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RODINGITES FROM THE KAMUIKOTAN TECTONIC BELT, HOKKAIDO

by

Takayuki Katoh and Kiyoaki Niida

(with 12 text-figures and 3 tables)

Abstract

A large number of rodingites were found in and around serpentinite masses of the Kamuikotan Tectonic Belt. The original rocks of the rodingite were also found. They are microdiorite-microgabbro, olivine clinopyroxenite, and slate. Reaction zones between the serpentinite and the original rock are divided into two zones; one is rodingite zone composed mainly of diopside, hydrogrossular, wollastonite, chlorite, prehnite, and tremolite, and the other is chlorite zone which contains large amounts of chlorite.

The rodingites are characterized by the higher contents of CaO, Al₂O₃, TiO₂, and H₂O and the lower contents of SiO₂, Na₂O and K₂O than those in the original rocks. Compositional variation observed in the reaction zones suggests that the rodingites were formed through the following metasomatic process; (1) Ca, Al, Ti, and H₂O migrated from serpentinite into the reaction zone, (2) Si and alkali moved from the original rock towards serpentinite through the reaction zone, and (3) a considerable amount of Mg, Fe, and Mn as well as Ca, Al, Ti, and H₂O fixed within the chlorite zone.

On the basis of hydrothermal experiments on stability ranges of xonotlite-wollastonite, vesuvianite, diopside, and hydrogrossular, most of the rodingites from the Kamuikotan Tectonic Belt are considered to have been formed at the temperature higher than 350°C.

Introduction

Rodingites occur as inclusions or dykes within serpentinite. As well known, they are composed mainly of hydrogrossular, chlorite, diopside, vesuvianite, and prehnite. The rocks are generally derived from mafic igneous rocks (Honnorez and Kirst, 1975; Coleman, 1977). In rare cases, some rodingites metasomatized from intermediate to acidic igneous rocks and even from sedimentary rocks have been reported by Coleman (1966 and 1967).

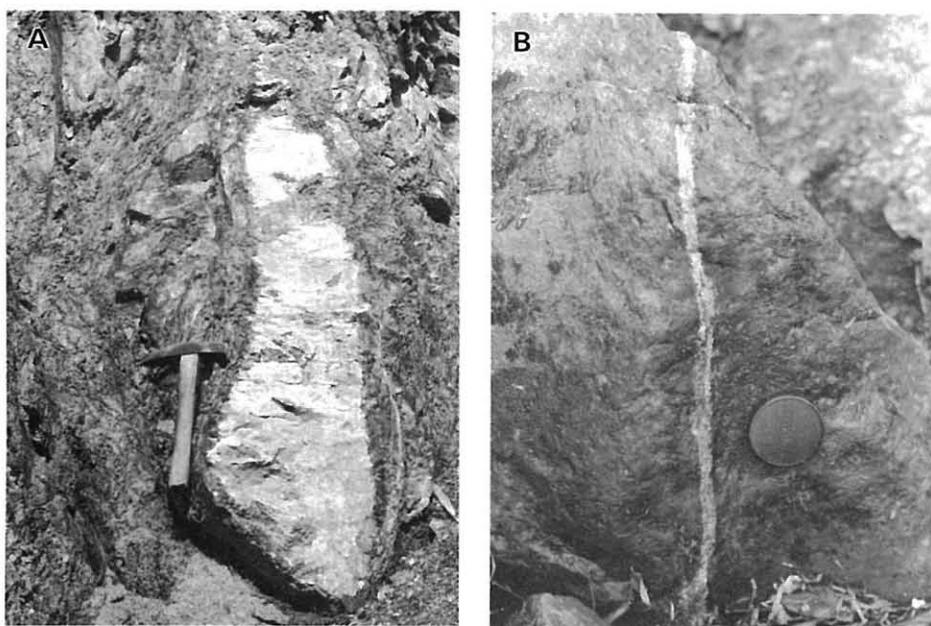
Metasomatic alteration resulting in the formation of rodingite is considered to be a process common to serpentinization of peridotites. Suzuki (1954) described some rodingites from the Kamuikotan Tectonic Belt and suggested that the rocks were formed from dioritic to gabbroic rocks by lime-metasomatism.

Recently, a number of rodingites derived from olivine clinopyroxenite, microdiorite-microgabbro, and slate have been found in the southern half of the Kamuikotan Tectonic Belt (Niida and Katoh, 1978). Furthermore, partly metasomatized sedimentary rocks surrounding serpentinite mass are found at the tectonic contact.

In this paper, the mode of occurrence and petrographical and petrochemical characteristics of the rodingites are given. The process of rodingite formation will be also discussed.

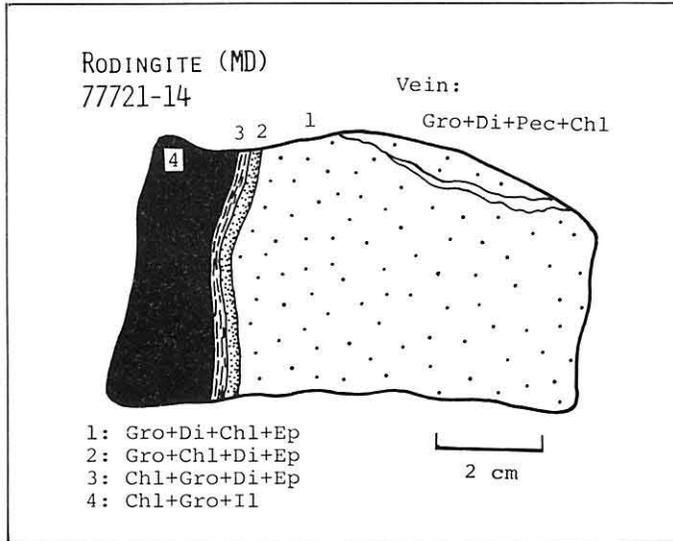
Features of Occurrence

A considerable numbers of rodingites are found associated with serpentinites in the Kamuikotan Tectonic Belt. The rodingites occur as xenoblocks and intrusives showing various shapes such as spheroid, ellipsoid, lens, dyke, and vein, which are 1cm to 3m in diameter. As shown in Text-fig. 1A, these rodingites are commonly found in strongly serpentinized ultramafic rocks such as foliated and sheared serpentinites. Rodingite veins are rarely found in massive serpentinites (Text-fig. 1B). Occasionally, original rocks can be seen at the core of rodingites. The width of rodingite reaction zone between serpentinite and original rock is several centimeters to a few meters from the contact plane of serpentinite. A narrow zone which commonly shows dark green to black colour and ranges from 0.5cm to several cm thick is occasionally observed between serpentinite and the completely metasomatized rock. This zone usually contains a large amount of chlorite. In this paper, the chlorite-rich narrow zone is called "chlorite zone". Accordingly, the reaction zone (rodingite) is divided into two zones; one is rodingite zone which has a representative mineral assemblage of rodingite, and the other is chlorite zone. The rodingite zone and chlorite zone sometimes have a few to several subzones, which are bounded by clear planes, as shown in Text-fig. 2.



Text-fig. 1 Photographs showing the mode of occurrence of rodingite in the Sarugawa serpentinite massif.

- A: Rodingite surrounded by partly foliated serpentinite, along the Penke-yukutorashinai-zawa, a tributary of Sarugawa River.
- B: Rodingite vein metasomatized from clinopyroxenite cutting the massive serpentinite, along the Ruukeshuomanai-zawa, a tributary of Sarugawa River.



Text-fig. 2 Four reaction sub-zones in rodingite metasomatized from microdiorite (Sample No. 77721-14). Nos. 1 and 2: rodingite zone. Nos. 3 and 4: chlorite zone. Gr: hydrogrossular; Di: diopside; Chl: chlorite; Ep: clinzoisite-epidote; Il: ilmenite; Pec: pectolite.

Text-fig. 3 shows distribution of rodingites in the Sarugawa serpentinite massif. The distribution of rodingites is limited in the marginal parts of the massif and in strongly sheared areas along the faults. The ultramafic rocks including rodingites are intensely serpentinitized. No rodingite has been found around Mt. Iwanai-dake where the ultramafic rocks are well preserved as dunite and harzburgite (Katoh, 1978), suggesting that the metasomatic process into rodingite is due to serpentinitization. Such rodingites in the Sarugawa massif are derived mostly from olivine clinopyroxenites and microdiorite-microgabbros. In some places, sedimentary rocks (country rocks) are partly metasomatized into rodingites at the contact with serpentinites (Text-fig. 4). The reaction zones are up to about several ten centimeters. Text-fig. 3 also shows the localities of rodingites formed along the tectonic contact plane of the massif.

Petrography

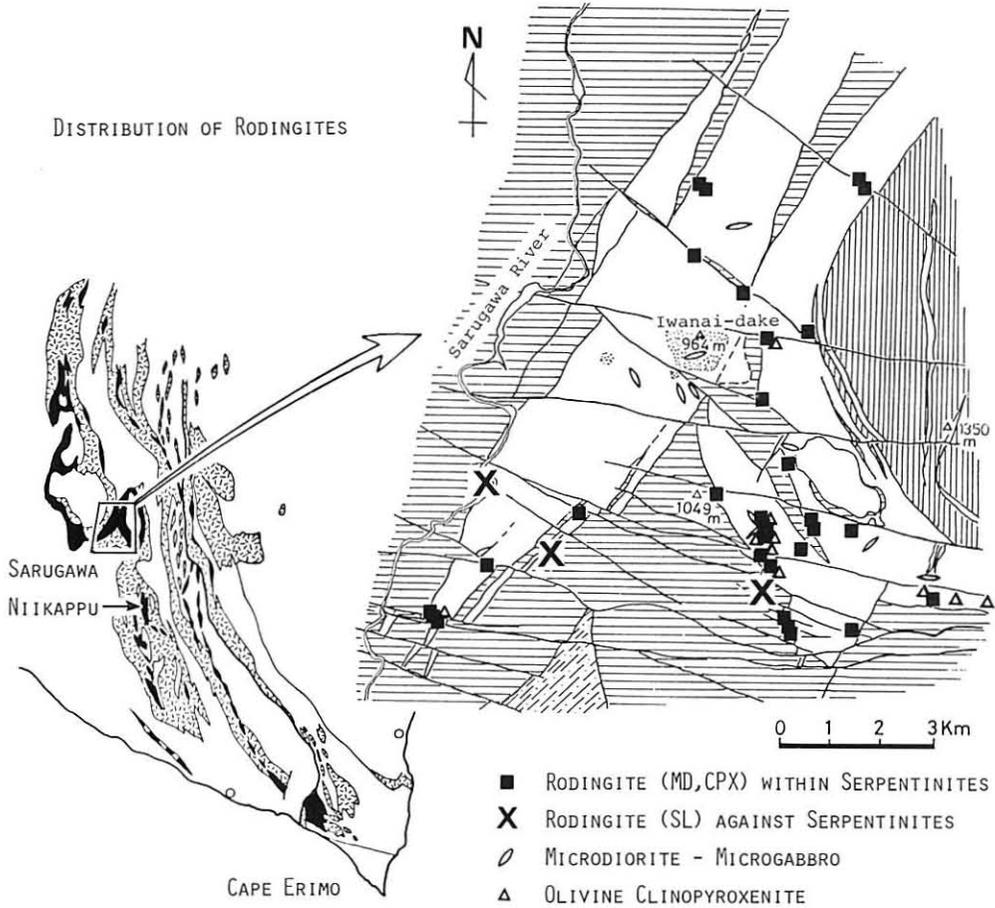
Original Rock Types

The original rock types of rodingite in the southern part of the Kamuikotan Tectonic Belt are as follows.

- 1) Microdiorite-microgabbro dykes in serpentinites.
- 2) Olivine clinopyroxenite dykes and veins in serpentinites.
- 3) Slates as exotic blocks in serpentinites and as wall rocks of serpentinite.

These rock types are often observed at the exposure, where the original rock changes gradually into rodingite. Olivine clinopyroxenite is the most predominant type of rodingites in this belt. Microdiorite-microgabbro is also abundant type, whereas rodingites derived from sedimentary rocks are rarely found in a limited area.

In the southern part of the Kamuikotan Tectonic Belt, dykes of trondhjemite and quartz albitite occur also closely associated with the serpentinites. No reaction zone of rodingite, however, has been observed in these dykes.

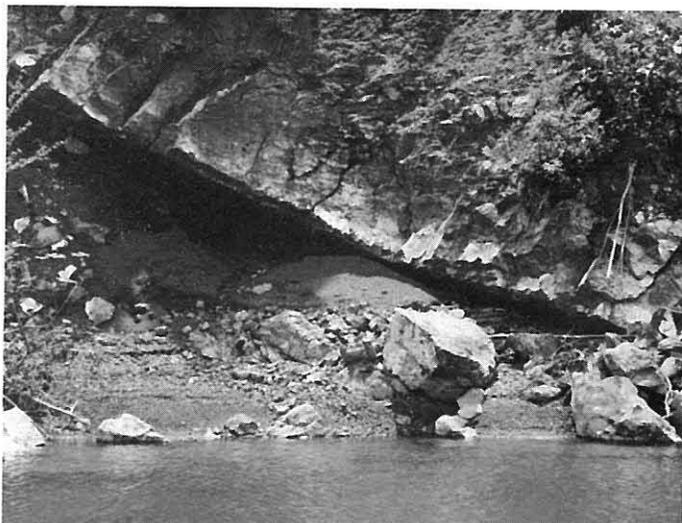


Text-fig. 3 Distribution of rodingites in the Sarugawa serpentinite massif. Dotted area: fresh dunite-harzburgite, white area: serpentinite. Original rocks; MD: microdiorite-microgabbro, CPX: clinopyroxenite, and SL: slate.

Microdiorite-microgabbro

A considerable number of microdiorite-microgabbros are found in serpentinite masses of the Kamuiokotan Tectonic Belt. The dykes commonly range from 0.5 to 4m in thickness. In rare cases, the dyke more than 100m wide can be traced within a distance up to about 300m. The chilled margin which consists of fine-grained minerals without glass is conspicuously observed at the exposure.

The rocks are composed mainly of plagioclase, hornblende, and clinopyroxene as primary constituents, showing an equigranular to subophitic texture less than 0.2mm in grain size. The colour indices vary from 30 to 70%. Petrographically, the dykes are classified into diorite, hornblende gabbro, and gabbro. In this paper, however, the term "microdiorite-microgabbro" represents all of these dykes.



Text-fig. 4 Metasomatized slate (white) tectonically bordered by serpentinite (left corner) along the Sarugawa River. The rodingite reaction zone about 50cm thick from the contact plane.

Olivine clinopyroxenite

Olivine clinopyroxenites belong to the dunite – wehrlite – olivine clinopyroxenite – clinopyroxenite series (W-Series) which occurs as a small dyke and stock-like mass intruding magmatically into dunite – harzburgite tectonites (H-Series). A large number of olivine clinopyroxenites were reported from the Kamuikotan Tectonic Belt by Niida (1977) and Katoh (1978). Olivine clinopyroxenites are composed of clinopyroxene and olivine with minor amounts of iron oxides. They have conspicuous variation in the modal composition. The rocks show a typical cumulate texture. Constituent minerals range from 2mm to 3cm in grain size. In most cases, olivine grains are replaced by serpentine minerals. Accordingly, olivine clinopyroxenite dykes are considered to have intruded before serpentinization, and after that, to have been metasomatized into rodingites.

Slate

Serpentinities in this belt occasionally carry many xenoblocks from different levels and sources. In such cases partly metasomatized sedimentary rocks are found in the serpentinities. Slates free from the rodingite metasomatism are originally made up of quartz, albite, chlorite, sericite, analcime, and small amounts of iron oxides.

Rodingites

Rodingite from microdiorite (Sample No. 77721-14)

Rodingite (Nos. 77721-14-1 to 4) from the Sarugawa River has the following four reaction subzones as shown in Text-fig. 2. The reaction subzone No. 1 is typical of rodingite which is white to grey. No. 2 is also rodingite zone which is bluish grey and 2 to 5mm thick. No. 3 is a chlorite zone which shows pinkish grey colour and occurs as a thin band about 5mm thick. No. 4 ranging from 2 to 5cm thick is typical of chlorite zone characterized by black colour. Reaction boundaries between the above subzones are distinct in hand

specimen.

The reaction subzone No. 1 (Rodingite) is composed mainly of hydrogrossular and diopside with minor amounts of chlorite and epidote(?) (Table 1). Although the original texture of microdiorite remains in the rodingite, original minerals are completely changed into the above phases. In this case, the hydrogrossular appears as very fine granular crystal forming monomineralic aggregations. The clinopyroxene is euhedral to subhedral, ranging from 0.05 to 0.2mm in grain size.

The reaction subzone No. 2 (Rodingite) is made up of hydrogrossular, chlorite, diopside

Table 1 Mineral assemblages of the rodingites from the Kamuikotan Tectonic Belt.

Sample No.	Original rock	Mineral assemblage Rodingite	Vein	Metasomatism degree (%)	Relict mineral
77721-14-1	MD	Gro>Di>>Chl+Ep(?)	Gro>Di+Pec+Chl	100	
14-2	"	Gro>Chl>Di>Ep(?)		100	
14-3	"	Chl>Gro>Di>Ep(?)		100	
14-4	"	Chl>>Gro>Il		100	
80606-12e	MD	Di+Pre>Chl>>Wo>Ep	Pre>Di	100	
12d	"	Pre>>Di>Wo>>Gro+Chl+Ep	Pre	100	
12c	"	Di>Wo+Gro>Pre>>Ves+Ep	Tre, Pre	100	
12b	"	Di>Pre+Gro>>Wo>Ep(?)	Pre	100	
12a ₂	"	Pre>Di>>Chl+Wo+Gro	Chl, Chl+Tre, Tre	100	
12a ₁	"	Chl+Di>>Tre+Ep(?)		100	
80606-10d	MG	Pre>Wo+Gro+Di+Chl>Xo	Pec	20	Ab>Ho>Chl
10c	"	Pre>Gro>Di+Chl	Chl, Cc	30	Ab>Chl>Ho
10a	"	Pre+Wo>Di>Xo	Pec	100	
76720-3	CPX	Di>Chl	Chl+Serp	5	Di>Serp
4	"	Gro>Chl>>Di>Tre+Ep	Gro, Chl+Gro	70	Di
2-3	"	Chl>Gro>>Di>>Ep	Chl+Gro	100	
2-2	"	Chl>Gro>>Di>>Ep		100	
2-1	"	Chl>Gro	Chl+Gro	100	
80606-8c	CPX	Gro>Di>>Chl	Chl, Chl+Gro	15	Di>Serp
8b	"	Di>Gro>>Chl>Ves	Chl, Gro, Chl+Gro	100	
8a	"	Di+Gro>>Chl	Gro, Chl+Gro	100	
74109-6a	SL	Gro>Di>>Chl	Chl>>Ves+Di	100	
6b	"	Gro>>Di>Chl+Ep(?)>Ves	Ves>Gro>Di+Chl	100	
			Gro>Di>>Chl		
			Ves>Di+Chl		
74923-1	SL	Pec>Pre>Gro+Chl		100	

MD: microdiorite; MG: microgabbro; CPX: olivine clinopyroxenite; SL: slate.

Gro: hydrogrossular; Di: diopside; Chl: chlorite; Ep: clinozoisite-epidote; Pec: pectolite; Il: ilmenite; Pre: prehnite; Wo: wollastonite; Ves: vesuvianite; Tre: tremolite; Xo: xonotlite; Cc: calcite; Ab: albite; Ho: hornblende; Serp: serpentine (lizardite).

and epidote(?). Original texture also remains in this subzone. The most crystals of diopside are replaced by chlorite. Reaction boundary plane between subzone Nos. 1 and 2 is clearly observed under the microscope (Text-fig. 5A). Even in a single grain, diopside and chlorite show sharply contact just on the boundary plane as shown in Text-fig. 5B.

The reaction subzone No. 3 (Chlorite zone) is characterized by appearance of large amounts of chlorite, and therefore, the reaction zone is termed "Chlorite zone". The chlorite zone consists mainly of chlorite, hydrogrossular, diopside and epidote(?). Although primary grains of plagioclase are completely replaced by hydrogrossular, and hornblende by chlorite, the pseudomorphs are well preserved. Accordingly, the original texture remains distinctly in this subzone.

The reaction subzone No. 4 (Chlorite zone) is composed almost entirely of chlorite. Small amounts of hydrogrossular and ilmenite are also found in the matrix.

Rodingite from microdiorite (Sample No. 80606-12)

The reaction zone of rodingite (Nos. 80606-12a₁, a₂, b, c, d, and e) from the Niikappu serpentinite mass occurs between serpentinite and fresh microdiorite. Six samples were collected at the points of 1cm (sample No. 80606-12a₁), 5cm (12a₂), 10cm (12b), 20cm (12c), 30cm (12d), and 50cm (12e) from the contact plane against serpentinite.

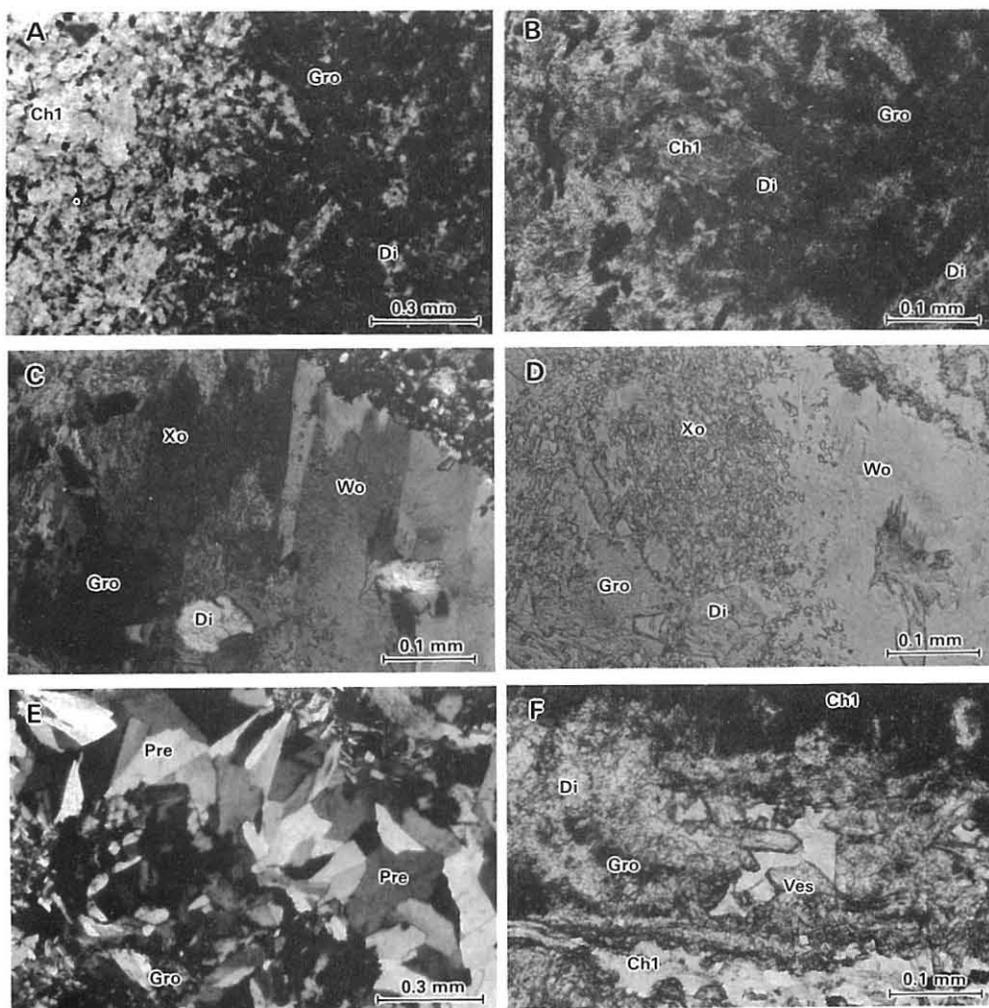
At the marginal part of the reaction zone towards serpentinite there is a chlorite zone greenish grey to black and about 1cm thick. The chlorite zone (12a₁) is made up mostly of chlorite and diopside with subordinate tremolite and epidote(?).

Rodingites (12a₂, b, c, d, and e) from the rodingite zone are composed mainly of diopside, prehnite, wollastonite, hydrogrossular, and of accessory minor amount of chlorite, vesuvianite, and epidote. Diopside and prehnite are predominant phases. The diopside shows two different modes of occurrence; one is porphyroblastic crystal showing subhedral to euhedral grain shape up to about 1mm in grain size, and the other occurs as flaky or granular crystals in the matrix. The prehnite appears as a poikiloblastic crystal ranging from 0.5 to 2mm in grain size and as a flaky crystal in the interstices. Sometimes, plagioclase grains are completely replaced by prehnite. The rodingites Nos. 12a₂, b, c, and d contain small amounts of hydrogrossular. No hydrogrossular has been found in the specimen No. 12e. Therefore, a typical rodingite is represented by that (Nos. 12a₂, b, c, and d) from the rodingite zone. In rare cases, vesuvianite appears only in druse of the rodingite (No. 12c).

Many veins and veinlets having a rodingite phase assemblage are observed in the rodingite zone. In the specimen No. 12a₂, there are monomineralic chlorite vein, chlorite + tremolite vein, and monomineralic tremolite vein, in all of which the phase assemblages are similar to those in the chlorite zone No. 12a₁. Monomineralic prehnite veins ranging from 0.05 to 0.5mm wide are found in the rodingite zone (Nos. 12b, c, and d), as shown in Text-fig. 5E. Tremolite veins are also found in this zone.

Rodingite from microgabbro (Sample No. 80606-10)

The rodingite derived from microgabbro (Nos. 80606-10a, c, and d) was found in the Niikappu serpentinite mass near the Niikappu Dam. The specimen No. 10a from the reaction zone is completely metasomatized into rodingite, whereas Nos. 10c and d are partly



Text-fig. 5 Photomicrographs showing the mode of occurrence of the coexisting constituent minerals in rodingite. Di: diopside; Gro: hydrogrossular; Chl: chlorite; Wo: wollastonite; Xo: xonotlite; Pre: prehnite; Ves: vesuvianite.

A: Reaction boundary between two rodingite subzones Nos. 1 (right) and 2 (left) shown in Text-fig. 2 (Sample No. 77721-14). Parallel nicols.

B: A single ferromagnesian mineral replaced by diopside (right) and chlorite (left) on the boundary plane (Sample Nos. 77721-14-1 and 2). Parallel nicols.

C: Porphyroblastic wollastonite containing large numbers of small grains of xonotlite (Sample No. 80606-10a). Crossed nicols.

D: The same wollastonite as C. Parallel nicols.

E: Prehnite monomineralic vein in the rodingite No. 80606-12d. Crossed nicols.

F: Vesuvianites in a vesuvianite + grossular + diopside + chlorite vein cutting the rodingite No. 74109-6a. Parallel nicols.

metasomatized. Rodingite No. 10a is characteristically white with small pinkish grey parts. The white parts are composed mainly of prehnite and diopside, whereas the pinkish grey parts of prehnite and wollastonite. As shown in Text-fig. 5C and D, some coarse-grained wollastonites contain a number of small grains of xonotlite. The coexistence of wollastonite and xonotlite probably suggests a condition of metasomatism on the reaction boundary between them.

Partly metasomatized microgabbros Nos. 10c and d are made up of prehnite, hydrogrossular, diopside, chlorite, and wollastonite with minor amount of xonotlite. These phases representing a rodingite are found in crashed parts and/or along the grain boundaries. Many relict minerals such as plagioclase, hornblende and chlorite are also found.

Pectolite occurs as a monomineralic vein about 3mm thick, cutting the rodingite. Monomineralic calcite veins and chlorite veins are also observed in sample Nos. 10c and d.

Rodingite from olivine clinopyroxenite (Sample No. 80606-8)

The rodingites from the reaction zone in the Niikappu serpentinite mass consist mainly of diopside and hydrogrossular with small amounts of chlorite. Rodingites Nos. 8a and b are completely metasomatized from olivine clinopyroxenite, whereas the specimen No. 8c is partly metasomatized into 15 volume % rodingite.

Generally, rodingites derived from olivine clinopyroxenite are composed of two different parts; one shows pale yellowish green colour which were originally of cumulus clinopyroxene, and the other is white matrix. Primary clinopyroxene grains are completely replaced by diopside containing many granular inclusions and/or lamellae of hydrogrossular. Rarely, chlorite lamellae are found in the diopside. Small diopside grains, euhedral to subhedral and about 0.05mm in size, independently appear in the white matrix of rodingite. Hydrogrossular is found mostly in this matrix changed from serpentine minerals.

Rodingite from slate (Sample No. 74109-6)

On the borders of the Sarugawa serpentinite massif, the country rocks are partly metasomatized into rodingite. The rodingites derived from slate were found in the reaction zone in contact with serpentinite. Rodingites Nos. 6a and b are from the points of 2 to 3cm from the contact plane. No chlorite zone has been found in this reaction zone.

Hydrogrossular and diopside are the most predominant phases in the rodingites. Chlorite occurs as a minor phase in the interstices. Vesuvianite attains to 3 volume % in the matrix of the rodingite No. 6b. Moreover, vesuvianite appears as a main phase in some veins composed of vesuvianite, hydrogrossular, diopside, and chlorite, as shown in Text-fig. 5F.

Petrochemistry

Sixteen samples of the rodingites and the original rocks from the Kamuikotan Tectonic Belt were analyzed. The chemical compositions are given in Table 2. SiO₂, TiO₂, Al₂O₃, Fe₂O₃, CaO, K₂O, and P₂O₅ were analyzed by X-ray emission spectrometer (AFV-777, Toshiba), and MnO, Na₂O, and MgO by atomic absorption spectro-photometer (170-30, Hitachi). Some analyses of MgO (Nos. 4, and 6 to 11) were made by X-ray emission spectrometer (JESX-S7, JEOL). FeO was determined by titration using potassium

Table 2 Chemical analyses of rodingites and their original rocks from the Kamuikotan Tectonic Belt.

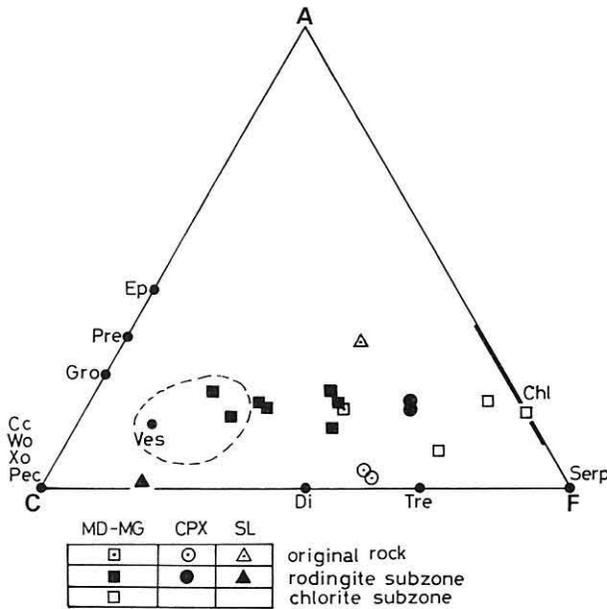
	(1) MG	(2) RD	(3) RD	(4) CHL	(5) CHL	(6) RD	(7) RD	(8) RD	(9) RD
SiO ₂	51.11	37.92	34.57	31.51	29.74	40.85	45.37	44.82	46.00
TiO ₂	0.25	0.92	1.20	1.16	1.25	0.55	0.38	0.38	0.30
Al ₂ O ₃	14.14	14.02	17.66	14.43	14.28	15.23	14.38	14.78	13.04
Fe ₂ O ₃	0.38	6.31	2.68	2.40	3.56	1.23	0.44	0.55	0.43
FeO	8.91	6.56	12.89	14.07	14.62	9.81	6.59	6.18	4.74
MnO	0.28	0.19	0.33	0.31	0.55	0.20	0.14	0.17	0.16
MgO	7.78	3.51	6.94	20.01	23.02	9.93	6.93	6.55	6.32
CaO	12.49	27.97	16.53	2.75	0.27	16.95	22.20	22.61	25.96
Na ₂ O	1.74	0.12	0.13	0.03	0.04	0.24	0.32	0.29	0.29
K ₂ O	0.24	0.05	0.05	0.02	0.05	0.02	0.02	0.02	0.02
P ₂ P ₅	tr.	0.24	0.23	0.17	0.14	0.10	0.07	0.07	0.06
H ₂ O(t)	2.59	2.18	6.92	11.62	12.14	5.41	3.62	3.73	2.17
Total	99.91	99.99	100.13	98.48	99.66	100.52	100.46	100.15	99.49

	(10) RD	(11) CHL	(12) CPX	(13) CPX	(14) RD	(15) RD	(16) SL	(17) RD
SiO ₂	44.29	44.37	47.71	48.70	32.44	31.21	65.53	43.88
TiO ₂	0.32	0.32	0.10	0.17	0.34	0.29	0.48	0.47
Al ₂ O ₃	12.01	6.88	1.96	4.40	17.69	17.21	12.26	8.27
Fe ₂ O ₃	0.65	1.82	3.80	2.34	3.61	2.52	2.45	1.91
FeO	6.73	9.54	1.46	5.40	10.29	9.43	2.45	2.25
MnO	0.28	0.34	0.10	0.18	0.22	0.24	0.17	0.09
MgO	12.27	19.41	22.28	17.33	16.20	19.24	2.16	3.35
CaO	18.83	11.31	17.95	17.88	10.16	11.56	2.83	28.05
Na ₂ O	0.34	0.21	0.03	0.25	0.02	0.02	2.84	5.31
K ₂ O	0.02	0.03	0.05	0.05	0.05	0.02	2.01	0.03
P ₂ O ₅	0.06	0.05	0.03	0.03	0.02	0.02	0.09	0.09
H ₂ O(t)	4.59	6.08	4.45	3.16	9.40	8.73	5.24	6.24
Total	100.39	100.36	99.92	99.89	100.44	100.49	98.51	99.94

- 1: Microdiorite-microgabbro (Suzuki, 1954)
 2-5: Rodingite subzone (2 and 3) and chlorite subzone (4 and 5) from the Sarugawa serpentinite massif (Sample Nos. 77721-14-1 (2); 77721-14-2 (3); 77721-14-3 (4); 77721-14-4 (5)).
 6-11: Rodingite subzone (6, 7, 8, 9 and 10) and chlorite subzone (11) from the Niikappu serpentinite mass (Sample Nos. 80606-12e (6); 80606-12d (7); 80606-12c (8); 80606-12b (9); 80606-12a₂ (10); 80606-12a₁ (11)).
 12: Olivine clinopyroxenite from the Sarugawa serpentinite massif (Sample No. 75924-6).
 13-15: Clinopyroxenite (Sample No. 76720-3 (13)) and rodingite (Sample Nos. 76720-4 (14) and 76720-2-3 (15)) from the Sarugawa serpentinite massif.
 16-17: Slate from the Sarugawa Formation (Sample No. 74923-2 (16)) and rodingite metasomatized from the slate (Sample No. 74923-1 (17)).

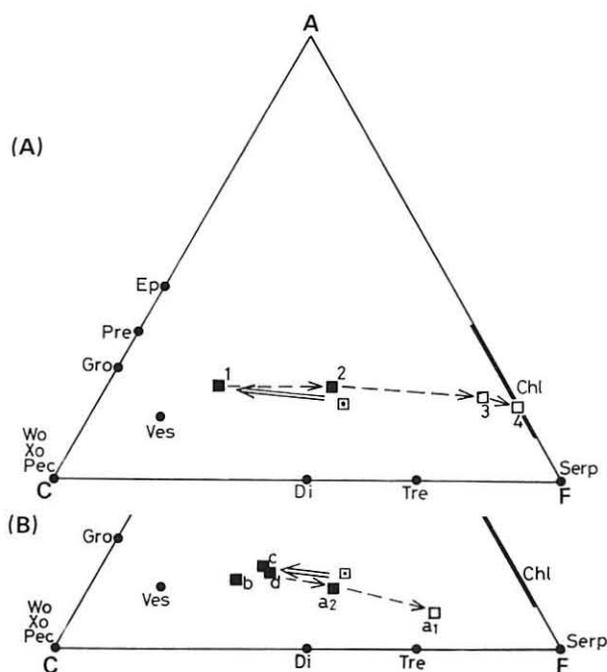
permanganate. The analytical procedures and conditions using the X-ray emission spectrometer followed those of Yamasaki (1979) and Yamasaki et al. (1980). Total H₂O was directly measured as wt % using a penfield tube.

Rodingite analyses given in Table 2 are plotted on ACF diagram (Text-fig. 6). Coleman (1977)'s "rodingite composition" is also plotted. As clearly shown in this diagram, two analyses of rodingite derived from microdiorite-microgabbro fall in the area of "rodingite composition", whereas all of the rest outside of this area. Compositions of such original rocks as microdiorite-microgabbro, olivine clinopyroxenite, and slate are plotted on the same diagram (Text-fig. 6). The plots tend to be scattered in different areas limited by those of each original rock. Rodingites derived from clinopyroxenite are plotted in the area closer to the AF tie-line than those from microdiorite-microgabbro. Rodingites derived from slates fall within the area rich in Ca near the C-apex.



Text-fig. 6 ACF diagram showing the compositional variations of rodingites and their original rocks. The area limited by broken line shows the rodingite composition after Coleman (1977). MD-MG: microdiorite-microgabbro. CPX: clinopyroxenite. SL: slate. Ep: epidote; Pre: prehnite; Gro: hydrogrossular; Cc: calcite; Wo: wollastonite; Xo: xonotlite; Pec: pectolite; Ves: vesuvianite; Di: diopside; Tre: tremolite; Chl: chlorite; Serp: serpentine.

Text-figs. 7A and B show a compositional variation in reaction zone between the original rock and the serpentinite. As mentioned above, several subzones are commonly observed in one reaction zone. The chemical analyses from each subzone are listed in Table 2. Nos. 1 to 4 in Text-fig. 7A correspond to the analyses of rodingites from the subzone Nos. 1 to 4 in Text-fig. 2. The original rock for these rodingites is microdiorite-microgabbro from the Sarugawa serpentinite massif. Open square with dot is rodingite from the original microgabbro, and solid squares (Nos. 1 and 2) from the rodingite subzones. Nos. 3 and 4 are plots of the chlorite subzones. Solid arrow shows a direction of chemical variation from the original microgabbro to the rodingite. Accordingly, it is noticed that the process of the rodingite formation is directed towards the grossular composition in the ACF diagram. A



Text-fig. 7 ACF diagrams showing compositional variations in the reaction zones. Symbols as in Text-fig. 6. Numbers refer to analyses shown in Table 2.

A: Rodingites metasomatized from microdiorite in the Sarugawa serpentinite mass (Sample No. 77721-14).

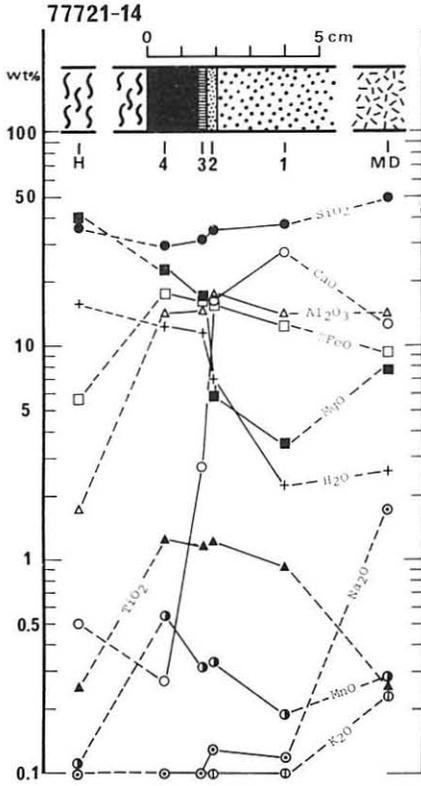
B: Rodingites metasomatized from microdiorite in the Niikappu serpentinite mass (Sample No. 80606-12).

reverse trend is also recognized. Broken line linking between Nos. 1, 2, 3, and 4 shows the direction of compositional change from the grossular towards the chlorite composition on the AF join along the grossular – chlorite tie-line. The similar relationships are also shown in Text-fig. 7B. In this case, the reverse trend proceeds towards the intermediate composition between chlorite and tremolite along the grossular-serpentine tie-line.

Variations in chemical composition are shown in Text-figs. 8 to 10, in which major elements are plotted as oxides on the logarithmic scale. It is obvious from these variation diagrams that the rodingites are characteristically high in the contents of H_2O , CaO , Al_2O_3 and TiO_2 and low in the contents of SiO_2 , Na_2O and K_2O as compared with the original rocks. In the case of rodingites derived from microdiorite-microgabbro (Text-figs. 8 and 9), the $FeO + Fe_2O_3$ content of rodingites as well as H_2O , CaO , Al_2O_3 , and TiO_2 contents is higher than that of the original rocks, whereas MgO as well as SiO_2 and alkali is lower. CaO content of rodingites derived from clinopyroxenite is conspicuously lower than that of the original rocks, as shown in Text-fig. 10. Such an exceptional trend is originally due to high CaO content of clinopyroxenites. Al_2O_3 content of the reaction zones shows the similar tendency of compositional variation as that of CaO .

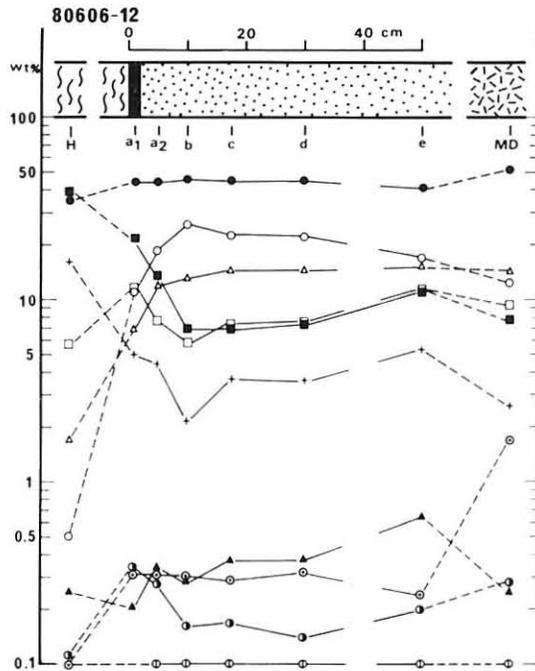
As shown in the variation diagram (Text-figs. 8 to 10), notable anomalies in H_2O variations can be observed at the points, 5 to 10cm inside from the boundary between the chlorite and the rodingite zones (Sample Nos. 77721-14-1, 80606-12b, and 76720-2-3). The anomalies show a conspicuous diminution of H_2O . This fact probably means that the dehydration was taken place mainly by hydrogrossulars, and sometimes by xonotlite.

In chlorite subzone, a distinct tendency of diminution of SiO_2 , CaO , Al_2O_3 , Na_2O , and



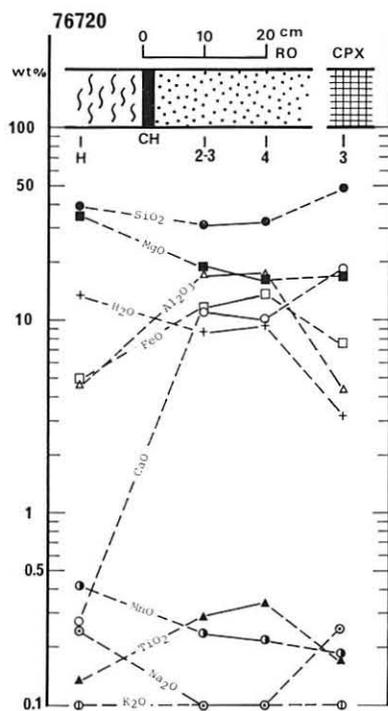
Text-fig. 8 Semilogarithmic plots of compositional variations of oxides for the rodingites (Nos. 77721-14-1 to 4) from the reaction zone in the Sarugawa serpentinite massif. Numbers 1 to 4 show the positions of chemical analyses. H: serpentinitized harzburgite, MD: fresh microdiorite.

Text-fig. 9 Semilogarithmic plots of compositional variations of oxides for rodingites (No. 80606-12) from the reaction zone in the Niikappu serpentinite mass.



K_2O contents and addition of H_2O , MgO , $FeO + Fe_2O_3$, MnO , and TiO_2 contents can be recognized. This tendency is pronounced in the chlorite zones metasomatized from microdiorite-microgabbro.

Rodingites are composed generally of Ca-rich minerals and have high CaO content. The origin of calcium is commonly accepted to be byproduct of serpentinization (Coleman, 1967; Barnes and O'Neil, 1969). Table 3 shows an average CaO content in serpentinitized dunite, harzburgite, and lherzolitic harzburgite, and in the constituent minerals from the Sarugawa serpentinite massif. The CaO content of fresh to weakly serpentinitized harzburgite and that of harzburgitic massive serpentinite are almost same. Diminution of CaO is notable



Text-fig. 10 Semilogarithmic plots of compositional variation of oxides for rodingites (No. 76720) from the reaction zone in the Sarugawa serpentinite massif. H: serpentinized harzburgite, CH: chlorite zone, and CPX: olivine clinopyroxenite.

Table 3 CaO contents in peridotite and serpentinite and in minerals from the Sarugawa serpentinite massif.

CaO content in bulk rocks (wt%)			
Original rock	Fresh to weakly serpentinitized \dagger	Massive serpentinite \ddagger	Foliated serpentinite
Dunite	0.18	0.08	—
Harzburgite	0.57	0.60	0.30
Lherzolithic H.	—	1.23	—

CaO content in minerals (wt%)		
	Fresh rock	Serpentinite
Olivine	0.08 – 0.04	0.08 – 0.05 lizardite
Orthopyroxene	2.3 – 1.3	0.39 – 0.20 lizardite

in the foliated serpentinite. Particularly, replacement of bastite from orthopyroxene is accompanied with a marked decrease of CaO content. Taking the above characteristics into consideration, it is possible to require the source of Ca to harzburgite.

Metasomatic Process into Rodingite

The foregoing descriptions demonstrate that the various rocks such as igneous ones ranging from ultrabasic to intermediate in composition and sedimentary ones may alter into rodingite. Field relationship and chemistry of rodingite show that the alteration into rodingite have taken place at the contact between the original rock and serpentinite. The process of rodingite formation has been discussed as a contact metamorphic process (Turner and Verhoogen, 1960) and as a magmatic process (Seki and Kuriyagawa, 1962; Cady et al., 1963). Following these discussions, metasomatic alteration has been pointed by some workers. As mentioned in the preceding sections, the compositional variation in the reaction zones reveals that the rodingite formation is due to metasomatic process in which a certain solution works effectively. Coleman (1966, 1967 and 1977) mentioned that the chemical nature of the metasomatic process is similar for all original rock types and the end products are also similar. For rodingites in the serpentinite masses of the Kamuikotan Tectonic Belt such a chemical trend quite resembles that mentioned by Coleman. Distribution of calcium is important to a metasomatic process of ultramafic rocks concentrated in Ca such as clinopyroxenite. The calcium in rodingites derived only from olivine clinopyroxenite is conspicuously poor, as shown in the chapter on petrochemistry. It is obvious that the metasomatism is controlled by the initial Ca content in the original rocks.

At the contact between serpentinite and metasomatized rock, chlorite zone containing a considerable amount of chlorite is occasionally observed. The formation of chlorite in this zone is believed to indicate a loss of alumina from the original rocks. Although all the ferromagnesian minerals are chloritized completely, the amount of chlorite exceeds, in most cases, that of the initial ferromagnesian minerals. It seems truly that the metasomatism has been most intensive in the chlorite zone.

The chlorite zone is characterized by a prominent decrease of CaO, Al₂O₃, and SiO₂ contents and an increase of total H₂O, MgO, total FeO, MnO, and TiO₂, as compared with those in the rodingite zone. Taking the petrographic and chemical evidence into consideration, it seems likely that Ca and H₂O migrated towards rodingite from serpentinites during the metasomatism. Throughout the chlorite zone, Si and alkali are considered to have moved outward from the original rock. On the other hand, a considerable amount of Mg, Fe, Mn, and Ti as well as Ca and Al might have fixed in the chlorite zone.

Towards the original rock, degree of metasomatism rapidly decreases. The metasomatic alteration is observed partly within veins and/or crashed parts near the original rock. Because of insufficient permeation of H₂O through the reaction zone, it is considered that the metasomatism has not well proceeded towards the original rocks.

Temperature and Pressure Conditions of Metasomatism

The geological environment where the rodingites were formed has been estimated by many workers on the basis of experimental investigations.

Buckner et al. (1960) studied the stability relation between xonotlite and wollastonite under hydrothermal condition and demonstrated that the highest stability limit of xonotlite is located between about 400°C at 1 atm and about 430°C at 2000 atm. At higher

temperature side wollastonite is formed by dehydration of xonotlite. On the other hand, according to Kalinin (1967), the lowest temperature at which wollastonite begins to crystallize is about 350°C at pressure of 200 atm, and no wollastonite was found in the runs at 350°C and 500 atm. Xonotlite and wollastonite coexist in the rodingites (Nos. 80606-10a and b) from the Niikappu serpentinite mass. The wollastonite contains many saved grains of small xonotlite. Assuming that both minerals are in equilibrium, the temperature range during the metasomatism was from about 350°C to 430°C, at which the xonotlite grains were replaced by wollastonite. Independent crystals of wollastonite are found in the rodingite zone (Sample Nos. 80606-12a₂, b, c, d, and e) of the Niikappu serpentinite mass. This means that the wollastonite would be formed at the temperature higher than the reaction boundary between xonotlite and wollastonite. In this case, some wollastonites coexist with vesuvianite (Sample No. 80606-12c).

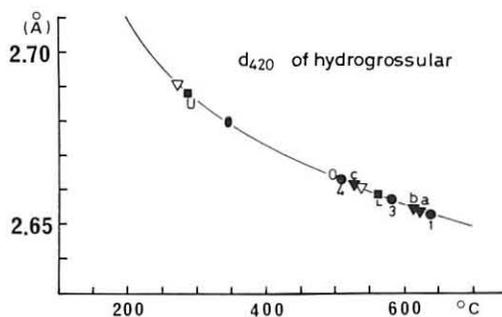
Hydrothermal experiments on the low pressure type vesuvianite were carried out by Rapp and Smith (1958) and Ito and Arem (1970). Vesuvianite has a wide stability field ranging from about 400°C to 720°C with water pressure of 2kb, and from about 350°C to 650°C at 0.5kb in alkali-free system (Ito and Arem, 1970). The vesuvianite breaks down into diopside + hydrogarnet + Ca₂SiO₄·nH₂O below the lower temperature limit. According to Shoji (1971), the stability field is narrower than that of Ito and Arem. At the pressure of about 0.5kb, vesuvianite is stable from 400°C to 600°C.

Small amounts of vesuvianites are found in rodingites from the Kamuikotan Tectonic Belt (Sample Nos. 80606-12c, 80606-8b, and 74109-6b). The vesuvianites are usually coexisting with diopside and hydrogrossular, and sometimes with chlorite. Vesuvianite veins composed of vesuvianite, diopside, chlorite, and rarely hydrogrossular also occur in the rodingite No. 74109-6b.

The formation of diopside was examined by Kalinin (1967) under low CO₂ and H₂O pressures. The results indicate that the lower temperature limit at 0.5kb lies between 350°C and 380°C.

Characteristically, the rodingites from the Niikappu serpentinite mass (Nos. 80606-12 and 10) contain prehnite and chlorite. Some rodingites (No. 80606-12) are associated with epidote. No pumpellyite has been found in these rocks. From the experimental investigations by Schifeman and Liou (1981), such assemblages are considered to occur at the temperatures between 300°C and 400°C at the pressures between 1kb to 5kb.

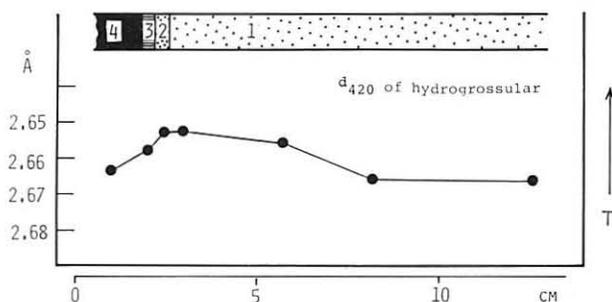
Variation of interplanar spacing d_{420} of the hydrogrossulars in some rodingites from



Text-fig. 11 The d_{420} -temperature diagram showing the variation in d_{420} of hydrogrossular from rodingites. The variation curve taken from Shoji (1971). 1, 3, and 4: from the rodingites Nos. 77721-14-1, 3, and 4; a, b, and c: Nos. 80606-8a, b, and c; U: No. 74923-1; L: No. 74109-6-2.

the Kamuikotan Tectonic Belt was examined from X-ray powder diffraction pattern. The data are plotted on the d_{420} -temperature diagram (Text-fig. 11) to estimate the temperature of formation of grossular by using the variation curve given by Shoji (1971). The plots distribute in a considerably wide temperature range from 250°C to 650°C. The most plots cluster between about 500°C and 650°C. It is unlikely, however, that the rodingites were formed at these high temperature, as discussed before.

Text-fig. 11 also shows a distribution of d_{420} of hydrogrossular in some reaction zones. Numbers in this diagram show the positions in the reaction zone (Sample Nos. 77721-14-1 to 4; as shown in Text-fig. 2) of the Sarugawa serpentinite massif. It is clearly shown that the crystallization temperature of hydrogrossular decreases from the rodingite zone towards the contact plane with serpentinite. This tendency is also observed in the reaction zone (Nos. 80606-8a, b, and c) of the Niikappu serpentinite mass. As shown in Text-fig. 12, the temperature of crystallization of hydrogrossular attains maximum. The hydrogrossular in the rodingite (No. 77721-14-1) closest to the boundary plane between the rodingite and chlorite zones represents the highest grade product of the metasomatism. The position of rodingite showing the highest grade corresponds approximately to that of which has the highest dehydration rate, as mentioned earlier. It can be said, therefore, that the chlorite zone was formed retrogressively during the metasomatism.



Text-fig. 12 Plots of d_{420} of hydrogrossular showing the variation in reaction zone (Sample No. 77721). Numbers 1 to 4: the reaction subzone Nos. 1 to 4 shown in Text-fig. 2.

Concluding Remarks

(1) A large number of rodingites were found in the Sarugawa serpentinite massif, the Niikappu mass, and other serpentinite masses of the Kamuikotan Tectonic Belt. The rodingites occur as xenoblocks, dykes, and pipe-like small masses, which in places grade into the original host rocks. In most cases, the rodingites are derived from microdiorite-microgabbro, olivine clinopyroxenite, and slate. On the borders of the Sarugawa serpentinite massif, the country rocks (slates) are partly altered into rodingite.

(2) The rodingite reaction zone is divided into the following two zones. One is rodingite zone which has a representative mineral assemblage of rodingite composed mainly of diopside, hydrogrossular, wollastonite, chlorite, prehnite, and tremolite. The other is chlorite zone which characteristically contains a large amount of chlorite.

(3) Compositional variation shows that the process of rodingite formation is metasomatic. The rodingites from the reaction zones are conspicuously enriched in CaO, Al_2O_3 , TiO_2

and H₂O, and depleted in SiO₂, Na₂O and K₂O, as compared with the original rocks. In the chlorite zone, a distinct tendency of diminution of SiO₂, CaO, Al₂O₃, Na₂O, and K₂O, and addition of H₂O, MgO, FeO + Fe₂O₃, MnO, and TiO₂ is recognized. Therefore, the following metasomatic process can be considered. Ca, Al, Ti and H₂O migrated from serpentinites into the reaction zone during the metasomatism. Throughout the reaction zone, Si and alkali moved outward from the original rocks. On the other hand, a considerable amount of Mg, Fe, and Mn as well as Ca, Al, Ti, and H₂O fixed in the chlorite zone.

(4) Taking the experimental results under hydrothermal condition into consideration, it seems likely that the temperature range of crystallization of some wollastonites with many xonotlite grains were from about 350°C to 430°C, at which the xonotlite grains were replaced by wollastonite. Many other grains of wollastonite which occurs independently in rodingite would be formed at the temperature higher than the reaction boundary between xonotlite and wollastonite. It is also considered from the stability ranges of vesuvianite, diopside, and hydrogrossular that the temperature during the metasomatism were generally higher than 350°C. On the other hand, some of hydrogrossular, prehnite, and chlorite were probably formed at slightly lower temperature. The hydrogrossular in the rodingite closest to the contact plane with chlorite zone represents the product at the highest grade in metasomatism.

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