OLIVINE WITH WELL-DEVELOPED CLEAVAGES—ITS GEOLOGICAL AND MINERALOGICAL MEANINGS

YOSHIMASU KURODA* and SUSUMU SHIMODA*

(Received January 26, 1967)

I. INTRODUCTION

Olivine commonly has no well-developed cleavage. WINCHEL and WINCHEL (1951) describe "distinct 010 and less distinct 100 cleavages", and DEER, HOWIE and ZUSSMAN (1962) "(010), (100) imperfect cleavages". Generally, it has been considered that olivine is short prismatic or rounded crystal without perfect cleavages.

From the Kômorî(Ôeyama) ultrabasic rock mass of Kyôto prefecture, we reported olivine with well-developed cleavages parallel to (100), (010) and (001), resembling in appearance to pyroxene(KURODA, OGURA and SHIMODA 1964). Since then we have found the other occurrences of the cleavable olivine in two ultrabasic masses, Izushi and Sekinomiya masses(Fig. 1). Moreover, in 1966, KURODA and MATSUHISA found similar cleavable olivine from the Happo-One ultrabasic mass, which is located within the Hida marginal structural belt. For the present, in Japanese Islands, the cleavable olivine bearing ultrabasic masses are restricted to the northern side of the Maizuru structural belt and the Hida marginal structural belt.

In northern California, USA, HAWKES(1946) reported olivine with remarkably well-developed cleavages parallel to (010) and (100). In the photographs the Californian cleavable olivine is very similar to the Japanese ones. In USSR, too, several ultrabasic masses containing the cleavable olivine have been found(RUDNIK and DOBRETSUOV, personal communications).

Besides these occurrences, there are some reports on the well-developed cleavages of olivine; for example, in kimberlite(NIXON *et al.* 1963) and in achondrite (VINOGRADOV and VDOVYKIN 1963).

Olivine is possibly the most important mineral of the Upper Mantle, and many experimental and theoretical works such as the phase transition of olivine $\rightleftharpoons$ spinel have been done. However, it seems that detailed mineralogical and petrological investigation of olivine itself is scarce. We hope that this paper would stimulate and promote the study of olivine itself.

ACKNOWLEDGEMENTS. Dr. M. GORAI and Dr. T. SUDO gave us many valuable suggestions and criticisms. This is a part of the project of P. R. G. (Plutonism Research Group). Members of P. R. G. and Dr. Y. OGURA kindly helped us. Mr. Y. MATSUHISA worked with us in his graduation thesis of the Tokyo University of Education, 1967. We would like to express our thanks to Dr. S. AKIMOTO for supplying synthetic olivine powders. The expense of this study was partly defrayed by UMP (Upper Mantle Project) and Scientific Fund of Ministry of Education.

II. LOCALITIES AND OCCURRENCES OF THE OLIVINE WITH WELL-DEVELOPED CLEAVAGES

1. Japanese ultrabasic masses

As shown in Fig. 1, the ultrabasic masses, from which the cleavable olivine was found, are distributed along the Maizuru structural belt and the Hida marginal structural belt. The Maizuru structural belt divides the Inner zone of South-West Japan into the Sangun zone and the Tanba zone. The belt is made up of

Fig. 1. Locality of large ultrabasic masses along the Maizuru structural belt and Hida marginal structural belt.

I : Itoigawa-Shizuoka line, II : Hida marginal structural belt, III : Maizuru structural belt, Ko : Kotaki, A : Asahidake, H : Happo-Oné, O : Ohshima, K : Kômorî(Ôeyama), Iz : Izushi, S : Sekinomiya, W : Wakasa.

* Geological and Mineralogical Institute, Tokyo University of Education.

JOURNAL OF THE GEOLOGICAL SOCIETY OF JAPAN,
Vol. 73, No. 8, p. 377-388, AUGUST 1967.

various igneous rocks ranging from ultrabasic to acidic rocks and weakly metamorphosed Paleozoic sediments. On the northern side of this belt there are four large ultrabasic masses: from east to west, Kômorî(Ôeyama), Izushi, Sekinomiya and Wakasa masses. All the masses include the cleavable olivine bearing dunite, though from the Wakasa mass area we have found only two small boulders of this kind of rocks, but not the actual exposure.

Within the Maizuru structural belt there is only one large ultrabasic mass named Ohshima, which does not contain cleavable olivine.

The age of intrusion of these ultrabasic masses may be Triassic-Jurassic(IGI and KURODA 1965).

The Hida marginal structural belt may be similar to the Maizuru structural belt in respect to their structural geology. In this belt there is a large ultrabasic mass named Happo-Oné mass which contain the cleavable olivine.

It is noteworthy that the cleavable olivine bearing ultrabasic masses mentioned above are comparatively large and occupy in the peculiar position in the geology of Japan.

i) Kômorî(Ôeyama) mass

This mass consists of serpentinized dunite and a small amount of amphibolized clinopyroxenite. Besides these, very small amounts of harzburgitic peridotite, gabbro-diabase, rodingite, albitophyre, zoisite-mica rock (KURODA *et al.* 1964) etc. are found. In the dunite, pentlandite bearing chalcopyrite(-cubanite)-pyrrhotite deposit occurs.

The dunite is classified into two kinds: primary dunite of southern part and metamorphosed dunite of northern part(Fig. 2). It is clearly recognized under

Fig. 2. Geological map of the Kômorî mass (After KURODA, OGURA and SHIMODA unpublished).

1 : primary dunite, 2 : metamorphosed dunite, 3 : clinopyroxenite, 4 : Paleozoics, 5 : granite.

the microscope that the metamorphosed dunite was formed by recrystallization of the primary dunite (KURODA, OGURA and SHIMODA unpublished). The boundary between the primary and metamorphosed dunites is gradual in several meters or several 10 meters width. The recrystallization seems to have been taken place in the contact aureole, probably under the condition of the amphibolite or epidote-amphibolite facies, by the younger granite.

The primary dunite consists mainly of cleavable olivine and serpentine minerals(mainly antigorite, crysotile and lizardite, rarely chlorite and brucite), and magnetite is an accessory mineral. Rarely minute fibrous crystal of clinopyroxene and small rounded crystal of carbonate(mainly calcite) are found. Talc and tremolite are negligible found, but near the ore deposit the former is plentiful. Chemical composition of the primary dunite is rather magnesian: $100 \times \text{MgO} / (\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3)$, 83—85. Serpentinization is generally strong. In various parts of the area of the primary dunite completely serpentinized dunite without relic cleavable olivine is found, but judging from the texture the rock seems to have been serpentinized from the primary dunite.

The metamorphosed dunite consists mainly of rounded olivine such as those of the ordinary peridotite and serpentine minerals(crysotile, antigorite and lizardite; chlorite and brucite absent). Magnetite is an accessory mineral. Besides these talc and tremolite are commonly found in small amounts. Carbonate is commonly present. Chemical composition of the rock is very similar to that of the primary dunite: $100 \times \text{MgO} / (\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3)$, 82—83. Serpentinization is not so strong as in the case of the primary dunite.

It must be mentioned that small lenses(several meters to several 10 meters in width) of harzburgitic peridotite occur in the area of the primary dunite. The rock is composed mainly of common olivine without remarkable cleavages, orthopyroxene with exsolution lamellae and serpentine minerals(crysotile and antigorite). Besides these, chromite, which is never found in the primary and metamorphosed dunites, and clinopyroxene are found. Chemical composition of the harzburgitic peridotite is similar to that of the primary dunite: $100 \times \text{MgO} / (\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3)$, 83—84. The reason, by which the cleavable olivine does not occur in the harzburgitic peridotite in spite of its location in the area of the primary dunite, seems that the origin of the peridotite is different from that of the primary dunite.

ii) Izushi mass

This mass, located at 5 km east of Izushi town, is wholly surrounded by the Cretaceous granite and quartz-porphyry. Although the detailed study on this

Fig. 3. Geological map of the Izushi mass (modified from Geological Map of Hyôgo Prefecture 1961).

1 : primary dunite, 2 : metamorphosed dunite, 3 : granite, 4 : quartz-porphphy.

mass is now in progress, it has been clarified that in the central part of the mass there is a small area of the primary dunite containing the cleavable olivine comparable with that of the Kôtori mass. The main part of the mass is composed of metamorphosed dunite similar to that of the Kôtori mass (Fig. 3). The primary dunite seems to be preserved, because the central part of the mass may have not been affected by the thermal metamorphism of the later granite.

The petrographical features under the microscope of the primary dunite and the metamorphosed dunite of this mass are similar to those of the Kôtori mass.

iii) Sekinomiya mass

This large mass is located at the west of Yôka town. The northern part of the mass is covered by Miocene formation, and to the south and west it is bordered by the Yakuno intrusives, Paleozoic sediments and Sangun metamorphic rocks (Fig. 4). The preliminary survey

by HIRANO and KURODA revealed the small amount of the dunite including the cleavable olivine in the central part of the mass, but almost all parts of the mass seem to be composed of metamorphosed dunite. The petrography of these primary and metamorphosed dunite is also similar to those of the Kôtori mass.

iv) Happoné mass

The mass is located at 5–10 km southeast of Mt. Shirouma. This is a fairly large mass elongated in NE–SW direction. It is bordered on the west by the crystalline schists and by the Paleozoics. The latter are metamorphosed into various hornfelses such as cordierite-biotite rock. On the east the mass is bordered by Mesozoics with fault. To the south it is intruded by granite (Fig. 5)*. The age of the intrusion of the ultrabasic rock mass is not yet cleared up, but probably close to that of the intrusion of the ultrabasic masses on the northern side of the Maizuru structural belt. The rocks of the Happoné mass are also classified into two kinds; primary dunite and metamorphosed dunite. In petrography, they are similar to those of the Kôtori mass, respectively, but in the metamorphosed dunite of this mass there is a kind of rock so sheared and recrystallized, in which recrystallized olivine forms streaks. The metamorphism of the primary dunite may have been caused mainly by the intrusion of the Cretaceous granite.

Constituents minerals of the primary dunite and the metamorphosed dunite are the same as those of the Kôtori mass, and chemical compositions are also similarly magnesian.

v) Summary

1. Occurrence of the cleavable olivine bearing ultrabasic rocks is restricted to the northern side of the Maizuru structural belt and a part of the Hida marginal

Fig. 4. Geological map of the Sekinomiya mass (modified from Geological Map of Hyôgo Prefecture 1961).

1 : primary dunite, 2 : metamorphosed dunite, 3 : Yakuno intrusive rocks and Paleozoics, 4 : Sangun metamorphic rocks, 5 : Tertiary formation, 6 : andesite, 7 : acidic intrusive rock.

* The detailed investigation on geology and petrography of the mass will be published by MATSUHISA.

Fig. 5. Geological map of the Happo-Oné mass (After MATSUHISA unpublished.)

1 : Primary dunite, 2 : metamorphosed dunite, 3 : crystalline schists, 4 : hornfels from Paleozoics, 5 : Mesozoics, 6 : granite, 7 : andesite-dacite.

structural belt. Both belts occupy the peculiar situation in the geology of Japan.

2. The cleavable olivine occurs only in the central and unaffected(non-metamorphosed) part of the comparatively large masses in these belts*.

3. Two kinds of dunite are classified: primary dunite containing the cleavable olivine and metamorphosed dunite with ordinary olivine.

4. The metamorphosed dunite would have been made through the recrystallization of the primary dunite.

5. In conclusion the primary dunite seems to be a relict rock in these ultrabasic masses. According to the degree of the later modification it persisted in large scale in some masses and in small scale in another.

2. Another examples.

i) Northern California.

HAWKES(1946) reported olivine showing perfect cleavages on the (010) and (001) crystal planes from a dunite near Dunsmuir, Siskiyou County, California. As shown in Fig. 6, it is a very large mass; several times in area as those in Japan. This mass consists of ultra-

* The thermal effect may have not been caused only by granite intrusion, but it is possible that some geological factors played their role in the course of intrusion of the ultrabasic masses.

basic and basic rocks, and intruded into Paleozoic sediments and the age of intrusion is considered to be Jurassic(STRAND 1963).*

HAWKES states "Although part of the dunite of the Little Castle Creek is composed of olivine that shows very conspicuous cleavages, a large part is also made up of normal olivine". This description suggests that the cleavable olivine bearing dunite may be the relict rock similar to the primary dunite in the Japanese masses, though unfortunately the detailed geological description is not given.

ii) Olivine in kimberlite.

NIXON *et al.* (1963) reported the euhedral crystals of olivine, up to 2 mm long, partially serpentinized, showing conspicuous (001) parting, from kimberlite of Molatoli, South Africa. They mentioned "well cleaved olivine" grains in the ultrabasic nodules in the kimberlite of Thabaputosa, too. But most of the olivine phenocrysts in kimberlite are considered to have been derived probably from ultrabasic nodule by fragmentation and show similar appearance to common olivine in common peridotite.

In the book on diamond deposits of Siberia BOBRIEVICH *et al.* (1959) described the chemical and physical data on olivine included in kimberlite, peridotite nodule and diamond crystals, but they do not mention cleavable olivine.

A few olivine crystals in kimberlite or in peridotite nodule of kimberlite show well-developed cleavages or parting.

iii) Olivine in meteorites.

VINOGRADOV and VDOVYKIN(1963) discovered diamond in the ureilites, a kind of achondrites, from New Urei and Goalpara. In this paper they presented the photograph of olivine showing distinct cleavages or partings intersecting at a right angle. This photograph looks just like pyroxene. They did not discuss on these cleavages, probably because their attention might be attributed to confirm the presence of diamond.

In the thin sections of the Kesen, Mino and Sasagase chondrites**, olivine with well-developed cleavages or partings is not found, though the Mino chondrite several grains of olivine showing slightly developed partings.

Thus, it may also be considered that a few olivine crystals in meteorites show the well-developed cleavages.

III. MINERALOGY OF OLIVINE WITH WELL DEVELOPED CLEAVAGES

1. Cleavages

* We wish to express our thanks to Dr. R. G. COLEMAN for his help in getting the map.

** Dr. M. GORAI kindly permitted to examine the thin sections.

Fig. 6. Geological map of the ultrabasic mass near Dunsmuir, northern California (After R. F. Strand 1963)

1 : ultrabasic rock, 2 : basic rocks, 3 : granitic rocks, 4 : pre-Silurian metamorphic rock, 5 : Silurian and Ordovician, 6 : Devonian and pre-Devonian meta-volcanics, 7 : Tertiary and Quaternary, C : Little Castle Creek Canyon from where cleavable olivine was found by Hawkes.

Fig. 7. Microscopic photographs of thin sections of the cleavable olivine (Kômorî mass). single nicol, about $\times 160$. right; longitudinal parallel to (010), lateral to (100), left; longitudinal parallel to (100), lateral (001).

Typical feature of the cleavable olivine is shown in Fig. 7. The perfect cleavages are parallel to (100), (010) and (001), and along the cleavages serpentinization commonly occurs. On hand specimens or outcrop surface the rock containing the olivine with well-developed cleavages gives a sparkling appearance similar to that of pyroxenite.

There are slight differences between the degrees of developments of these cleavages parallel to (100), (010) and (001); the most strongest cleavage is generally parallel to (010). The cleavages parallel to (100) and (001) are also completely distinct as shown in Fig. 7. The degrees of cleavage developments parallel to (100) and (001) are nearly the same, though that parallel to (100) seems to be rather stronger. In some case cleavage parallel to (100) is the strongest in one grain but in another grain that parallel to (001) is the strongest. Anyhow, the differences between the degrees of developments of three cleavages are very small.

In some grains distinct parting probably parallel to (110) can be seen, and along that serpentinization also takes place.

Sometimes deformed cleavages such as those shown in Fig. 8 can be seen as in the case reported by HAWKES (1946). Although we did not make the exact analysis olivine fabric, there would be the concentration of *a*-axis of crystals to the lineation of the rocks.

Even in entirely serpentinized dunite pre-existed cleavable olivine can be recognized by the relic texture.

Fig. 8. Microscopic photograph of thin section of olivines showing deformed cleavages (Kômorî mass). single nicol, about $\times 160$.

HAWKES (1946) described the conspicuous cleavages on the (010) and (100) planes of olivine. The photograph given by HAWKES shows the possible existence of the (001) cleavage, though he does not mention it in the description.

These perfect cleavages of olivine gradually disappear in the transitional zone between the primary dunite and the metamorphosed dunite in the Japanese ultrabasic masses described above. The width of the transitional zone is variable from hundred meters to several meters. In this zone various types of olivine are found. Olivine showing indistinct cleavages, as seen in Fig. 9, is common. On the other hand newly formed olivine as vein-like streak is sometimes found (Fig. 10).

2. Chemical composition

Chemical analyses of two cleavable olivines from the Kômorî mass are listed in Table 1. The contents of forsterite molecule are 92.8 and 94.3. They are not so different in chemical composition from common olivine of various Alpine-type peridotites. The CaO contents are slightly higher, though this may not be a cause of the well-developed cleavages. The cleavable olivines from the Happo-Oné mass do not show high content of CaO; partial analyses of two specimens give 0.21% and 0.18% CaO.

Forsterite content of the cleavable olivine from the Happo-Oné mass is 90–95 by the x-ray method after

Fig. 9. Microscopic photograph of olivine of transitional stage from cleavable olivine to common olivine (Kômorî mass). single nicol, about $\times 160$.

Fig. 10. Microscopic photograph of streak of recrystallized olivine. R : recrystallized olivine, C : relic of cleavable olivine. single nicol, about $\times 80$.

YODER and SAHAMA(1957). By chemical analysis HAWKES(1946) determined forsterite content of the cleavable olivine from a dunite near Dunsuir as 91.3.

For the present no chemical control would be expected as the cause of the remarkable cleavage of the olivine.

3. X-ray study on powdered samples

As shown in Fig. 11, the cleavable olivine gives the very strong intensity of 020 reflection on the X-ray powder diffraction patterns.

With an apprehension that the strong intensity of 020 reflection would have been caused by the preferred orientation of the powder by the well-developed (010) cleavage, we x-rayed it by the various method: some are ground in short time and some in long time, or some

Fig. 11. X-ray powder charts of the cleavable olivine of the primary dunite (upper) and common olivine of the metamorphosed dunite (lower), Kômorî mass. ($2\theta\text{CuK}\alpha$).

are packed closely in the sample holder, some loosely. In all cases the intensity of 020 was the strongest. Moreover, the charts of powder having the preferred orientation on slide glass do not particularly show stronger intensity of 020 than those obtained from the randomly oriented powder samples in the common sample holder of x-ray apparatus.

We made sure appearance of reflections of 040 and 060, which do not appear in common powder charts of ordinary olivine. They might appear, if the strongest intensity of 020 was given by the preferred orientation due to the well-developed cleavage of (010). But such reflections did not appear. Moreover, as stated in the foregoing paragraph, there is few difference between that of developments of cleavages parallel to (100), (010) only and (001), and thus preferred orientation parallel to (010) cleavage should not appear.

Therefore, it seems that the strongest intensity of 020 reflection in the powder charts of the cleavable olivine is not due to a preferred orientation of the well-developed cleavages.

In order to compare more quantitatively the intensity of reflection of 020 and others (130, 131 and 112), we calculated the integral intensity ratios of 020/130, 020/131 and 020/112.

In these x-ray investigations copper target was used for all the experiments. X-ray powder data of natural olivine must be treated statistically in the case of calculating the intensity ratios. Because natural olivines show variable intensity relation even in the same sample, though synthetic olivine shows stable intensity relation in whole samples of the same specimen. For the comparison of the intensity ratios of these reflections are used the olivines having compositional range of Fo 80—95. In the case of pure forsterite these intensity ratios may be slightly different from those of olivines

Table 1. Chemical analyses of the cleavable olivine from the Kômorî mass. (After KURODA, OGURA and SHIMODA unpublished)

	63-41	63-67
SiO ₂	40.10 0.975	40.46 0.980
TiO ₂	0.01	0.02
Al ₂ O ₃	1.11 0.032	0.49 0.015
Fe ₂ O ₃	1.90 0.035	1.95 0.034
FeO	6.76 0.137	5.52 0.110
MnO	0.09 0.001	0.11 0.001
MgO	48.62 1.774	49.95 1.817
CaO	1.07 0.028	0.98 0.025
Na ₂ O	0.07 0.003	0.13 0.006
K ₂ O	0.01	0.10 0.003
NiO	0.28 0.006	0.42 0.009
Cr ₂ O ₃	0.03	0.02
H ₂ O(+)	0.21	0.19
H ₂ O(-)	0.08	0.03
Total	100.34	100.37
Fo%	92.8	94.3

Analyst : Y. Ogura.

which Fo content is less than Fo 95, even though the P-T condition of formation is the same. For example, intensity ratios of 020/130, 020/131 and 020/112 in pure forsterite synthesized from oxides mixture under atmospheric pressure are 0.381, 0.351 and 0.303, respectively, but those of Fo 90 and Fo 80 olivines synthesized from oxides mixtures under nearly the same conditions as those for the pure forsterite are 0.234, 0.206, 0.201; 0.289, 0.268, 0.204, respectively. These ratios of the latter are the same as those of the synthetic olivine from serpentine under atmospheric pressure (Table 2).

We chose the following six groups of olivine and compare the intensity ratios of 020/130, 020/131 and 020/112 with care as mentioned above.

1. Cleavable olivine from the Kôkori mass*.
2. Cleavable olivine from the Happoné mass.
3. Common olivine from metamorphosed dunite from the Kôkori and the Happoné masses.
4. Common olivine from various Alpine-type peridotites.
5. Common olivine from various volcanic rocks.
6. Synthetic olivine from various serpentines under the conditions of 800–1000°C, atmospheric pressure and 1 hr.,

The data were statistically analysed and the result is shown in Table 2. As seen in this table, the reflection of 020 is the strongest in the cleavable olivine from the Kôkori mass and is the weakest in the synthetic olivines. Between them there are some intermediate ones.

For the comparison of differences of these values we calculated *t*-distribution between respective intensity ratios. The result is shown in Table 3. In the table, if we take above 99.9 of 100 (1-P) as the reliable boundary, these olivines are grouped into three types by the order of the intensity of 020: 1; Kôkori and Happoné type, 2; metamorphosed Kôkori—Happoné type, Alpine type and volcanic type, 3; synthetic type**. If we take above 99.0 of 100 (1-P) as the reliable boundary, some differences between Kôkori type and Happoné type, metamorphosed Kôkori—Happoné type, Alpine type and volcanic type are recognized. Thus, it is further subdivided into five; that is, 1a, Kôkori type, 1b, Happoné type, 2a, metamorphosed Kôkori—Happoné type and Alpine type, 2b, volcanic type, and 3, synthetic type.

The synthetic olivines mentioned above are formed from serpentines. But the olivines synthesized from oxides mixtures under high temperature and atmos-

Table 2. Intensity ratios of 020 and other strong peaks for olivines of various origins.

	Kôkori			Happoné			metamorphosed		
	n	$\bar{x}$	σ	n	$\bar{x}$	σ	n	$\bar{x}$	σ
020/130	5	2.268	1.058	22	1.429	0.485	13	0.637	0.120
020/131	5	2.158	0.965	22	1.176	0.391	13	0.464	0.152
020/112	5	2.340	0.604	22	1.466	0.517	13	0.620	0.141

	Alpine			volcanic			synthetic		
	n	$\bar{x}$	σ	n	$\bar{x}$	σ	n	$\bar{x}$	σ
020/130	21	0.582	0.165	8	0.425	0.077	9	0.276	0.071
020/131	21	0.501	0.119	8	0.447	0.063	9	0.233	0.100
020/112	21	0.532	0.113	8	0.420	0.099	9	0.233	0.043

Alpine type: Shimonita and Ohgawara masses in the Sambagawa zone, Horoman mass in the Hidaka belt, Tanigawa mass in the Jôetsu belt, and Ohshima mass in the Maizuru structural belt.

Volcanic type: Miyake-shima volcano, Hachijoshima volcano, Sado-ga-shima Island, and Hawaii Islands.

Synthetic: From various serpentines.

pheric pressure for the purpose of investigation of olivine $\rightleftharpoons$ spinel transition in the Institute of Solid State Physics, University of Tokyo, show also the similar intensity ratios to those of the synthetic ones from serpentines: the intensity ratios of the former are 0.20–0.29. All the olivines synthesized under low pressure (atmospheric pressure) seem to be show weak intensity of 020. Volcanic olivines show lower intensity of 020 than those of the Alpine-type peridotites. Between them there is a reliable difference.

Recrystallized olivine in the metamorphosed dunite of the Kôkori and Happoné masses shows weak intensity of 020. The recrystallization is considered to have been taken place under lower pressure than that of the formation of the primary dunite. Some experimental works showed the lowering of intensity of 020 of the cleavable olivine by heating above 1000°C under atmospheric pressure. It is interesting that olivine from the metamorphosed Kôkori—Happoné type is nearly the same as the normal olivine from Alpine-type peridotites in the intensity of 020 and also in appearance under the microscope.

The differences of intensity ratios between the six types of olivine may be gradual and due to the gradual differences of the P-T conditions of formations of olivines.

From these facts, the followings are concluded. The typical cleavable olivine, showing the strongest intensity of 020, is recrystallized by the heat effects of the granite intrusion into the common olivine, showing weak intensity of 020. Intensity of 020 of olivine in volcanic

* In the Kôkori mass there are various transitional rock types in the transitional zone between the primary and metamorphosed dunites. Near the transitional zone the cleavable olivine shows comparatively weak intensity of 020, though it shows the perfect cleavages under the microscope. Such type is similar to the cleavable olivine of the Happoné mass.

** This means olivines synthesized under atmospheric pressure.

Table 3. t-distribution of intensity ratios of 020 and other strong reflections between each pair in Table 2.

		Synthetic			Volcanic			Alpine			Metamorphosed			Happo-Oné		
		ν	t	100· (1-P)	ν	t	100· (1-P)	ν	t	100· (1-P)	ν	t	100· (1-P)	ν	t	100· (1-P)
Kômorî	020/130	12	5.201	>99.9	11	4.500	>99.9	24	6.690	>99.9	15	5.000	>99.9	25	2.582	98-99
	020/131	12	5.484	>99.9	11	4.650	>99.9	24	7.336	>99.9	15	5.64	>99.9	25	3.501	99-99.9
	020/112	12	9.622	>99.9	11	8.517	>99.9	24	12.469	>99.9	15	8.77	>99.9	25	3.253	99-99.9
Happo-Oné	020/130	29	17.313	>99.9	28	5.640	>99.9	41	7.430	>99.9	33	5.61	>99.9			
	020/131	29	17.366	>99.9	28	5.062	>99.9	41	7.411	>99.9	33	6.12	>99.9			
	020/112	29	17.133	>99.9	28	5.372	>99.9	41	7.812	>99.9	33	5.47	>99.9			
Metamorphosed	020/130	20	7.713	>99.9	19	4.257	>99.9	32	2.88	99-99.9						
	020/131	20	3.805	99-99.9	19	0.246	10-20	32	0.766	50-60						
	020/112	20	7.588	>99.9	19	3.356	99-99.9	32	1.96	90-95						
Alpine	020/130	28	5.183	>99.9	27	2.508	98-99									
	020/131	28	5.680	>99.9	27	1.173	70-80									
	020/112	28	7.475	>99.9	27	2.50	98-99									
Volcanic	020/130	15	4.14	>99.9												
	020/131	15	4.83	>99.9												
	020/112	15	4.80	>99.9												

Table 4. Atomic coordinates of olivine

	BRAGG & BROWN (1926)			BELOV et al. (1951)			CANDLIN & DAVIS (1965)			This paper		
	x	y	z	x	y	z	x	y	z	x	y	z
Si	0.375	0.083	0.250	0.415	0.095	0.250	0.430	0.090	0.250	0.433	0.080	0.250
O _I	0.250	0.167	0.000	0.262	0.152	0.027	0.280	0.162	0.030	0.290	0.150	0.050
O _{II}	0.250	0.417	0.250	0.221	0.430	0.250	0.220	0.452	0.250	0.230	0.440	0.250
O _{III}	0.250	0.917	0.750	0.229	0.917	0.750	0.230	0.920	0.750	0.271	0.940	0.750
Mg _I	0.000	0.000	0.000	-0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mg _{II}	0.000	0.250	0.250	0.01	0.281	0.250	-0.01	0.280	0.250	0.000	0.270	0.250

rocks is the weakest among the various natural materials. Synthesized olivines under atmospheric pressure shows the weakest intensity of 020 among the various types of olivine. Moreover, the description on the presence of olivine, showing the well-developed cleavages or partings, are restricted to kimberlite and meteorites, which seem to be formed under high pressure. But these olivines have not been confirmed whether their intensity of 020 is strong or not. Thus, it may be considered that the intensity of 020 of olivines reflects the P-T condition of the formation, especially pressure. If olivine synthesized under the same condition as that of the natural cleavable olivine, probably high pressure, it may show strong intensity of 020*.

The differences of the intensity ratios between oli-

vinces of various origins must be explained from the view point of crystal structure. Moreover, as crystal structure of olivine should be affected by pressure, temperature and others, and interpretation of intensity ratios of 020 and other reflections may not be simple.

4. Crystal structure of olivine

Crystals structure of forsterite was determined first by BRAGG and BROWN(1926)(Fig. 12, Table 4). The model was calculated on the basis of the hexagonal closest packing of oxygen atoms in the structure of the symmetry, *Pbmm*. It is interesting that the Si-O bond length in their model is longer(average 1.83 Å) than that in common silicates(about 1.6 Å).

We proposed a structural model of olivine, in which Si-O bond length is about 1.61 Å(KURODA *et al.*1965). In our model the symmetry of *Pbmm* is also adopted. The structure is shown in Fig. 12 and Table 4. This model may give cleavages parallel to (100), (010) and (001). Moreover, it is noteworthy that the calculated intensity of 020 is strong, although the intensities of other

* Recent preliminary works on the synthesis of olivine under high pressure and temperature (40-70kb, 1200-1600°C and 20-40 mts.) do not show the strongest intensity of 020, but show the strongest intensity of 021 with also relatively strong intensity of 020. These works were kindly done by Dr. S. AKIMOTO of the Institute of Solid State Physics, Univ. of Tokyo.

Fig. 12. Crystal structures of olivine BRAGG & BROWN (upper) and this paper (lower). Large circle; oxygen, small circle; magnesium.

Table 5. Calculated F-values of various crystal models.

d (Å)	hkl	I	II	III	IV
5.105	020	19.7	30.4	34.9	50.5
3.885	021	-33.4	-48.2	-39.4	-40.8
2.768	130	35.7	45.3	65.6	58.2
2.552	040	8.6	-6.0	9.4	17.3
2.513	131	61.1	59.4	56.8	62.0
2.460	112	57.3	60.3	67.0	63.4
2.270	122	46.3	-49.9	-45.2	43.4
2.249	140	-46.0	47.8	56.1	-47.8
1.750	222	92.2	81.4	81.3	76.6
1.702	060	-33.5	-32.9	-4.1	-20.0

Note; I : BRAGG and BROWN (1926)

II : BELOV *et al.* (1951)

III : CANDLIN & DAVIS (1965).

IV : This paper.

reflections are almost unchanged (Table 5). X-ray photographs of single crystal were taken. However, in

this olivine is present much amount of serpentine along the cleavages and cleavage flakes slip on each other, so it has not yet been succeeded to refine the structure.

BELOV *et al.* (1951) and CANDLIN and DAVIS (unpublished, BRAGG and CLARINGBULL 1965) separately proposed the crystal structure models, which also show the shorter distance of Si-O bond than that of BRAGG and BROWN (1926). Between two models proposed by BELOV *et al.* and CANDLIN and DAVIS there are slight differences in the atomic coordinates. Namely Si-O bond length is shorter in CANDLIN and DAVIS' model than BELOV's one. As to the position of Mg and Si, too, there are slight differences (Table 4). It was a question why such differences were caused in spite of their refinement of the structure by the analyses of the single crystal of olivine. Regrettably there is no description on the olivine specimens used for the refinement by BELOV *et al.* and CANDLIN and DAVIS, but it is expected that their materials are different in origin.

the olivines if were formed under different P-T conditions, they may have different crystal structures, showing different intensities of 020.

Our speculative model seems to be more reasonable for explaining the strong intensity of 020 than BELOV's and CANDLIN and DAVIS' models (Table 5).

Now let us consider the origin of cleavages. Under the microscope olivine commonly shows weak cleavages parallel to (010) and (100) and rarely that parallel to (001). In BRAGG and BROWN's model cleavages parallel to (100) and (001) are not expected, but from BELOV's and CANDLIN and DAVIS' models they may be expected. There is a transition between perfectly cleavable olivine and common olivine in the ability of making cleavages and this may be reflected in the slight differences of crystal structure between our model and other models.

The slight differences of crystal structure of olivine may depend mainly on the length of Mg-O bond. The length of Mg-O bond may be more variable than that of Si-O. Thus it is considered that olivine formed under high pressure is expected to have smaller unit cell than that crystallized under low pressure.

IV. CONCLUSION

Cleavages of minerals must be related to their crystal structure. Some kinds of parting may be appeared by some mechanical forces, but distinct cleavages of minerals uniformly appeared in rock mass seem to be caused by their crystal structures.

As stated above, our model of crystal structure of olivine gives cleavages parallel to (100), (010) and (001). In BELOV's and CANDLIN and DAVIS' model, too, cleavages parallel to these three directions may be appeared, but they might be weaker than those in our model. There are various structures of olivine, being shown by the differences of intensity of 020, and by the differences of the structure some olivine does not show well-developed cleavages.

The main factor causing such differences in the structure of olivine is not well known. However, the following facts suggest that the cleavable olivine showing the strong intensity of 020 would be formed under high pressure. The cleavable olivine, having the strong intensity of 020, in the primary dunite has been recrystallized into the common olivine, having the weak intensity of 020, in the metamorphosed dunite by the thermal effect of the later granite intrusion. The strong intensity of 020 of the cleavable olivine becomes weak by heating (above 1000°C) in the furnace under the atmospheric pressure. The occurrences of dunite, containing the cleavable olivine, are restricted to some geological situation. The other occurrence of the cleavable olivine are found kimberlite and achondrite including diamond.

able olivine are found kimberlite and achondrite including diamond.

Olivine is stable under a wide range of pressure and temperature. Polymorphic transformation is not seen until to the transformation to spinel structure under very high pressure and temperature. From these characteristics of olivine it would be concluded that there are some structural differences between olivines which are formed under conditions of different temperatures and pressures of olivines of different origins.

REFERENCES

- BELOV, N. V., BELOVA, E. N., ANDRIANOVA, N. N. and SMIRNOVA, R. F. (1951), Determination of parameters in the structure of olivine (forsterite) by the method of three dimensional harmonic synthesis. *Doklady, Academy of the Sciences USSR*, Vol. 81, No. 3, 399—402. (in Russian)
- BOBRIEVICH, A. P. *et al.* (1959), Diamond deposits in Yakut. *State Scientific and Technical Publisher*, Moscow, 1—527. (in Russian)
- BRAGG, W. L. and BROWN, G. B. (1926) Die Struktur des Olivins. *Zeit. Krist.*, Vol. 63, 538
- BRAGG, W. L. and CLARINGBULL, (1965), The crystalline state, Vol. IV. Crystal structure of minerals. 1—409. *Cornell Univ. Press.*
- DEER, W. A., HOWIE, R. A. and ZUSSMAN, J., (1962), Rock-forming minerals, Vol. 1, *Longmans*, 1—333.
- HAWKES, H. E. (1946), Olivine from northern California showing perfect cleavages. *Amer. Mineral.*, Vol. 37, 276—286.
- HENRIQUES, R. (1966), The crystal structure of olivine with reference to inclusions in diamond. Abstract of IMA.
- IGI, S. and KURODA, K. (1965), Geological map of Japan, 1 : 50,000, Ōeyama sheet. *Geol. Surv. Jap.*
- IKEBE, N. *et al.* (1961), Geological map of Hyōgo prefecture. Hyōgo prefecture.
- KURODA, Y., SATO, M., OGURA, Y. and HASHIDA, E. (1964), Two kinds of white mica found in the Kōmori ultrabasic mass, Kyōto prefecture, Japan. *Jour. Jap. Assoc. Min. Pet. Econ. Geol.*, Vol. 51, No. 4, 149—157.
- KURODA, Y., OGURA, Y. and SHIMODA, S. (1964), Ultrabasic rocks of Komori mine, Kyoto prefecture. *Jour. Geol. Soc. Jap.*, Vol. 70, No. 826, 417—418 (Abstract in Japanese).
- , ——— and ——— (1965), Petrological study of Ōeyama(Kōmori) ultrabasic mass and the problem of ultrabasic rock. *Jour. Geol. Soc. Jap.*, Vol. 71, No. 388, 362 (Abstract in Japanese).
- NIXON, P. H., KNORRING, O. and ROOKE, J. M. (1963), Kimberlites and associated inclusions of Basutoland: A mineralogical and geochemical study. *Amer. Mineral.*,

- Vol. 48, 1090—1132.
- VINOGRADOV, A. P. and VDOVKIN, G. P. (1963), Diamonds in stony meteorites. *Geochemistry*, No. 8, 715—720 (in Russian with English abstract).
- WINCHEL, A. N. and WINCHEL, H. (1951), Elements of optical mineralogy, Part II. *John Wiley*. 1—551.
- YODER, H. S. and SAHAMA, T. G. (1957), Olivine X-ray determinative curve. *Amer. Mineral.*, Vol. 42, 475.

へき開の発達したかんらん石—その地質学的・鉱物学的意義

黒田 吉益・下田 右

(要 旨)

舞鶴帯の北側に分布する河守（大江山），出石，関の宮の三超塩基性岩体，およびひだ外縁の八方尾根超塩基性岩体から，（100），（010），（001）にひじょうによくへき開の発達したかんらん石を発見した．それらの岩体は，主としてダンかんらん岩よりなるが，へき開の発達したかんらん石よりなる初生的ダンかんらん岩とふつうのかんらん石からなる変成ダンかんらん岩とが区別される．初生的ダンかんらん岩は残存岩体であり，へき開の発達したかんらん石からふつうのかんらん石への漸移的再結晶作用がみとめられる．

へき開の発達したかんらん石のX線粉末データは020のピークが異常に高い．これは（010）面に試料が定方位するためではなく，結晶構造に由来するものである．そのために，新しい結晶構造モデルを考えた．それによると，020の反射が強くなり，同時にへき開が（100），（010），（001）に生じやすくなる．この020の強度と130，131，112の強度比を，1．河守型，2．八方尾根型

3．変成河守～八方尾根型，4．Alpine型，5．火山岩型，6．合成型（1気圧下）のものについて測定した．その結果は，その順序で020の強度が弱くなることが判明した．ただ，3と4ではほとんど有意の差がみとめられない．

このようなデータから，かんらん石の結晶構造は，その生成条件により，少しずつちがっており，そのちがいは主として020の強度にあらわれていること，熱により再結晶したものや，1気圧下で合成したものでは020の強度が低下することから，それには圧力条件が一番きいているであろうと推論した．

地 名	
Asahidake	朝日岳
Happo-Oné	八方尾根
Izushi	出石
Kômorî	河守
Kotaki	小滝
Ôeyama	大江山
Ohshima	大島
Sekinomiya	関ノ宮
Wakasa	若桜
Yôka	八鹿