other words, olivine field expands beyond Di-En join, and the invariant point also situates at SiO₂ rich side of the join, and the basaltic melt produced at the invariant point will be saturated in SiO₂.

When the derivation of basaltic magma takes place at certain high pressure condition in the presence of slight water fluid phase, the liquidus boundary mentioned above will be situated at SiO₂ rich side than that of anhydrous condition.

If the basaltic magma is produced at invariant point, water vapour would partly be absorbed into magma promptly. The system will undergo less hydrous condition and forsterite-pyroxene liquidus boundary will move toward Fo-Di side than that of hydrous condition. Then the crystallization from magma will take place at pyroxene field.

If the elimination or decrease of water vapour from slightly hydrated basaltic magma takes place in the course of crystallization, the state of magma will change from hydrous condition to rather anhydrous.

The temporal pressure increase is not plausible in this case because increasing pressure will expel the melt upward and has no effect on crystallization.

Exsolution: Concerning the exsolution phenomena in pyroxenes, the results of high pressure experiment on enstatite-diopside system is useful.

The solvus of enstatite side in the enstatite-diopside system is expected nearly vertical at En₉₃-Di₇ in weight percent, whereas the solvus of diopside side is suggested as higher as 50°C than that of atmospheric pressure by the application of 20 Kb. pressure (KUSHIRO, 1968a).

Applying these results of high pressure experiment for the ultramafic nodules from Aratoyama, the orthopyroxene from the type B nodule (En_{95.2}-Di_{4.8}) could not exsolve as two phases at 20 Kb. pressure. Therefore, the exsolution of the orthopyroxene from type B nodules would take place at a shallower depth than 20 Kb. pressure.

Subsolidus and subsolvus relations of enstatite-diopside system at atmospheric pressure investigated by BOYD and SCHAIRER (1964) are illustrated in Fig. 6. Subsolidus relation of Di-En system gives some remarks on the Aratoyama pyroxene pairs with little reform, since the Fs molecule are less

Fig. 6. Solvus relation of coexisting pyroxenes in En-Di system after BOYD and SCHAIER (1964). Dotted area represents the compositional range of pyroxenes from the Aratoyama nodules.

than 20% in orthopyroxene and less than 10% in clinopyroxene. Dotted area in Fig. 6 represents the compositional range of those coexisting pairs of pyroxene from the Aratoyama nodules.

The temperatures which the exsolution occur in the type B and C nodules and megacryst pyroxenes range approximately from 1000 to 1050°C in Fig. 6. Considering Fs molecule in these pyroxenes, this temperature would fall slightly.

Marginal rim: The marginal rims composed of micrographic intergrowth of olivine and clinopyroxene are conspicuous around the nodules from Aratoyama as stated in the foregoing section. These rims are considered to be the dissociation products of orthopyroxene through the process of the pressure release. Dissociation would take place at a shallower depth than 5—7 Kb.

The glassy part of the marginal rims will be ascribed to the process in which ultramafic nodules and megacrysts fall suddenly into melting condition by uprising of magma.

Conclusion

The crystallization process of the Aratoyama ultramafic nodules are summarized as follows:

The primary basaltic source melt would be produced in the depth deeper than 10 Kb. and shallower than 25—30 Kb. pressure depth. Forsteritic olivine, enstatite and diopside firstly crystallize to precipitate in the melt.

Owing to the precipitation of a large amount of olivine, the basaltic melt is comparatively condensed for aluminian component. Then the basaltic melt would give rise to aluminian bronzite and aluminian salite with a small amount of

olivine.

The chemical composition of primary basaltic melt would be tholeiitic or olivine tholeiitic. The fractionation trend of coexisting pyroxene pairs does not resemble to alkaline basaltic trend such as Black Jack sill (WILKINSON, 1957) or Garbh Eilean sill (MURRAY, 1954), but it is similar to the early stage of fractionation of the tholeiitic basaltic trend such as Skaergaard intrusion (BROWN, 1957) or Bushveld intrusion (ATKINS, 1969).

In the course of segregation of type A~ type C nodules, basaltic melt might change its chemical composition to alkaline olivine basalt. The crystallization of type A~ type C nodules would proceed under rather hydrated condition.

In the ascending process, basaltic melt might precipitate megacrystic pyroxenes through the decreasing water vapour.

The basaltic melt might change its chemical composition from alkaline olivine basaltic to basanitic one through the precipitation of aluminous pyroxenes. Rapid ascending of basaltic melt would take place at a slightly deeper place than 5—7 Kb. depth, and the marginal rim would be produced at a shallower place than 5—7 Kb. depth where orthopyroxene would melt incongruently into olivine and melt.

As shown in Table 9, the chemical composition of marginal rim is rich in CaO and low in SiO₂ in comparison with that of bronzite and suggests that the chemical reaction between pyroxene and magma would have occurred in the dissociation process of orthopyroxene.

As mentioned in mineralogy, clinopyroxene in the Nochi websterite is rich in CaTiAl₂O₆ and acmite molecules, and orthopyroxene is also rich in CaTiAl₂O₆ molecule. The websterite nodule from Nochi would be the early crystal cumulates from host alkaline basalt.

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吉備高原，アルカリ玄武岩に包有された超苦鉄岩ノジュールと巨晶輝石

田 崎 耕 市

(要 旨)

吉備高原，荒戸山の小ドームをなす，アルカリ玄武岩中には，種類の超苦鉄岩ノジュールと巨晶輝石が包有されている。

超苦鉄岩ノジュールは，カンラン石を多量にふくむタイプA（複輝石かんらん岩，斜方輝石かんらん岩，純かんらん岩），輝石を主としカンラン石をふくむタイプB，カンラン石をほとんど含まないタイプC（輝岩），単斜輝石巨晶のタイプD，斜方輝石巨晶のタイプE，にわけられる。

これらのノジュールから，カンラン石3ヶ，斜方輝石5ヶ，単斜輝石3ヶ，タイプBにおける反応縁1ヶを分離し，母岩のアルカリ玄武岩とともに化学分析をおこない，その成因について検討した。

カンラン石は， $Fe_{83} \sim Fe_{90}$ にわたって変化し，輝石類はタイプAからタイプCにかけ，斜方輝石が頑火輝石か

ら古銅輝石へ，単斜輝石は透輝石からサーラ輝石へと組成が変化する。

これらの造岩鉱物の平衡共存条件を検討した結果，タイプA～タイプCのノジュールは，ある種の玄武岩マグマ（カンラン石ソレアイト質）の高圧下における，早期晶出鉱物の一連の集積相をしめし，巨晶輝石は上記ノジュールより，浅い条件下で，水蒸気圧が減少する過程での晶出相をしめすものであろう，ということがわかった。

Aratoyama	荒戸山
Chugoku mountainousland	中国山地
Kibi plateau	吉備高原
Nochi	野馳（哲西）
Ni-iyama	新山
Yatomi-yama	弥富山