HORNBLENDE-RICH GABBRO-DIORITE SEQUENCE IN THE ŌURA IGNEOUS COMPLEX, MAIZURU CITY, JAPAN, PART I: A GENERATION OF LATE DIFFERENTIATES MIDWAY IN THE LAYERED SEQUENCE

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The Main Appinitic Sequence in the Ōura Igneous Complex of gravity stratiform mafic and ultramafic plutonites, is a lenticular body of hornblende-rich gabbroic and dioritic rocks with a small amount of leuco albite tonalite and covers stratigraphically from 2,500 to 3,500 m above the base of the 4,000 m thick sequence of cumulates. There is a gradual transition from plagioclase-clinopyroxene adcumulate to the rocks of the Main Appinitic Sequence showing characters of late differentiates of the Ōura magma.

The hornblende-rich rocks often contain appreciable amounts of earlier formed cumulus minerals and take their origin from mush after accumulation of crystals on the floor of the magma chamber: they are varieties of cumulate.

In formation of the Main Appinitic Sequence the liquid in the mush is trapped among the accumulated crystals; crystallization from the trapped liquid takes place at lower temperature than that in the formation of the cumulus minerals and, resorbing the accumulated minerals, produces the hornblende-rich rocks. Part of quartz-feldspathic fraction of the trapped magma is concentrated in fissures and pockets within the appinitic body and forms leuco albite tonalite.

INTRODUCTION

The Ōura Igneous Complex is a series of gravity stratiform mafic and ultramafic plutonites in northern Maizuru City and has an exposed area of about 23 km² (Agata, 1974).

An appinitic rock group including hornblendite, hornblende gabbro, and mela-

lbite diorite† sometimes with leuco albite tonalite occurs in layers and lenses at several horizons in the layered sequence of the Ōura Igneous Complex. These hornblendic rocks show characters of later crystallization products and are markedly different from the cumulate in the layered sequence. In the appinitic bodies hydrothermal mineral veinlets are spread out,

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† In this paper various kinds of hornblende-rich rocks in the Ōura Igneous Complex are named appinitic rocks. The Ōura appinitic rocks are different in rock association from those in other appinitic suites accompanying large amounts of granodioritic rocks. The Ōura hornblendic rocks, however, are petrographically similar to other appinitic rocks as described later, and then the term "appinitic" is here applied.

and an appreciable amount of copper sulfide concentration occurs in some net-work veins.

The Main Appinitic Sequence is a suite of gabbroic and dioritic varieties exposed over about 3.5 km² in the west of Ōyama (Fig. 1). It is lenticular and represents so far the largest body of appinitic rocks.

The appinitic rocks in the Ōura Igneous Complex are the unique late differentiates that do not occupy the top of the layered intrusion and do occur midway in the layered sequence. In the present paper the origins and genetical processes of hornblende-rich and related rocks are worked out. The next companion paper, "Hornblende-rich gabbro-diorite sequence, Part II", will cover mainly hydrothermal events accompanying the formation of appinitic and related rocks. The study in these papers might also furnish a key to solve the nature of some other hornblendic rocks, e.g. so-called "granitized gabbro", associated with large amounts of granodioritic rocks.

Originally a fortified port area, only a reconnaissance regional geology (Kochibe, 1894) was available until the end of World War II, and Hirokawa and Kuroda (1958) gave brief accounts of geology and petrography of the igneous rocks in the Ōura Peninsula. Through field and laboratory investigations I found out layered structures in them and worked out the nature of cumulates in the layered sequence (Agata, 1974). I also realized the iron enrichment in the fractionally crystallizing Ōura magma being exceptionally weak in contrast to the strongly iron-enriched trend reported in most other layered intrusions.

The southern and western margins of the Ōura Igneous Complex terminate against Paleozoic volcanic and sedimentary rocks;

the contacts appear to be tectonic and there is no trace of a chilled margin. In the northern part the complex is invaded by the Miyazu granite of Cretaceous age and to the east is covered with Tertiary sedimentary and volcanic rocks. On the basis of field relations, the complex is divided into two units: (1) the Mafic Unit comprising a sequence of gabbroic and pyroxenitic piles, about 4,000 m thick, and (2) the Ultramafic Unit composed of several bodies of dunite with a small amount of pyroxenite which intruded into the Mafic Unit as solid masses.

LAYERED SEQUENCE IN THE MAFIC UNIT

1. Sequence, rock types, and cumulus minerals

The layered features in the Mafic Unit are nearly vertical with EW trend, and gravity stratification indicates the sequence of the intrusion being upper toward the south. Three zones, subdivided by the entrance of essential minerals, are given with their spatial changes in Fig. 2; the Lower, the Middle, and the Upper Zone are 400, 3,500, and 100 m thick, respectively.

A major rock type in the layered sequence is of adcumulate. Equigranular cumulus minerals exhibit unzoned perieuhedral to anhedral crystals and show their well-developed mutual interference. Small amounts of intercumulus minerals are usually noticeable among the cumulus minerals.

The order in which the cumulus minerals appear in the layered sequence is clinopyroxene, plagioclase, and magnetite. The ratio of plagioclase to clinopyroxene in the Middle and Upper Zone is close to 1:1 by volume and magnetite content in the Upper Zone attains to 6%. Cryptic layering

is well-developed and shows a general trend from magnesian to iron-rich for clinopyroxene and from calcic to sodic for plagioclase upward in the layered sequence.

The amounts of intercumulus minerals in the Mafic Unit usually range by volume from 0.5 to 15% with an average of 4%.

on the polished specimens, but its concentration is generally less than 2%.

Apatite fills some interstices of the cumulus minerals at several horizons of the Middle and Upper Zone. Minute grains of orthopyroxene are observed in a few specimens. In a lower portion of the layered sequence chalcopyrite, pyrrhotite, cubanite, pentlandite and mackinawite are very common, but most of these sulfides are considered to be genetically related to a sulfide-rich rock series of harrisite, allivalite and eucrite cutting this portion of the Mafic Unit as net-work veins. (Agata, 1974).

The Mafic Unit was essentially formed by crystals accumulating on the floor of the magma chamber. The chemical composition of magma changed gradually under extreme fractionation conditions.

Interprecipitated ilmenite occurs at many horizons of the layered sequence. At several horizons ilmenite content is high enough for making up a thin layer traceable

The composition of magma at Horizon P, about 2,000 m high above the base, is

Table 1. Chemical analysis and mode of a pore material at Horizon P, Ōura Igneous Complex.

Mode, Vol. %	Analysis	Norm
Quartz	SiO ₂ 57.55	Q 8.02
Plagioclase	Al ₂ O ₃ 17.91	Or 0.67
Clinopyroxene	Fe ₂ O ₃ 2.11	Ab 39.41
Cummingtonite	FeO 7.36	An 27.57
Hornblende	MgO 3.10	Wo 0.59
Apatite	CaO 6.03	Di 0.24
Biotite	Na ₂ O 4.67	Fs 0.35
Ore	K ₂ O 0.11	Hy 7.48
Miscellaneous	H ₂ O ⁺ 0.20	Fs 10.88
	H ₂ O ⁻ 0.02	Mt 3.06
100.0	TiO ₂ 0.64	Il 1.21
	P ₂ O ₅ 0.17	Ap 0.39
	MnO 0.22	H ₂ O 0.22
	Total 100.11	Total 100.09

Sample No. TA70082307
(Loc. 1, 500 m northwest of Ōyama)

estimated from the composition of filter-pressed pore material forming thin layers within plagioclase-clinopyroxene adcumulate (Agata, 1974). It is similar to an andesitic composition, oversaturated in silica, rich in alumina and soda, moderate in iron, and poor in magnesia (Table 1).

The layered sequence contains no olivine and comprises the thick ultramafic piles in its lower portion, and the initial magma of the Mafic Unit is considered to be of a tholeiitic composition.

DESCRIPTION OF THE MAIN APPINITIC SEQUENCE

The Main Appinitic Sequence consists of various kinds of hornblende gabbro and mela albite diorite with a small amount of leuco albite tonalite. In the northern and southern margins of the Main Appinitic Sequence it joins with the layered sequence of the Mafic Unit, while at the western end it is terminated by a fault and in the east is overlain by Tertiary rocks (Fig. 1). The trend of this elongated appinitic sequence is concordant with that of layered structures, and within the layered sequence it covers from 2,500 to 3,500 m above the base of the Mafic Unit.

Because of poor exposures in the western half of the Main Appinitic Sequence, the present description is concentrated in the eastern portion.

1. Hornblende gabbro

A hornblende gabbro zone occupies a marginal portion of the Main Appinitic Sequence: it joins the plagioclase-clinopyroxene adcumulate sequence in its outer

Fig. 3 Generalized geological map of the eastern portion of the Main Appinitic Sequence.

margins and encloses mela albite diorite bodies (Figs. 1 and 3). In the northern part the hornblende gabbro zone measures 100 to 500 m in width and in the southern part below 20 m.

The joins of hornblende gabbro and cumulate represent their gradational zone, less than 5 m wide. In the joining cumulates intercumulus hornblende forms coronas around the earlier formed cumulus clinopyroxene crystals. With going to the hornblende gabbro zone, the coronas of hornblende increase gradually in amounts, and correspondingly clinopyroxene is sparser.

Brown to green pleochroic hornblende and calcic plagioclase are essential minerals in most hornblende gabbro and clinopyroxene an accessory. Ilmenite and apatite sometimes with quartz and zircon are sparingly present.

Hornblende usually ranges in amounts from 35 to 60% in the rocks by volume. Most hornblende grains are peri-euhedral to anhedral and measure 0.5 to 2.0 mm in size. They extend to interstices among the subhedral to anhedral plagioclase grains

and usually show mutual interference with them. In a few hand specimens the hornblende grain is enlarged to a poikilitic oikocryst and envelopes several plagioclase laths. N_z refractive indices and $2V_x$ range from 1.662 to 1.685 and 78 to 73°, respectively. Conspicuous zonal growth is observed in some of the crystals: brown hornblende is rimmed with greenish varieties. The hornblende crystals commonly contain sparse inclusions of ilmenite, 5 to 10 μ in diameter.

Clinopyroxene is preserved in the cores of hornblende crystals. The crystal boundaries of clinopyroxene exhibits a smooth peri-euhedral to anhedral outline and show characters of a resorption relation between them.

Plagioclase, ranging from 0.5 to 2.0 mm in size, is unzoned. The composition, estimated from optical properties, is generally An_{76} to An_{88} : it is nearly identical with the composition of cumulus plagioclase in the layered sequence at the horizon of the Main Appinitic Sequence.

Chemical analyses and modes of two specimens of hornblende gabbro are given in Tables 2 and 3, respectively.

2. Mela albite diorite

An extensive lenticular body of mela albite diorite is exposed within the eastern portion of the Main Appinitic Sequence (Figs. 1 and 3). On the geological map the northern boundary is nearly parallel to the trend of layered structures, while the southern border appears to be discordant with the stratiform sequence. Mela albite diorite consists predominantly of albite, hornblende and ilmenite. The ratio of albite to hornblende is usually close to 1:1 by volume and ilmenite content attains up to 4%.

Fig. 4 Plot of $2V$ against N_z for hornblende from the Mafic Unit, Ōura Igneous Complex.

Table 2. Chemical analyses of cumulate, appinitic and related rocks from the Ōura Igneous Complex.

	1	2	3	4	5	6
SiO ₂	46.54	44.63	45.06	51.06	51.99	77.01
Al ₂ O ₃	17.24	18.36	18.10	16.29	14.65	12.49
Fe ₂ O ₃	1.85	4.01	3.69	5.23	3.72	2.11
FeO	4.66	6.14	5.27	8.00	6.74	0.49
MgO	10.01	8.50	9.03	3.53	7.13	0.28
CaO	15.31	11.81	13.12	6.48	7.53	0.50
Na ₂ O	1.35	1.34	1.83	5.34	4.21	5.85
K ₂ O	0.12	0.15	0.13	0.29	0.20	0.60
H ₂ O ⁺	2.52	3.46	2.69	1.91	2.21	0.10
H ₂ O ⁻	0.27	1.26	0.26	0.31	0.81	0.32
TiO ₂	0.15	0.32	0.25	0.77	0.57	0.15
P ₂ O ₅	0.02	0.01	0.01	0.07	0.06	0.05
MnO	0.14	0.15	0.13	0.26	0.23	0.01
S	—	—	—	0.32	—	—
Total	100.20	100.14	99.57	99.86	100.05	99.96
Ca*	140	10	96	110	32	3
Ni*	104	170	41	30	46	8
Co*	51	47	60	36	39	2

Norms						
Q	—	—	—	—	—	39.34
Cor	—	—	—	—	—	1.45
Pl	Or	0.72	0.89	0.78	1.73	1.17
	Ab	11.43	11.33	15.47	45.21	35.61
	An	40.62	43.62	40.78	19.61	20.50
Di	Wo	14.72	6.23	10.12	5.03	6.89
	En	10.45	4.21	7.18	2.45	4.31
	Fs	2.98	1.53	2.09	2.49	2.14
Hy	En	0.44	11.78	0.68	3.43	12.69
	Fs	0.13	4.30	0.21	3.48	6.27
	Fe	9.84	3.63	10.26	2.05	0.55
Ol	Fa	3.10	1.47	3.20	2.30	0.31
	Mt	2.69	5.81	5.35	7.57	5.40
Hem	—	—	—	—	—	1.31
Il	0.29	0.61	0.47	1.46	1.08	0.28
Ap	0.04	0.03	0.02	0.16	0.13	0.13
Py	—	—	—	0.60	—	—
H ₂ O	2.79	4.72	2.95	2.22	3.02	0.42
Total	100.24	100.16	99.56	99.79	100.07	99.96
S. G.	—	—	2.89	2.89	2.91	2.63

* ppm.

1. Plagioclase-clinopyroxene adcumulate (TA69072904). Loc. 1,600 m north of Kawabeyuri.
2. Hornblende gabbro (TA69072522). Loc. 2,000 m west of Ōyama.
3. Hornblende gabbro (TA70081902). Loc. 600 m northwest of Ōyama.
4. Mela albite diorite (TA70081904). Loc. 800 m west of Ōyama.
5. Mela albite diorite (TA71111307). Loc. 150 m west of Ōyama.
6. Leuco albite tonalite (TA70082003). Loc. 1,100 m north of Tachio.

The mela albite diorite body contacts the hornblende gabbro zone in its outer margin, and a transitional zone, less than 5 m wide, occurs. Within the transitional zone sodic plagioclase and ilmenite join

Table 3. Modes of cumulate, appinitic and related rocks from the Ōura Igneous Complex, in volume %.

	1	2	3	4	5	6
Primary Minerals						
Quartz	—	—	—	trace	—	38.8
Plagioclase	43.3	39.3	57.1	55.0	47.3	58.1
Clinopyroxene	31.4	0.1	1.0	—	—	—
Hornblende	5.3	58.1	38.8	29.5	39.9	—
Ilmenite	—	—	trace	2.6	1.8	—
Apatite	—	—	trace	trace	trace	trace
Secondary Minerals						
Epidote	—	trace	1.3	5.8	2.8	trace
Plagioclase	—	0.1	1.2	—	1.0	—
Amphiboles	14.1	0.3	0.1	trace	trace	—
Vermiculite	—	—	—	0.3	3.9	1.8
Chlorite	5.9	2.1	—	6.3	3.3	—
Miscellaneous	—	—	0.5	0.5	—	1.3
Total	100.0	100.0	100.0	100.0	100.0	100.0

Numbers refer to those in Table 2.

hornblende as essential phases, with disappearance of calcic plagioclase: namely, albite rims envelope the pre-existing calcic plagioclase crystals, and ilmenite fills some interstices of the silicate minerals.

Several textural varieties of mela albite diorite are recognized. Most specimens exhibit an automorphic poikilitic texture. An oikocryst of hornblende, rarely of ilmenite, encloses and embays several plagioclase laths. In other cases the texture is xenomorphic granular: equigranular hornblende and plagioclase grains are perihedral to anhedral and show their mutual interference.

Hornblende, up to 5 mm across, is brown to green pleochroic. It often shows faint to well-developed zonal growth: a dark brown core is mantled with bluish green margins. *N_z* refractive indices and 2*V_x* range from 1.661 to 1.692 and 84 to 64°, respectively. The optical properties markedly vary among the specimens even within a 100 m² area, and in the southern portion of the mela albite diorite body the refractive index tends to be lower. EPMA (electron probe X-ray micro analyser) anal-

yses of hornblende from three hand specimens are given in Table 4.

Table 4. EPMA analyses of hornblende specimens from mela albite diorite in the Main Appinitic Sequence.

	1	2	3	4
SiO ₂	48.0	45.4	49.8	47.7
Al ₂ O ₃	7.02	8.08	4.93	7.54
TiO ₂	1.37	1.37	0.52	1.75
FeO*	16.4	20.2	14.9	13.6
MnO	0.39	0.42	0.33	0.34
MgO	11.1	9.82	14.6	14.8
CaO	11.2	10.7	11.8	11.3
Na ₂ O	0.86	0.88	1.09	1.20
K ₂ O	0.34	0.30	0.26	0.22
Total	96.7	97.2	98.2	98.5
Numbers of ions on the basis of 23 (O)				
Si	7.15	6.89	7.27	6.92
Al ^{IV}	0.85	1.11	0.73	1.08
Al ^{VI}	0.38	0.34	0.12	0.22
Ti	0.15	0.16	0.06	0.19
Fe	2.04	2.56	1.82	1.65
Mn	0.05	0.05	0.04	0.04
Mg	2.47	2.22	3.18	3.20
Ca	1.79	1.74	1.85	1.76
Na	0.24	0.26	0.31	0.34
K	0.05	0.06	0.05	0.04
2V _x	76°	64°	—	71°
N _x	1.678	1.685	—	1.685
N _y	1.667	1.676	—	1.677
N _z	1.654	1.658	—	1.656

* Total Fe as FeO

1. Green hornblende from 150 m west of Ōyama (TA71111307).
2. Brownish green hornblende from 800 m west of Ōyama (TA70081904).
3. Greenish margin of a hornblende crystal from 750 m west of Ōyama (TA72090407).
4. Brownish core of a hornblende crystal from 750 m west of Ōyama (TA72090407).

In a few specimens cummingtonite ($2V_z = 88^\circ$, $N_x = 1.661$, $N_y = 1.678$, $N_z = 1.684$; Mg: Fe = 41:59) is present, and its content attains up to 30% by volume. Cummingtonite is usually mantled with hornblende and rarely occurs in discrete grains.

A small amount of clinopyroxene is often observed in the cores of hornblende crystals. These clinopyroxene grains are enclosed, resorbed, and often separated into islands. The composition of relict clinopyroxene is $Wo_{43}En_{37}Fs_{20}$, and the composition is identical with that of cumulus

clinopyroxene at the same horizon with that of the Main Appinitic Sequence.

Plagioclase in the poikilitic mela albite diorite is not equigranular: the size of larger grains ranges from 1.0 to 2.0 mm, and the smaller grains measure about 0.5 mm. Plagioclase in the granular mela albite diorite averages 1.5 mm in size. The composition of plagioclase from optical properties is An_4 to An_7 , but more calcic plagioclase (An_{10-48}) is locally present. The appearance of andesine and calcic oligoclase is restricted only in the cummingtonite-rich specimens. By the (201) spacing, Or in albite is lower than 5 mole % (Bowen and Tuttle, 1950). From the optical properties and the 2θ ($\bar{1}31$)–(131) (Smith and Yoder, 1956), it is of the low temperature type.

The impersistent calcic plagioclase core, often feebly clouded, sometimes occurs within the albite crystals. The composition of the mantled feldspar ranges from An_{63} to An_{88} in the mela albite diorite body, but labradorite is uncommon. The most calcic composition is identical with that of cumulus plagioclase stratigraphically 3,000 m high in the layered sequence (Fig. 2).

Ilmenite exhibits an anhedral crystal and fills interstices among the silicate minerals. The interstitial mineral sometimes contains sparse minute inclusions of hematite, and it dissolves about 10% pyrophanite molecule (Table 5). Magnetite comprises an essential constituent in a central portion of the mela albite diorite body and occurs as an interstitial mineral. It is intergrown with ilmenite, and in the exolved crystals minute hematite is sparsely disseminated.

Apatite and zircon are ubiquitous constituents but in small amounts. Interstitial quartz rarely occurs in an appreciable amount. Globular grains of chalcophyrite

Table 5. EPMA analyses of ilmenite specimens from mela albite diorite in the Main Appinitic Sequence.

	1	2	3
SiO ₂	0.72	0.06	0.17
TiO ₂	50.1	50.1	52.6
Al ₂ O ₃	0.81	0.02	0.02
FeO	42.5	44.3	40.6
MnO	4.49	4.05	5.67
MgO	0.14	nd	0.03
CaO	0.03	0.12	0.14
Total	98.6	98.7	99.2
Numbers of ions on the basis of 6 (O)			
Si	0.04	—	0.01
Ti	1.92	1.94	2.09
Al	0.05	—	—
Fe	1.81	1.91	1.79
Mn	0.19	2.01	0.16
Mg	0.01	—	—
Ca	—	0.01	0.01

* Total Fe as FeO

1. Loc. 150 m west of Ōyama. Sample No. TA7111307.

2. Loc. 800 m west of Ōyama. Sample No. TA70081904.

3. Loc. 750 m west of Ōyama. Sample No. TA72090407.

and pyrite, below 5 μ across, are sparingly present.

3. Leuco albite tonalite

Numerous bodies of leuco albite tonalite including irregular dikes, veins, and blebs scatter within the mela albite diorite body (Fig. 3). They range from 0.1 to 30 m in size and comprise less than 5 vol. % of the mela albite diorite body. In the field the quartz-feldspathic rock appears to clean-cut the adjacent mafic rock. However, the immediate contacts exhibit a concentration of albite and the albite grains at the boundaries are shared among the mafic and the silicic rock: in the melanocratic side they are embayed by poikilitic hornblende, while in the leucocratic part quartz fills interstices among the same plagioclase grains.

Leuco albite tonalite is nearly uniform in mineralogy throughout the individual bodies. It consists almost entirely of quartz and plagioclase. The ratio of plagioclase to quartz is close to 2:1 by volume.

The composition of plagioclase is soda-rich (An_{2-4}) and the albite is often rimmed with more sodic plagioclase (An_{0-2}). Or content from measurements of the $(\bar{2}01)$ spacing is less than 5 mole %. Optical and X-ray diffraction characteristics show that albite is close to the low temperature variety. Apatite, zircon, ilmenite and hornblende are also present in trace amounts. Leuco albite tonalite exhibits a hypautomorphic granular texture, which is sometimes modified by serrated grain boundaries and granophyric intergrowth of quartz and plagioclase.

DISCUSSION

1. General

The Main Appinitic Sequence in the Ōura Igneous Complex obviously is not a separate body which intruded into the Mafic Unit. In and near the Main Appinitic Sequence there is no evidence suggesting the presence of any late intrusive rocks that might have provided a hornblende-rich sequence produced by thermal metamorphism of mafic rocks. Presumably, the appinitic and related rocks are late differentiates crystallized from the Ōura magma. The presence of magnetite-ilmenite intergrowth may also imply that the mela albite diorite is igneous in origin.

The mela albite diorite in the Ōura Igneous Complex is similar to the appinite to appinitic diorite in the Scottish Highland (Anderson, 1935, 1937; Nockolds, 1941; Bailey, 1960): in both cases brown to green hornblende and sodic plagioclase are predominant, and clinopyroxene often an accessory. Unlike most appinites in Scotland the Ōura hornblendic rocks are not associated with kentallenite and grano-diorite, and do occur within the layered

intrusion. Read (1961) had an opinion that appinites take their origin from ultramafic magma or solid ultramafic rocks mixing with granitic magma. Nockolds and Mitchell (1949) thought that the hornblende-rich rocks are derived from a relatively silicic magma by crystallization and accumulation of mafic or ultramafic material, followed by hybridization of the ferromagnesian differentiates and the residual liquid. Another genetical hypothesis was suggested by Joplin (1959) that appinitic rocks are produced by contact metamorphism and hybridization of mafic rocks accompanying later intrusion of granitic magma.

2. Origin and genetical processes of the appinitic and related rocks

Unlike most silicic and intermediate rocks in other layered intrusions—granophyre in the Skaergaard intrusion (Wager and Deer, 1939), granite and melanodiorite in the Guadalupe igneous complex (Best, 1963), the Bushveld granite (Willemse, 1969), and granite and diorite in the Insch layered intrusion (Wadsworth, 1970)—the Ōura appinitic and related rocks never occupy the top of the layered intrusion; they are not formed simply by the gravitational fractionation of magma. The causes of formation of the Main Appinitic Sequence could be worked out only in the course of interpreting the processes of solidification of cumulates. Some of these processes will be discussed first and will be followed by an interpretation of the actual formation of the Main Appinitic Sequence.

(1) Solidification processes of cumulates and rate of accumulation of crystals

Accumulating crystals in the magma chamber form a layer of crystal mush on the floor. To estimate the porosity of the

mush, it is necessary to examine rocks comprising euhedral cumulus minerals not enlarged by crystallization from the pore space liquid in the mush (Jackson, 1961). Inasmuch as the cumulus minerals are perieuhedral to anhedral and show their mutual interference, all the specimens from the Ōura Igneous Complex are disqualified for this examination. The available specimen of a qualified rock is a chromite heteradcumulate from the Dwarze River Bridge, Bushveld Igneous Complex (sample No.=KS-70030818). Modes of occurrence of this chromitite were given by Suwa (1973; 1977), and Suwa and Suzuki (1977). In this specimen euhedral cumulus chromite makes up 49% of the rock by volume, and the remainder comprises interstitial plagioclase, orthopyroxene, clinopyroxene, and chromian phlogopite. Presumably, the mush originally contained about 50% liquid. The similar value was estimated also in the Skaergaard intrusion (Wager, 1969).

The amounts of intercumulus minerals in the Ōura cumulates are usually below 10 vol. %; hence, the major effect of the crystallizing pore space liquid was on growth of accumulated crystals. The lack of conspicuous zoning in the cumulus minerals suggests that they grew nearly at the same temperature with that in their generation. To explain the same temperature growth, Hess (1960) employed mechanism of diffusion from the pore space liquid in the mush layer to the overlying main mass of magma. With the heat loss necessitated for the post-depositional growth, Wager (1963) suggested super-cooling of convecting magma which sweeps over the top of piles.

Primo-crystals of cumulus minerals were formed as the result of heat loss from the top of the magma chamber, and then they accumulated on the floor. The ini-

tial interstitial liquid of mush has the chemical composition of the contemporary main magma, and crystallization from the interstitial liquid is brought about by heat loss from the bottom of the magma chamber and by super-cooling of the circulated magma sweeping over the top of the mush layer; growth of the accumulated primo-crystals comes out. A little enlargement of the accumulated minerals reduces the concentrations of their components in the interstitial liquid: a compositional gradient from the interstitial liquid to the overlying main mass of magma is set up. Then, diffusion between them takes place, and the interstitial liquid gets back to the composition of the contemporary magma. So long as diffusion remains rapid, this differential cycle may turn and turn about until the cumulus minerals grow to fill the entire space of the mush. Inasmuch as the chemical composition of the liquid in equilibrium with minerals remains constant, the temperature in the growth of the accumulated crystals is held also constant; their unzoned postdepositional growth results.

In the Ōura cumulates the intercumulus phases comprise hornblende, sometimes ilmenite, and rarely apatite; other minerals forming at lower temperatures are absent. The formation of intercumulus minerals crystallizing from the pore space liquid of the mush would occur under environments of slow diffusion as following manners.

In cementing the mush, slow diffusion changes the chemical composition of the interstitial liquid with growing the accumulated minerals. Crystallization from the interstitial liquid takes place at lower temperature than does the postdepositional growth, and a new phase or phases appear among the accumulated minerals. Inter-precipitation of the newly entered minerals

goes on and forms intercumulus materials; the residual pore space liquid is eliminated into the overlying magma.

Generally, the effectiveness of diffusion is correlated with the rate of accumulation of crystals in the magma chamber (Hess, 1960). Where accumulation of crystals is slow, diffusion is so effective; in the case of rapid accumulation most of the interstitial liquid is trapped among the accumulated crystals and crystallizes later.

In formation of the layered sequence of the Ōura Igneous Complex, accumulation of crystals is considered to have kept slow, and the cementation of cumulates would occur near the top of the piles where diffusion is effective.

(2) Formation of the Main Appinitic Sequence

Clinopyroxene and calcic plagioclase present in the Main Appinitic Sequence apparently are cumulus minerals, and the appinitic rocks took their origin from mush after accumulation of crystals. Hornblende, sodic plagioclase, ilmenite, quartz, and other lesser minerals are looked upon as intercumulus materials. The texture and mineralogy suggest that a resorption of accumulated minerals occurred in forming hornblende gabbro and mela albite diorite. The reaction between cumulus minerals and the pore space liquid has been recognized by many authors (Hess, 1960; Jackson, 1961; Coertze, 1970; Agata, 1974).

(a) Hornblende gabbro

The composition and texture of plagioclase in hornblende gabbro suggest that its crystals, originally euhedral, grew in the same manners with those of adcumulate in the layered sequence. With the accumulated clinopyroxene, significant enlargement did not take place. In formation of hornblende gabbro diffusion from the pore space

liquid to the main magma is interpreted to be not rapid, and a considerable rapid accumulation of crystals is brought forward. In view of reaction relation between hornblende and clinopyroxene (Holloway and Burnham, 1972; Eggler, 1972), the resorbing hornblende is considered to be a reaction product between cumulus clinopyroxene and the interstitial liquid.

A considerable rapid accumulation of crystals provides a high compositional gradient in the sequence of liquid in the mush layer. The temperature of the crystallizing pore space liquid drops gradually toward the bottom mush. The accumulated plagioclase grows near the top of the mush, where diffusion is very effective, at the same temperature with its generation. In a lower portion the effectiveness of diffusion is comparatively low, and hornblende forms in and around the accumulated clinopyroxene crystals; and the liquid also precipitates hornblende among the crystals. Scarce enlargement of clinopyroxene permits the porosity of the mush to be high, and the reaction with a volume increase proceeds, to form a replacement of hornblende after clinopyroxene. Even at the bottom of the mush layer diffusion fairly restores the composition of the pore space liquid, and the crystallization of hornblende continues until the entire space is filled up; the residual liquid diffuses upward to the overlying magma. Thus, hornblende gabbro would form within the layered sequence.

(b) Mela albite diorite

The exalted reaction of liquid at the expense of all the accumulated minerals is recognized in mela albite diorite, and it contains much later crystallization products than does hornblende gabbro. These suggest that most of the pore space liquid is

trapped among the accumulated crystals in forming mela albite diorite; the rate of accumulation of crystals may be high enough not to permit postdepositional growth of the cumulus minerals. In the magma chamber a rapid accumulation of crystals on a part of the floor piles up the deposit higher than the other contemporary horizon and forms a mountain-shaped heap of crystals. The southern boundaries of the mela albite diorite bodies on the geological map (Fig. 1) may represent an outline of the mountain-shaped heaps on the floor. The presence of adcumulate above the Main Appinitic Sequence indicates that the trapped liquid in the heaps, crystallizing later, was left in lenses of mush within solid cumulate.

With temperature dropping in the lenses of mush, the reaction between the cumulus minerals and the pore space liquid takes place and produces hornblende and sodic plagioclase. Concurrently, the trapped liquid precipitates hornblende, sodic plagioclase, ilmenite, magnetite, apatite, and zircon in the pore space among the crystals. This crystallization process may account for the generation of mela albite diorite midway in the layered sequence.

(c) Leuco albite tonalite

Leuco albite tonalite apparently has an intimate genetical relation with mela albite diorite, and it contains later crystallization products. In leuco albite tonalite there is no evidence suggesting the pre-existence of any accumulated minerals; it formed in fissures in the mela albite diorite bodies. The immediate contact relations suggest that the magma forming leuco albite tonalite affected mela albite diorite in its invasion and was not a simply differentiated one.

Natural convection may occur in porous

media. Hess (1972) calculated the Rayleigh number in the liquid of mush after accumulation of crystals in the magma chamber and proposed that composition-driven convection may occur. In the Main Appinitic Sequence the marked areal variation of refractive index of hornblende indicates that the chemical composition of the interstitial liquid forming mela albite diorite varied unsteadily from place to place, and suggests that the conditions of liquid were mechanically unstable.

In view of each reaction relation between minerals in forming mela albite diorite, the initial ratio of nucleus number of sodic plagioclase to hornblende is estimated from the numbers of the cumulus calcic plagioclase and the clinopyroxene grains in the cumulate, and the measured value is 1:1. On the other hand, the actual grain number of sodic plagioclase in mela albite diorite attains to twenty fold that of hornblende; a single hornblende crystal would resorb several cumulus clinopyroxene grains. This suggests that hornblende in the interstitial liquid is difficult to form nuclei.

In the mush forming mela albite diorite, fissuring occurred and numerous small bodies, filled with the interstitial liquid at their positions, were formed. In these small bodies precipitation of plagioclase occurs, but the liquid super-cools upon hornblende because of the difficulty of its nucleation. Now, consider composition-driven convection to occur in the sequence of interstitial liquid. Convection takes away the super-cooled liquid in the fissures and puts the new liquid in; the removed oversaturated magma crystallizes hornblende in the forming mela albite diorite body. This process may continue until mela albite diorite cements, and horn-

blende may rarely crystallize in the fissures. On the other hand, with mela albite diorite solidifying, convection currents concentrate later crystallization components of the trapped liquid into the fissures. Thus, the leuco albite tonalite composition would be led into the fissures within the mela albite diorite body.

CONCLUSION

The appinitic rocks in the Ōura Igneous Complex are varieties of cumulate. The Ōura magma, varying in composition from basalt to andesite, precipitated clinopyroxene and calcic plagioclase and formed adcumulate at low rates of accumulation of crystals. A rapid accumulation of crystals permits that the liquid is trapped among the accumulated crystals. With temperature dropping, reaction between the trapped liquid and the cumulus minerals takes place and produces mela albite diorite midway in the layered sequence. Leuco albite tonalite within the mela albite diorite body may be attributed to a late differentiate of the trapped magma. In the case of a considerably rapid accumulation, the effect of the liquid among the accumulated crystals contributes only to the adcumulus growth of plagioclase and the formation of hornblende; hornblende gabbro results.

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舞鶴市，大浦火成複合岩体中の角閃石はんれい岩-閃緑岩岩体

その 1： 層状貫入岩体中位の層準での末期分化物の生成

縣 孝 之

層状苦鉄質岩からなる大浦火成複合岩体中のアピン岩質岩体は角閃石に富むはんれい岩，優黒質閃緑岩で主に構成され，少量の優白質トータル岩を伴い，層状貫入岩体の中位の層準に約 3.5 km² にわたって産する。この岩体の構成岩石は層状貫入岩体の斜長石-単斜輝石付加集積岩から漸移し，大浦マグマの末期分化物とみなされる一方，アピン岩質岩石は集積鉱物をしばしば含有し，マグマ溜りの床に鉱物が沈積してできるクリスタル・マッシュから生成したもの，すなわち集積岩であると考えられる。アピン岩質岩体の形成はマッシュ中の間隙液が沈積結晶間にトラップされた結果と解釈され，この間隙液からの鉱物の晶出是集積鉱物の生成時よりも低温で起こり，集積鉱物は融食され，角閃石に富む岩石がつくられる。またトラップされたマグマの石英，長石成分の一部はアピン岩質岩体中の割れ目に濃集し，優白質トータル岩が生成したとみなされる。