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METAMORPHOSED DOLERITE INTRUSIVES FROM THE WESTERN ZONE OF THE HIDAKA METAMORPHIC BELT, HOKKAIDO

by

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(with 15 text-figures and 5 tables)

Abstract

Metamorphosed dolerite intrusives in ultramafic tectonites, cumulates, and metagabbros are first described from the Western Zone of the Hidaka Metamorphic Belt. The dolerite intrusives ranging from a few cm to 30m in thickness occur as a dyke or sheet. Most of the dolerite intrusives are metamorphosed into amphibolite or metadolerite in various degrees. The metamorphic grade attains generally up to the amphibolite facies, and partly to the hornblende granulite facies in the ultramafic tectonites. Primary textures and minerals are well preserved in some metamorphosed intrusives. After mylonitization of the ultramafic tectonite the dolerite magma is considered to have intruded into the tectonites and into the already consolidated cumulate and gabbro complexes. Petrochemical and mineralogical data indicate that all of the dolerite intrusives are co-magmatic and are formed by crystallization of an olivine tholeiite magma which is highly undersaturated in silica and less differentiated.

Introduction

Recent progress on geological and petrological studies of the Hidaka Metamorphic Belt is summarized in the following two points.

1. The Western Zone of the Hidaka Metamorphic Belt has been identified as an ophiolite zone which is completely made up of ultramafic to mafic cumulates, gabbros, dolerites, and submarine basic volcanics and pelagic sediments (Miyashita, in preparation).
2. In investigating the metamorphic rocks of the Main Zone of the Hidaka Metamorphic Belt, granulites were found and elucidated by Arita *et al.* (1978) and Komatsu (1980). Subsequent to description of the mode of occurrence of the boundary zone between the Main and Western Zones of the belt (Hashimoto, 1975, 1976; Miyashita and Maeda, 1978), the Hidaka Metamorphic Belt has been clearly divided into two zones (Komatsu *et al.*,1979). One is the Western Zone characterized as an ophiolite zone, and the other is the Main Zone, which has a nature of continental margin or island arc.

Ultramafic rocks in the Hidaka Metamorphic Belt are distributed along the boundary zone between the Main and Western Zones of the belt. Recently, the intrusive process of these ultramafic rocks has been studied (Niida, 1975; Komatsu, 1974, 1975). Komatsu (1977) stated that the ultramafic rocks are divided into two series on the basis of difference in equilibrium temperature as shown by the $Al_2O_3 - Cr_2O_3$ contents of pyroxenes. On the other hand, the Western Zone is mainly composed of greenschists, amphibolites, and metagabbros, which are originally effusive basaltic hyaloclastite and pillow lava(?), dolerite intrusives, and cumulate plutonics, respectively. These metamorphosed rocks show a nearly

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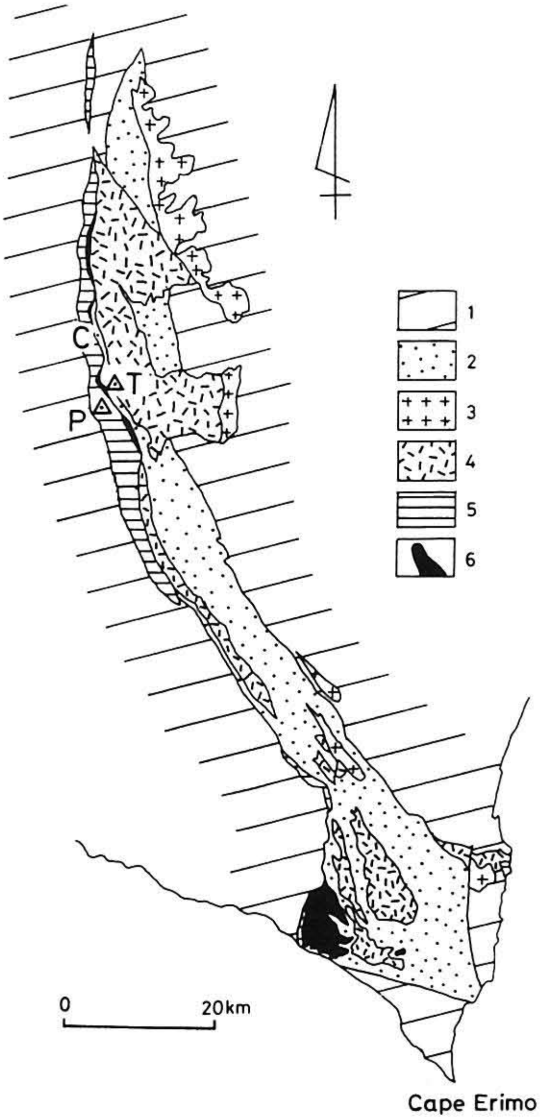
Contribution from the Department of Geology and Mineralogy, Faculty of Science, Hokkaido University, No. 1708.



Text-fig. 1. Simplified geologic map of the Hidaka Metamorphic Belt.
1: Hidaka Super Group. 2: Biotite schist, gneiss and migmatite. 3: Granite. 4: Mafic rocks of the Main Zone. 5: Mafic rocks of the Western Zone. 6: Ultramafic rocks. P: Mt. Poroshiri. T: Mt. Tottabetsu. C: Chiroro River.

complete stratigraphic succession in descending order. Additionally, some dunite-harzburgite tectonite masses which are arranged along the western side of the boundary zone are stratigraphically overlain by the above ophiolite succession with a tectonic contact.

Recently, a considerable number of metamorphosed dolerite dykes and sheets were found in these ultramafic tectonites, metamorphosed cumulates, and metagabbros in the Western Ophiolite Zone of the Hidaka Metamorphic Belt. The dolerites are usually metamorphosed into amphibolite or metadolerite. Small amounts of relict minerals such as olivine, clinopyroxene, and plagioclase were also found. In this paper, the occurrence and petrographic features of the dolerite intrusives and the characteristics of their chemical compositions will be described, then the nature of the dolerite magma will be discussed.

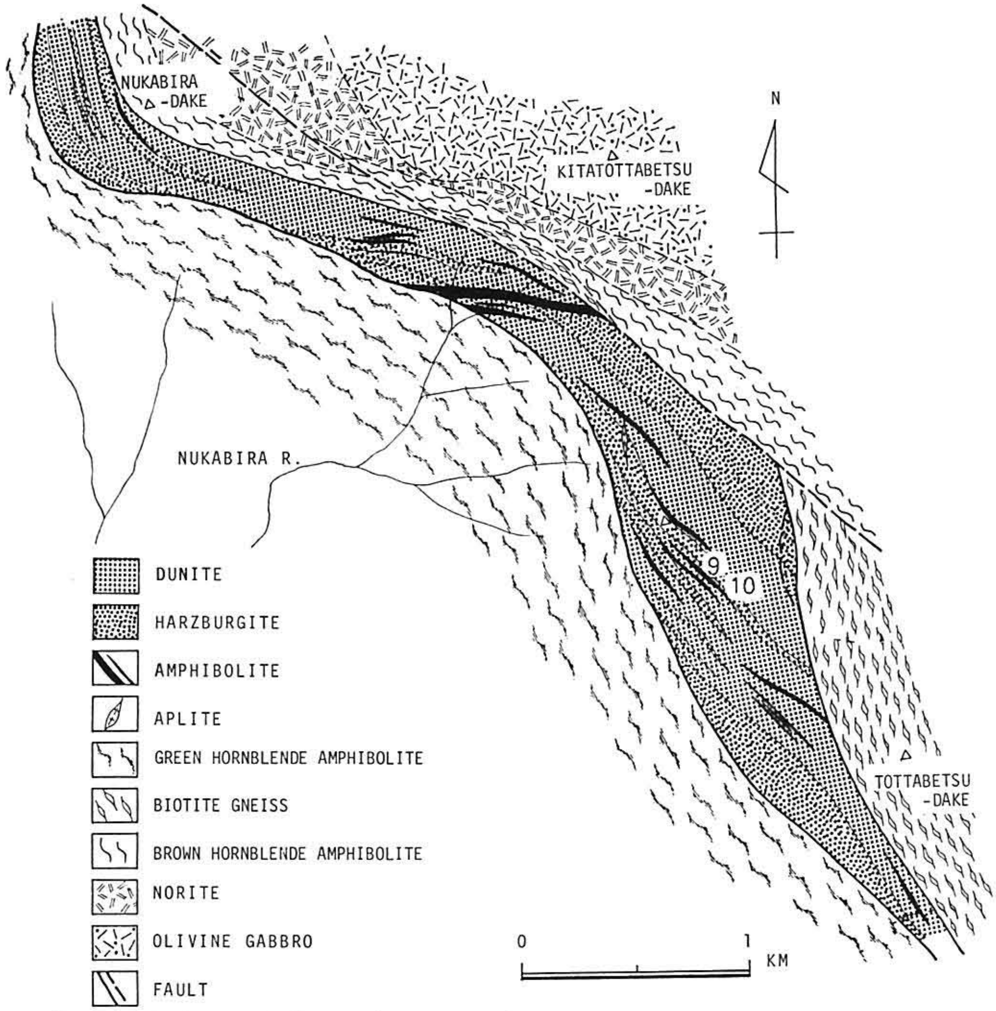
Features of Occurrence

The Western Zone of the Hidaka Metamorphic Belt which is mainly composed of blackschist, greenschist, epidote amphibolite, green hornblende amphibolite, metagabbro, metamorphosed cumulate, and ultramafic tectonite is exposed in an area about 70 km long and 1 to 4 km wide in the northern to middle part of the metamorphic belt (Text-fig. 1). Metamorphosed dolerite dykes and sheets are found as a minor intrusive body ranging from a few cm to 30 m thick in the ultramafic tectonites, metamorphosed cumulates, and metagabbros, which correspond to the lower half of the above ophiolite succession.

The metamorphosed dolerite intrusives in the ultramafic tectonites are found in the Uenzaru, Pankenushi, Tottabetsu, Oku-Niikappu, and Koibokushu-Shibichari masses. Considering the ultramafic rock types, the tectonite masses are clearly different from the other ultramafic masses. The former is completely composed of dunite and harzburgite with small amounts of orthopyroxenite, whereas the latter, represented by the Horoman, Nikanbetsu, Niobetsu, and Uenzaru masses, is mainly composed of dunite (including harzburgite), lherzolite, plagioclase lherzolite, and minor ortho- and clinopyroxenites (Niida and Katoh, 1978). It appears from the above that the metamorphosed dolerites intruded only in the dunite-harzburgite tectonites. The dolerite intrusives in the ultramafic tectonite are generally metamorphosed into brown hornblende amphibolite. Many amphibolite intrusives occur in the Tottabetsu dunite-harzburgite mass, as shown in Text-fig. 2. A low grade metamorphism, however, is rarely recognized in the dolerite intrusives along the Niikappu River. In many cases, the contact plane of the amphibolites is parallel to the primary phase layering and the mylonitization foliation plane of the ultramafic tectonites. In some cases, however, the amphibolite intrusives clearly cut the mylonitization foliation plane. As shown in Text-fig. 3A, a branching dyke is observed in a few cases. As a more rare occurrence, some ultramafic blocks are found in the amphibolite intrusives. In the exposure along the Niikappu River (Text-fig. 3B), where the dunite mylonite blocks in amphibolite can be seen, the blocks are entirely enclosed by the surrounding amphibolite. In addition, schistosity formed by an arrangement of metamorphic amphiboles is clearly observed in the field. The arrangement of amphiboles is completely parallel to the contact plane.

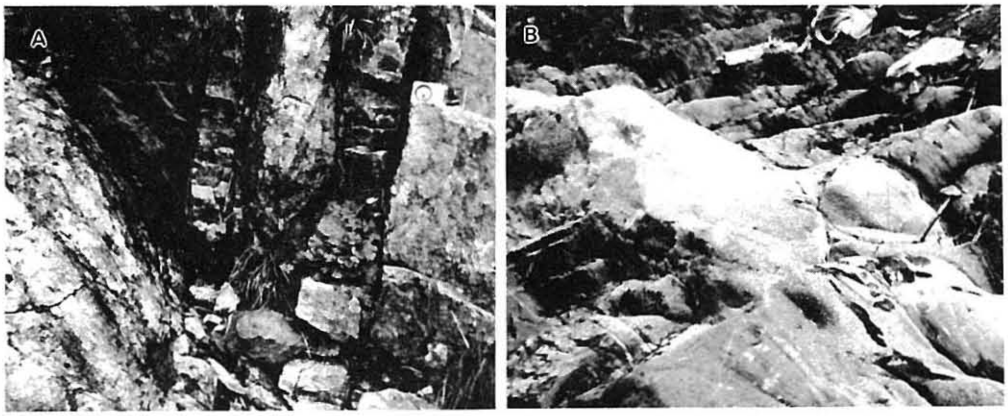
In the Mt. Poroshiri area, a metamorphosed cumulate complex which is composed mainly of anorthosite, troctolite, and dunite with various degree of recrystallization is exposed (Miyashita and Hashimoto, 1975). Several dolerite intrusives are also found in this area, as shown in Text-fig. 4. The intrusives are completely metamorphosed into amphibolites. The host anorthositic troctolite is also metamorphosed. Another type of dolerite dykes, clearly distinguished from these intrusives on the basis of bulk composition and mineral chemistry, is also observed around Mt. Poroshiri.

Dolerite intrusives in olivine gabbro or in the metamorphics are observed along the upper stream of the Chiroro River. Along the route twelve dykes are found within a distance about 1 km (Text-fig. 5). The width of the dolerite intrusives ranges from a few cm

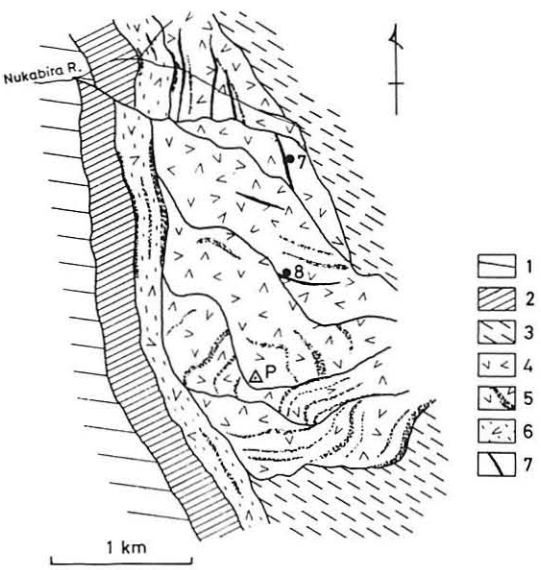


Text-fig. 2. Geologic map of the Tottabetsu ultramafic mass. Amphibolites with numbers 9 and 10 are analysed samples (in Table 5).

to 5 m. The geologic section is characterized by lensoid bodies of a relatively unmetamorphosed olivine gabbro which grades outward to plagioclase blastoporphyritic amphibolite with increasing schistosity (Grapes *et al.,* 1977). When the host rock did not suffer from metamorphism, the intrusives are also free from recrystallization. When the host rock is of plagioclase blastoporphyritic amphibolite, the intrusives are also metamorphosed into a fine-grained amphibolite. Usually, recrystallization of the dolerite intrusives is more complete than that of the host rocks. Such a discrepancy of the recrystallization between the intrusives and the host rocks is considered to be caused by difference in original grain size. The trend of the intrusives is slightly oblique against the layering plane of the host gabbros (Text-fig. 6). Chilled margin is observed in weakly metamorphosed dykes. At the



Text-fig. 3. Photographs showing the mode of occurrence of metamorphosed dolerite intrusives.
A: Amphibolite with a branch, on the SW slope of Mt. Kita-Tottabetsu. B: Dunite tectonite block in amphibolite, along the Niikappu River.



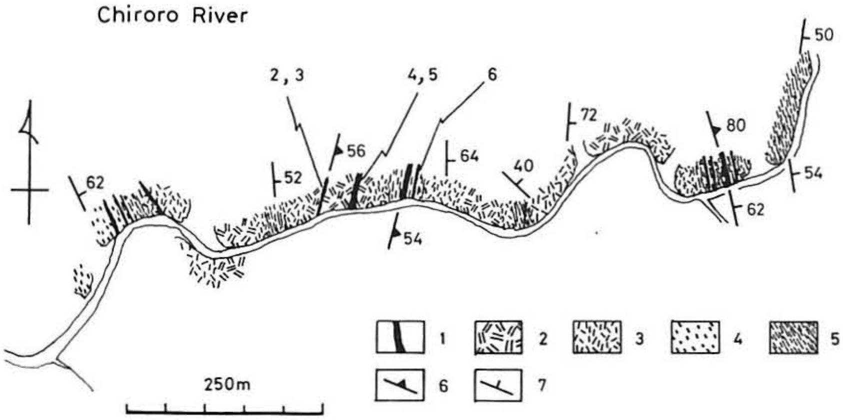
Text-fig. 4. Simplified geologic map of the Mt. Poroshiri area.
1: Hidaka Super Group. 2: Greenschist and epidote amphibolite. 3: Green hornblende amphibolite and plagioclase blastoporphyritic amphibolite. 4: Plagioclase-olivine cumulate. 5: Olivine cumulate. 6: Mylonite. 7: Metamorphosed dolerite intrusive. P: Mt. Poroshiri. Dots with numbers 7 and 8 are analysed samples (in Table 5).

chilled margin long prismatic grains of plagioclase show a parallel arrangement with the contact plane (Text-fig. 8A). Moreover, olivine phenocrysts are gradually concentrated toward the center of the intrusives, which indicates a flow differentiation.

Taking all these modes of occurrence of the dolerite intrusives into consideration, the time of the intrusion and the metamorphism is interpreted as follows.

1. The dolerites intruded into the ultramafic tectonites after a mylonitization of dunite and harzburgite tectonites. The intrusion level is considered to be at the shallow parts of the crust.

2. The dolerites intruded into cumulate and gabbro complexes after their consolidation and



Text-fig. 5. Geologic sketch map along the Chiroro River.
1: Metadolerite and amphibolite. 2: Metagabbro. 3: Transitional part between 2 and 5. 4: Metamorphosed anorthositic gabbro. 5: Plagioclase blastoporphyritic amphibolite. 6: Schistosity and layering plane. 7: Contact plane of intrusives.

Text-fig. 6. Metadolerite about 20 cm in thickness intruding into metagabbro and cutting the layering plane, along the Chiroro River.

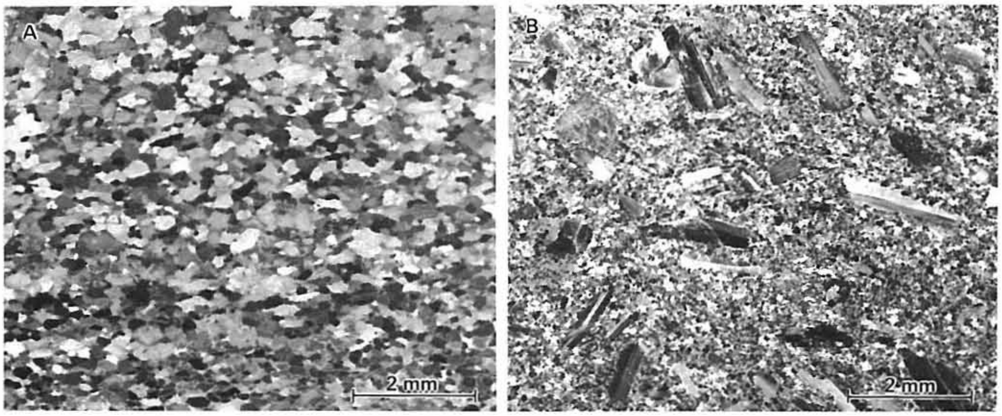
considerable cooling.

3. Metamorphism of the dolerite intrusives took place after the crystallization and consolidation of the dolerite magma and proceeded generally under a condition of the amphibolite facies.

Petrography

Metamorphosed dolerite in ultramafic tectonites

The amphibolite in the ultramafic tectonites is mainly composed of 60 to 80 % brown hornblende and 20 to 30 % plagioclase, with accessory opaque minerals. Some amphibolites having a well developed schistosity show a nematoblastic texture (Text-fig. 7A). Fine-grained amphibolites, generally from the marginal parts of the intrusives, tend to show a blastoporphyritic or mylonitic texture. The amphiboles are completely metamorphosed ones, pleochroic from pale brown to brown and 0.2 to 1.5 mm in grain size. As shown in Table 1, the Mg/Mg+Fe ratio of the amphiboles varies from 86.9 to 60.7. TiO_2 contents are relatively high, ranging from 0.56 to 2.08 %. In rare cases, the amphibolites contain primary olivines, clinopyroxenes, and plagioclases as relict minerals (Text-fig. 7B).



Text-fig. 7. Negative photomicrographs of amphibolite in ultramafic tectonite.
A: Amphibolite showing a nematoblastic texture (Sample No. 81205) B: Amphibolite containing relict plagioclases, clinopyroxenes and olivines (Sample No. TR 6).

Relict olivine usually shows anhedral shape ranging from 0.5 to 4.0 mm in grain size. The olivine grain is rimmed by small granular grains of orthopyroxene and is occasionally accompanied by euhedral chromian spinels. Sometimes, the olivine grain is completely replaced by equigranular orthopyroxenes. The En content of the orthopyroxenes varies from En_{83} to En_{61} (Table 2). Mg-rich orthopyroxene occurs on the contact side of the rims. Fo content of the olivine ranges from Fo_{86} to Fo_{69} (Table 3). Clinopyroxenes from the metamorphosed intrusives commonly occur as a relict mineral. The clinopyroxene shows a subhedral to anhedral grain shape ranging from 0.3 to 1.5 mm in size. The primary grains of clinopyroxene are directly surrounded by metamorphic amphiboles. The clinopyroxenes vary in composition from $Ca_{45}Mg_{46}Fe_9$ to $Ca_{42}Mg_{41}Fe_{17}$. The chemical composition of clinopyroxenes will be described together with those from the intrusives in metagabbros. Relict plagioclases are often found in the amphibolite. The plagioclase grains show an euhedral to subhedral shape ranging from 0.5 to 3.0 mm in size. The crystal habit of

Table 1 Selected EPMA analyses of hornblende.

	1	2	3	4	5	6	7
SiO_2	50.34	46.76	44.47	48.49	45.51	43.00	46.07
TiO_2	0.56	1.27	1.16	1.92	1.85	2.08	0.84
Al_2O_3	5.64	9.40	11.53	9.34	10.35	11.54	14.49
Cr_2O_3	0.98	0.06	0.06	n.d.	0.22	0.04	n.d.
FeO*	10.75	11.98	14.18	9.39	13.61	14.07	5.85
MnO	0.12	0.15	0.20	0.12	0.12	0.11	0.12
MgO	16.17	13.81	11.58	15.30	12.90	11.55	17.01
CaO	12.81	12.36	12.11	11.67	11.89	12.19	11.89
Na_2O	1.16	1.60	1.38	1.28	1.93	2.22	2.43
K_2O	0.11	0.18	0.34	0.25	0.30	0.37	0.22
Total	98.64	97.56	97.31	97.76	98.68	97.17	98.92
Numbers of cations on the basis of 23 oxygens							
Si	7.202	6.818	6.578	6.925	6.630	6.418	6.437
Al^{IV}	0.798	1.182	1.422	1.075	1.370	1.582	1.563
Al^{VI}	0.153	0.433	0.640	0.497	0.407	0.448	0.823
Ti	0.060	0.139	0.129	0.206	0.203	0.233	0.088
Cr	0.111	0.007	0.007	–	0.025	0.005	–
Fe^{2+}	1.286	1.460	1.754	1.122	1.658	1.750	0.684
Mn	0.015	0.019	0.025	0.015	0.015	0.014	0.014
Mg	3.499	3.001	2.554	3.257	2.802	2.570	3.543
Ca	1.963	1.930	1.919	1.786	1.855	1.949	1.780
Na	0.322	0.453	0.396	0.354	0.545	0.642	0.658
K	0.020	0.033	0.064	0.046	0.055	0.070	0.039
Total	15.378	15.475	15.488	15.283	15.565	15.687	15.630

* Total iron as FeO 1-3: from metadolerite in metagabbro 4-7: from amphibolite in ultramafic tectonite

plagioclase is occasionally characterized by a long prismatic one, which is commonly seen as a dolerite texture. Large grains of plagioclase range from An_{83} to An_{74} at the core and from An_{71} to An_{46} at the margin, showing a conspicuous normal zoning only at the marginal parts.

In some amphibolites in the ultramafic tectonites, fine-grained clinophroxene and orthopyroxene are rarely found associated with small grains of amphibole in the matrix of the amphibolites. Such orthopyroxenes are generally rich in Fe content (En_{61}, in Table 2). The amphiboles contain more than about 2 wt % in TiO_2 (No. 6 in Table 1). Accordingly, it might be stated that the metamorphic grade of amphibolites partly attains up to the hornblende granulite facies.

A later phase metamorphism can be sometimes distinguished from that of amphibolite facies. For example, chlorite + actinolite + albite + clinozoisite assemblage occurs in amphibolites from the Nikkappu River.

Table 2 Selected EPMA analyses of orthopyroxene.

	1	2	3	4	5
SiO_2	56.06	56.27	55.42	53.65	51.99
TiO_2	0.02	0.03	0.04	0.03	0.03
Al_2O_3	0.94	1.13	1.04	0.79	0.96
Cr_2O_3	0.07	n.d.	n.d.	0.08	0.06
FeO*	11.26	11.67	12.06	21.71	24.77
MnO	0.26	0.15	0.31	0.46	0.49
MgO	30.90	31.05	31.17	23.19	21.69
CaO	0.13	0.08	0.18	0.26	0.41
Na_2O	–	–	0.04	0.04	–
Total	99.63	100.39	100.26	100.22	100.39
	Numbers of cations on the basis of 6 oxygens				
Si	1.982	1.976	1.958	1.984	1.954
Al^{IV}	0.018	0.023	0.041	0.016	0.043
Al^{VI}	0.021	0.023	0.001	0.023	–
Ti	0.001	–	0.001	0.001	0.001
Cr	0.002	–	–	0.002	0.002
Fe^{2+}	0.333	0.342	0.356	0.671	0.778
Mn	0.008	0.004	0.009	0.015	0.016
Mg	1.629	1.625	1.641	1.278	1.215
Ca	0.005	0.003	0.006	0.010	0.017
Na	–	–	0.002	0.003	–
Total	3.999	3.999	4.020	4.003	4.026
Mg/Mg+Fe	0.830	0.826	0.822	0.656	0.609

* Total iron as FeO 1: from metadolerite in metagabbro 2 and 3: reaction rim from amphibolite in ultramafic tectonite. 4: aggregate from amphibolite in ultramafic tectonite 5: small grain in matrix of amphibolite in ultramafic tectonite

Metamorphosed dolerite in cumulates

The dolerite intrusives in the cumulates are metamorphosed into amphibolite which is composed mainly of amphibole, plagioclase, with small amounts of sphene and magnetite. The original textures and minerals are not generally preserved. The grain size of amphiboles (Z' = green to brownish green) ranges from 0.2 to 1.0 mm. Sometimes, the amphibolite contains large grains of relict plagioclase up to about 4 mm in size. Such a plagioclase has a notable normal zoning at the margins. The An content of the plagioclase ranges from An_{74} to An_{70} at the central parts and from An_{64} to An_{53} at the margins.

Metamorphosed dolerite in metagabbros

The dolerite intrusives in the metagabbros suffered from various degrees of recrystallization under the condition of the amphibolite facies as mentioned in the previous chapter.

Table 3 Selected EPMA analyses of olivine.

	1	2	3	4	5
SiO_2	40.21	39.72	38.68	37.96	36.99
Al_2O_3	0.07	0.09	0.00	0.00	0.02
Cr_2O_3	0.05	0.03	–	–	0.00
FeO*	14.42	17.26	22.23	26.62	27.37
MnO	0.15	0.19	0.30	0.32	0.38
MgO	45.22	42.30	39.69	35.06	34.61
CaO	0.23	0.08	–	0.03	0.00
Total	100.36	99.67	100.94	100.00	99.38
	Numbers of cations on the basis of 4 oxygens				
Si	1.002	1.009	0.995	1.007	0.994
Al	0.002	0.003	–	–	0.001
Cr	0.001	0.001	–	–	–
Fe^{2+}	0.301	0.367	0.478	0.590	0.615
Mn	0.003	0.004	0.006	0.007	0.009
Mg	1.680	1.603	1.522	1.386	1.386
Ca	0.006	0.002	–	–	–
Total	2.995	2.989	3.005	2.992	3.005
Mg/Mg+Fe	0.847	0.812	0.761	0.701	0.690

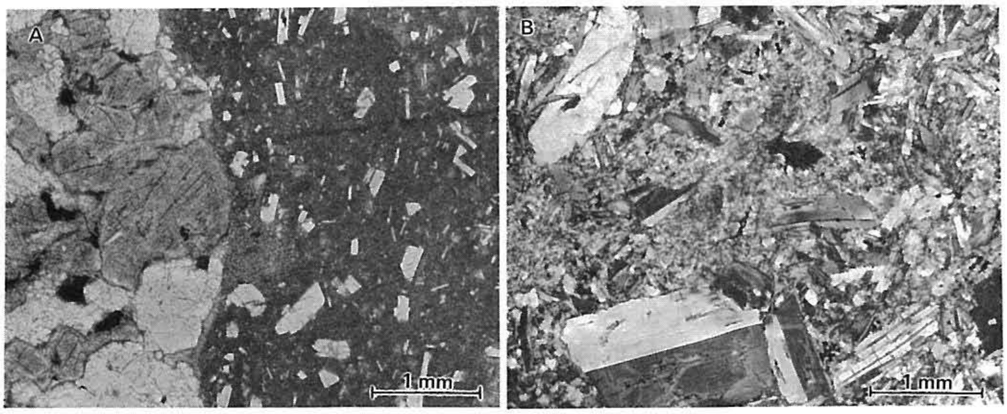
* Total iron as FeO 1-2: from metadolerite 3-5: from amphibolite in ultramafic tectonite

Approximately, a half number of the intrusives remain fresh. In the relatively unmetamorphosed dolerites which are exposed along the Chiroro River, the chilled margin is clearly distinguished into phenocryst and groundmass, and therefore shows porphyritic texture (Text-fig. 8A). The phenocrysts consist mainly of plagioclase. Small amounts of olivine and clinopyroxene are also found as primary phenocrysts. The groundmass is made up almost entirely of clinopyroxene, plagioclase, with accessory opaque minerals. Plagioclase laths are arranged in parallel with the contact plane. On the other hand, the metadolerite near the center has a subophitic texture as shown in Text-fig. 8B.

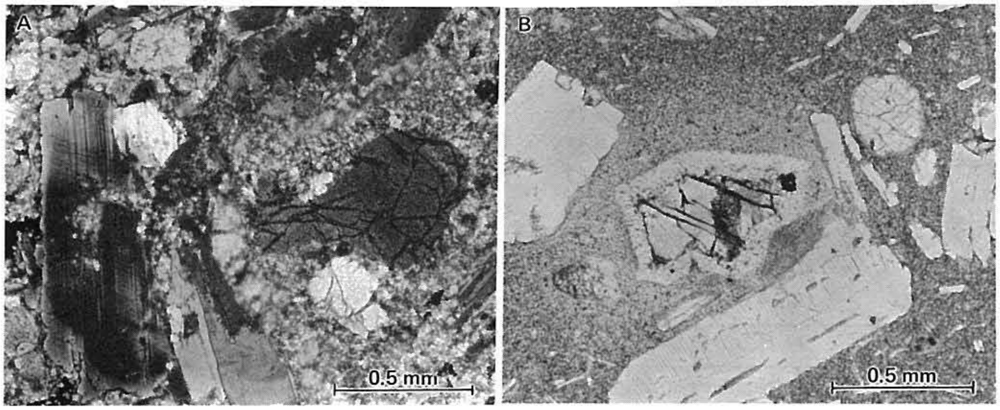
The main constituents of the dolerite are coarse to medium-grained plagioclase (0.2 to 3.0 mm in diameter), olivine (0.2 to 2.0 mm), and fine-grained clinopyroxene (0.05 to 0.3 mm). The olivines are usually mantled by small granular grains of orthopyroxene. The clinopyroxenes are enclosed by amphiboles with pleochroism (Z' = pale green to greenish brown). The plagioclases as a primary crystal are subhedral to euhedral and show conspicuous normal zoning. The An contents of the core range from An_{76} to An_{68}. The plagioclases contain relatively high Fe_2O_3 ranging from 0.74 to 0.40 wt %.

Olivines are generally subhedral to anhedral in grain shape, and sometimes embay plagioclase. The compositions of the olivine vary from $Fo_{84.7}$ at the core to $Fo_{81.2}$ at the margin (Table 3). Reaction rims of orthopyroxene and spinel + hornblende symplectite usually appear along the boundary between olivine and plagioclase crystals (Text-fig. 9A).

petrographic features of the dolerite intrusives and the characteristics of their chemical compositions will be described, then the nature of the dolerite magma will be discussed.



Text-fig. 8. Photomicrographs of weakly metamorphosed dolerite in metagabbro. A: Contact of metadolerite with metagabbro (Sample No. Ch 2c) B: Center of metadolerite dyke (Sample No. Ch 118)



Text-fig. 9. Photomicrographs of metadolerite showing a reaction relation.
A: Reaction rim (orthopyroxene - hornblende+spinel symplectite) between olivine and plagioclase. B: Olivine completely surrounded by orthopyroxene grains.

Orthopyroxene also occurs around the olivine grains when the olivine does not contact directly with plagioclase (Text-fig. 9B). Therefore, some orthopyroxenes may be formed not only by metamorphic reaction but also by reaction between olivine and magma. Olivine from the host olivine gabbros has the same reaction rims as those of the dolerite intrusives. It is considered from this evidence that the metamorphism producing the reaction rim occurred after the intrusion of the dolerite magma.

Fine-grained amphiboles with a varied pleochroism appear around the primary clinopyroxene and also within the interstices of the other minerals. Occasionally, the latter amphiboles are accompanied by small irregular grains of magnetite and Cr-spinel. The amphiboles surrounding the primary clinopyroxene tends to be Z' = pale green to green in pleochroism, whereas the amphiboles accompanied by opaque minerals tend to be Z' =

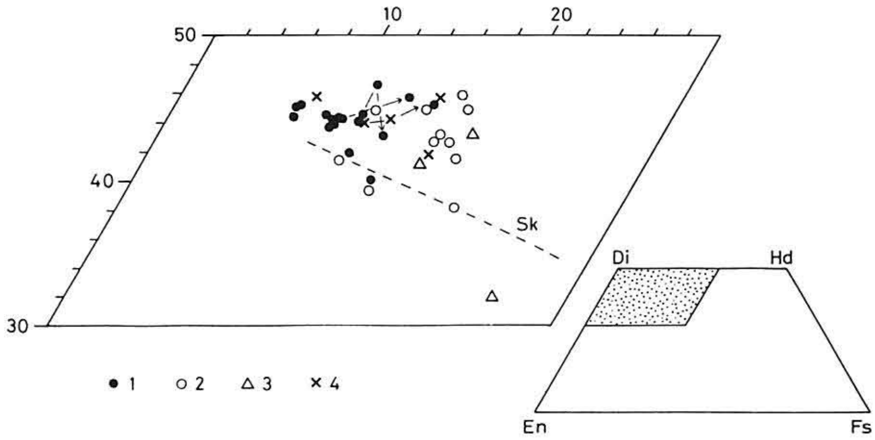
brownish green to brown. Chemical compositions of the amphiboles show a considerable difference between the above two amphiboles; the former is actinolitic hornblende, whereas the latter is hornblende, as listed in Table 1. Although it is questionable whether the amphiboles are of igneous origin or metamorphic origin, some amphiboles may be crystallized directly from the magma.

Primary clinopyroxene is subhedral to anhedral, and is commonly replaced by amphiboles from the margin. At the chilled margin of the dolerite intrusives, clinopyroxenes occur as a small phenocryst as well as in the groundmass. Sector zoning of clinopyroxenes is rarely found in those of the chilled margin. Analyses of the clinopyroxenes from the chilled margin are listed in Table 4, together with those of the amphibolites in the ultramafic tectonite. These analyses are plotted in Text-fig. 10. Both clinopyroxene analyses show a small variation nearly parallel to the diopside-hedenbergite join in the pyroxene quadrilateral. The Ca content is about 44 in the Ca/Ca+Mg+Fe ratio. Generally, the clinopyroxenes are slightly more calcic than a typical tholeiitic pyroxene (Brown and Vincent, 1963).

Table 4 Selected EPMA analyses of clinopyroxene.

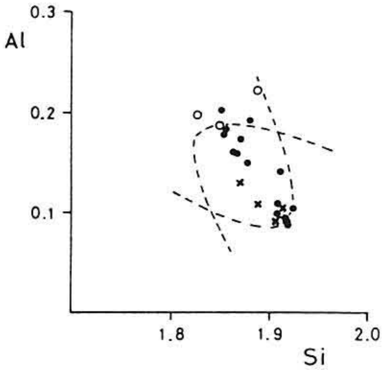
	1	2	3	4	5	6	7	8
SiO_2	51.90	50.17	51.51	49.28	49.94	50.97	50.90	50.48
TiO_2	0.25	0.65	0.79	0.82	1.04	0.60	0.49	0.65
Al_2O_3	2.18	4.65	3.76	4.55	5.44	3.09	2.44	4.01
Cr_2O_3	0.41	1.25	0.31	1.03	0.77	1.25	0.48	0.66
FeO*	4.60	5.60	7.27	8.84	9.73	5.18	7.97	9.90
MnO	0.12	0.16	0.12	0.18	0.22	0.12	0.19	0.18
MgO	17.34	15.81	16.21	13.35	14.00	16.50	14.92	13.78
CaO	22.71	21.33	20.44	21.13	19.10	22.90	21.47	19.41
Na_2O	0.29	0.33	0.32	0.73	0.38	0.33	0.12	0.45
Total	99.71	99.94	100.74	99.91	100.62	100.93	98.99	99.51
Numbers of cations on the basis of 6 oxygens								
Si	1.913	1.851	1.887	1.850	1.849	1.869	1.913	1.893
Al^{IV}	0.087	0.149	0.113	0.150	0.151	0.131	0.087	0.107
Al^{VI}	0.008	0.053	0.049	0.051	0.076	0.002	0.011	0.070
Ti	0.007	0.018	0.022	0.023	0.029	0.016	0.014	0.018
Cr	0.011	0.036	0.009	0.031	0.023	0.036	0.014	0.019
Fe^{2+}	0.142	0.173	0.222	0.277	0.301	0.159	0.251	0.311
Mn	0.004	0.005	0.004	0.006	0.007	0.004	0.006	0.006
Mg	0.948	0.870	0.885	0.747	0.773	0.902	0.836	0.770
Ca	0.897	0.844	0.802	0.850	0.758	0.900	0.865	0.780
Na	0.021	0.024	0.023	0.053	0.028	0.023	0.009	0.033
Total	4.039	4.022	4.022	4.038	3.995	4.041	4.005	4.007

* Total iron as FeO 1-5: from metadolerite in metagabbro 6-8: from amphibolite in ultramafic tectonite

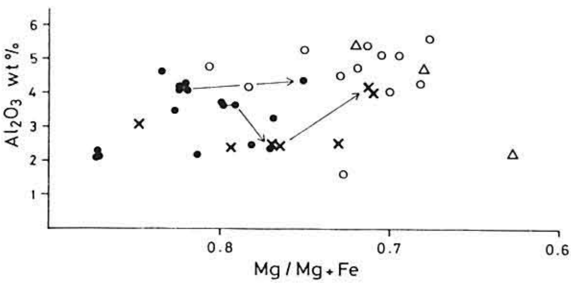


Text-fig. 10. Plots of clinopyroxene on Di-Hd-En-Fs diagram. Solid circles: phenocrysts from the chilled margin of metadolerite. Open circles: clinopyroxenes in groundmass. Open triangles: sector zoned clinopyroxenes. Cross: relict clinopyroxenes from amphibolite in ultramafic tectonite. Arrows: compositional zoning from the core to the margin. SK: clinopyroxene trend of the Skaergaard intrusion.

However, some of the analyses show a deviation from the main trend, and rarely attain to about 32 in the Ca/Ca+Mg+Fe ratio. The clinopyroxenes showing such a compositional deviation occur in the groundmass or the marginal ends of the phenocryst. The deviation toward Ca-poor composition may be produced by a considerably rapid cooling as indicated by Gamble and Taylor (1980). Cr_2O_3 and Al_2O_3 contents are noticeably high in both clinopyroxenes from the metadolerite intrusives in the ultramafic tectonites and in the metagabbros. The Al_2O_3 content varies from 2.11 to 5.59 wt %. Most of the clinopyroxene analyses are plotted into the overlapped field between the alkaline and non-alkaline ones of the Maruyama's diagram (1976), whereas some clinopyroxenes are plotted into the alkaline field (Text-fig. 11). The Al_2O_3 content tends to increase with decreasing in the Mg/Mg+Fe



Text-fig. 11. Al versus Si diagram for clinopyroxenes. Symbols are the same as in Text-fig. 10.



Text-fig. 12. Al_2O_3 versus Mg/Mg+Fe diagram for clinopyroxenes. Symbols are the same as in Text-fig. 10.

ratio as shown in the Al_2O_3 - Mg/Mg+Fe diagram modified from Takazawa and Hirano (1977) (Text-fig. 12). The Cr_2O_3 content ranges widely from 0.04 to 1.51 wt % and tends to decrease with decreasing in the Mg/Mg+Fe ratio. It is well known that the Cr_2O_2 contents of clinopyroxene abruptly decrease with decreasing in the Mg/Mg+Fe (e.g., Gibb, 1973; Dungun *et al.*, 1979). Generally, Cr_2O_3 contents do not exceed 0.2 wt % in the pyroxene, which has smaller value than 0.75 in the Mg/Mg+Fe ratio as shown by Schweitzer *et al.* (1979) and Tazaki (1980). However, some clinopyroxenes contain more than 0.2 wt % Cr_2O_3, although they have smaller value than 0.75 in the Mg/Mg+Fe ratio (Nos. 4, 5 & 10, in Table 4).

Petrochemistry

Fourteen samples from the metamorphosed dolerite intrusives were analysed. The chemical compositions are given in Table 5. SiO_2, TiO_2, Al_2O_3, Fe_2O_3, CaO, K_2O, and P_2O_5 were analysed by X-ray emission spectrometer (AFV-777, Toshiba), and MnO, Na_2O and MgO by atomic absorption spectro-photometer (AA-475, Varian Techtron). FeO was determined by titration using potassium permanganate. The analytical procedures and conditions using the X-ray emission spectrometer followed those of Yamasaki (1979) and Yamasaki *et al.* (1980).

In most cases the dolerites are metamorphosed into metadolerites or amphibolites in various degrees of recrystallization. Seven analyses are of amphibolites from the ultramafic tectonites, two of amphibolites from the cumulate complex, and five of metadolerites from the metagabbros. In Table 5, Nos. 1 to 5 are well preserved the original textures and primary minerals. Nos. 9 to 10 from the ultramafic tectonites include a number of primary plagioclase, olivine, and clinopyroxene crystals. The remaining seven samples in the table, are considerably metamorphosed.

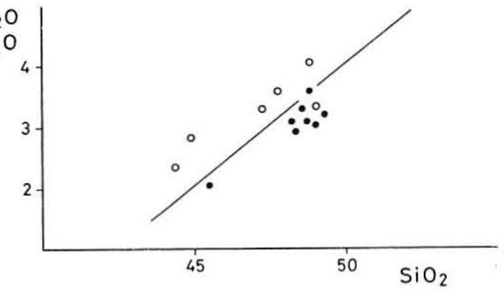
Both metamorphosed dolerites from the metagabbros and the cumulate complex (Nos. 1 to 8, in Table 5) have a similar composition regardless of the degrees of recrystallization, except for the analysis No. 8. This fact indicates that the chemical compositions of the intrusives did not change during metamorphism. As compared with the preceding analyses, the amphibolites from the ultramafic tectonites are slightly rich in Na_2O (No. 10) and K_2O (No. 13), and are poor in SiO_2 (Nos. 12 to 14). A considerable amount of normative nepheline ranging from 4.5 to 7.4% is calculated for these analyses. Some of the analysed samples of amphibolites which suffered from the later low grade metamorphism show no trace of the original minerals and textures (Nos. 11 to 14). On the other hand, the bulk compositions of the amphibolites which contain primary minerals (Nos. 9 and 10) are very similar to those of the metamorphosed intrusives in the metagabbro and the cumulate complex, as mentioned below. Therefore, it is presumed that some compositional change occurred in the amphibolites in the ultramafic tectonites during metamorphism. Accordingly, the following descriptions of chemical composition will mainly refer to the analyses in which the original composition is considered to be preserved.

The K_2O contents in the metamorphosed dolerite intrusives are very low, ranging from 0.02 to 0.13 wt % except for those from the tectonites. Text-fig. 13 shows a SiO_2 – alkali relation based on the unhydrous basis. Most of the analyses are plotted in the non-alkaline

Table 5 Chemical analyses of metadolerite and amphibolite from the Western Zone of the Hidaka Metamorphic Belt.

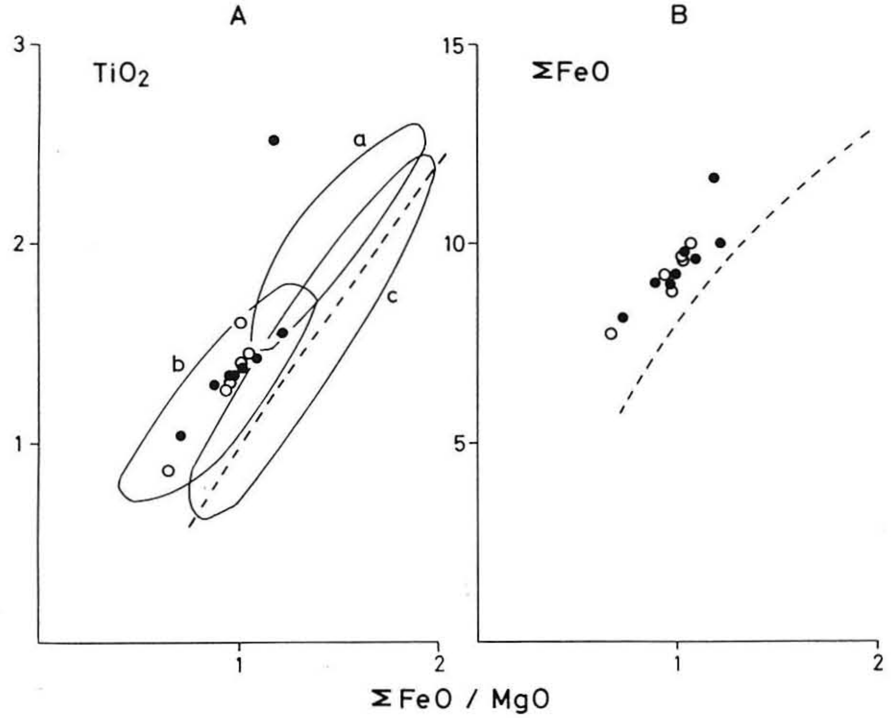
Sample No.	1 76821	2 Ch2c	3 Ch2	4 Ch117	5 Ch118	6 Ch4	7 2U15	8 KK15	9 TR6	10 TR7	11 Nl-4	12 Nl-5	13 902-4	14 902-8
SiO_2	48.19	48.51	48.02	48.28	47.87	48.46	47.29	44.38	48.86	48.22	46.59	45.81	44.17	43.79
TiO_2	1.52	1.41	1.33	1.27	1.03	1.38	1.31	2.46	1.39	1.29	0.85	1.39	1.24	1.58
Al_2O_3	15.58	16.30	16.66	16.52	16.96	15.55	16.24	13.06	15.88	16.20	17.18	15.20	17.82	17.79
Fe_2O_3	1.58	0.94	1.19	1.16	0.91	1.61	1.77	1.82	1.46	1.51	1.09	1.16	0.15	0.63
FeO	8.30	8.67	8.06	7.87	7.20	8.28	7.15	9.82	8.21	7.29	6.67	8.53	8.87	8.95
MnO	0.14	0.14	0.14	0.14	0.12	0.14	0.12	0.12	0.13	0.13	0.11	0.14	0.14	0.17
MgO	7.95	8.76	9.29	10.09	11.26	9.53	9.17	9.82	9.29	9.02	11.74	9.10	9.73	9.38
CaO	11.30	10.92	10.89	10.57	10.74	10.83	11.64	13.41	10.93	11.09	11.19	10.99	13.00	13.31
Na_2O	3.00	3.44	3.15	2.97	3.00	2.93	2.80	1.95	3.14	3.80	3.14	3.25	2.23	2.15
K_2O	0.14	0.14	0.13	0.09	0.07	0.09	0.06	0.02	0.19	0.22	0.13	0.21	0.58	0.20
P_2O_5	0.13	0.13	0.12	0.12	0.09	0.12	0.13	0.82	0.12	0.05	n.d.	0.13	0.08	0.14
H_2O (+)	1.68	1.21	1.23	1.08	0.96	1.39	1.40	1.77	1.41	2.41	1.96	3.27	1.95	2.09
Total	99.50	100.56	100.21	100.16	100.21	100.31	99.08	99.35	101.02	101.23	100.63	99.18	99.96	100.18
C. I. P. W. NORM														
or	0.8	0.8	0.8	0.5	0.4	0.5	0.4	0.1	1.3	1.1	0.8	1.2	3.4	1.2
ab	25.4	25.0	24.5	25.1	22.5	24.8	23.5	16.5	22.7	26.3	16.4	19.3	5.2	7.7
an	28.6	28.6	30.9	31.5	32.6	29.0	31.6	26.8	26.5	28.7	32.4	26.3	36.9	38.3
di	21.7	19.2	18.1	16.3	16.2	19.4	20.4	27.8	22.8	20.1	18.5	22.3	22.0	21.8
hy	2.4	–	–	1.3	–	3.7	–	1.0	–	–	–	–	–	–
ol	13.5	18.3	19.0	20.0	22.5	16.3	16.4	16.0	15.7	18.3	22.0	17.8	20.3	19.2
ne	–	2.2	1.2	–	1.6	–	0.1	–	5.1	0.2	5.5	4.5	7.4	5.7
mt	2.3	1.4	1.7	1.7	1.3	2.3	2.6	2.6	2.2	2.1	1.6	1.7	0.2	0.9
il	2.9	2.7	2.5	2.4	2.0	2.6	2.5	4.7	2.5	2.6	1.6	2.6	2.4	3.0
ap	0.3	0.3	0.3	0.3	0.2	0.3	0.3	1.9	0.1	0.3	–	0.3	0.2	0.3
ΣFeO/MgO	1.22	1.09	0.98	0.88	0.71	1.02	0.95	1.17	1.03	0.96	0.65	1.05	0.93	1.01

1: metadolerite in matagabbro, along Yon-no-sawa of the Pankenushi River. 2 and 3: chilled margin (2) and center (3) of metadolerite in metagabbro, Locs. 2 and 3 along the Chiroro River. 4 and 5: metadolerite in metagabbro, Locs. 4 and 5 along the Chiroro River. 6: amphibolite in plagioclase blastoporphyritic amphibolite, Loc. 6 along the Chiroro River. 7 and 8: amphibolite in metamorphosed cumulate, Locs. 7 and 8 in the north cirque of Mt. Poroshiri. 9 and 10: amphibolite in ultramafic tectonite, Locs. 9 and 10 at the northern ridge of Mt. Tottabetsu. 11 to 14: amphibolite in ultramafic tectonite along the Niikappu River. Analyst: S. Miyashita.

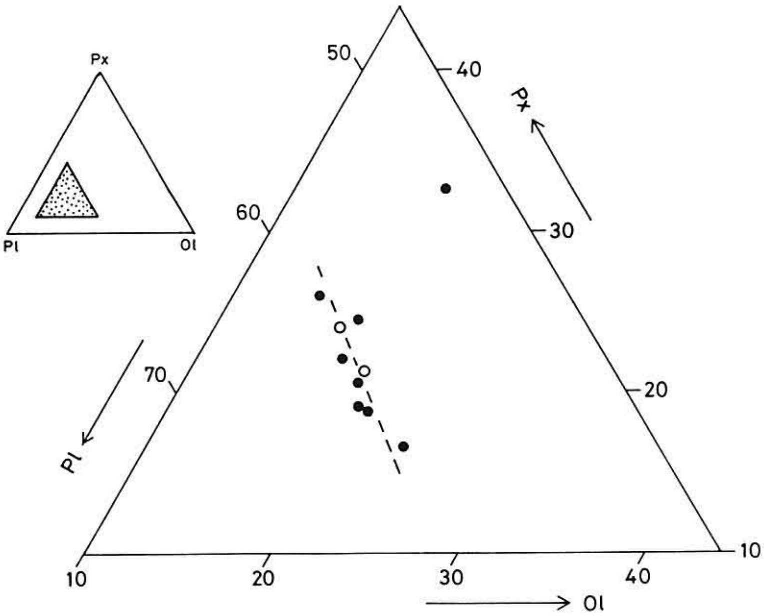


Text-fig. 13. Na_2O + K_2O versus SiO_2 diagram for metamorphosed dolerite intrusives.
Open circles: amphibolite in ultramafic tectonite. Solid circles: metadolerite and amphibolite in metagabbro and in cumulate. Line: boundary between alkaline and non-alkaline rocks (MacDonald and Katsura, 1964).

field close to the boundary between the non-alkaline and alkaline fields (MacDonald and Katsura, 1964). Some analyses considered to be deviated from the primary composition as mentioned above, are plotted in the alkaline field. $\Sigma FeO/MgO$ ratios characteristically show a small range from 0.65 to 1.22. As shown in Text-fig. 14A, TiO_2 contents varying from 0.85 to 1.58 wt % increase with increasing in $\Sigma FeO/MgO$. Plots on the TiO_2 versus $\Sigma FeO/MgO$ diagram show a definite positive relation. Similarly, the ΣFeO versus $\Sigma FeO/MgO$ relation is also positive (Text-fig. 14B). In comparison with the trends of abyssal tholeiites



Text-fig. 14. TiO_2 versus $\Sigma FeO/MgO$ (A) and ΣFeO versus $\Sigma FeO/MgO$ (B) diagrams.
Symbols are the same as in Text-fig. 13. Broken line represents the trend of mid-oceanic ridge tholeiite (Miyashiro, 1973). a: tholeiite from the Mid-Cayman Rise (Thompson *et al.*, 1980). b: tholeiite from the Mid-Atlantic Ridge at 43°N (Shibata *et al.*, 1979). c: tholeiite from mid-oceanic ridge (Thompson *et al.*, 1980)



Text-fig. 15. Plots of normative olivine, pyroxene and plagioclase. Symbols are the same as in Text-fig. 13.

(mid-oceanic ridge) on the above two diagrams proposed by Miyashiro (1973), the trend of the dolerite intrusives is plotted at a clearly high position in TiO_2 content and a slightly high one in ΣFeO content.

Normative olivine, plagioclase, and pyroxene are plotted on the triangular diagram of Text-fig. 15. The plots show a systematic variation in the proportions of the three normative minerals. This trend resembles the cotectic boundary between olivine and plagioclase in the An-Di-Fo experimental system (Osborn and Tait, 1952). Accordingly, it is considered that the metamorphosed dolerite intrusives are probably co-magmatic and that the magma is less differentiated, although the dolerites intruded in all of the succession from the tectonite to the metagabbro. The dolerite magma is characterized by low K_2O content, as mentioned above. It is well know that such a low content in K_2O is one of the chemical traits of abyssal tholeiite (e.g., Engel *et al.*, 1965). Actually, the other nature of the chemical composition of the dolerite intrusives also resembles to that of abyssal tholeiites (Nicholls, 1965; Kay *et al.*, 1970; Muir and Tilley, 1966). Normative olivine, however, attains to 22.5 as shown in Table 5. The abyssal tholeiite generally contains lesser amounts of normative olivine. Moreover, small amounts of normative nepheline or hypersthene appear in the metamorphosed dolerite. Considering the characteristics of SiO_2 and alkali contents as well as the above nature, the dolerite intrusives were formed by crystallization of an olivine tholeiite magma, which is highly undersaturated in SiO_2 and less differentiated.

Discussion

Petrographic and petrochemical data, in accord with the features of occurrence, indicate that all of the dolerite intrusives are co-magmatic. Additionally, the petrochemical and mineralogical traits indicate that the dolerite intrusives belong to highly silica undersaturated olivine tholeiite.

Characteristics of the chemical composition of oceanic basin basalts have been well known from the recent accumulation of chemical analyses. The TiO_2-$\Sigma FeO/MgO$ relation (Text-fig. 14A) shows three different fields for abyssal tholeiite. One of these is from typical oceanic ridge tholeiite, and whereas the other two fields are from the Mid-Cayman Rise (Thompson *et al.*, 1980) and the Mid-Atlantic Ridge at 43°N (Shibata *et al.*, 1979). As shown in Text-fig. 14A, the chemical analyses from the dolerites investigated quite resemble to those from the Mid-Atlantic Ridge tholeiites at 43°N. On the other hand, considering the present petrochemical data from oceanic environments, the alkali basalts from the oceanic basin are clearly distinguished from the abyssal tholeiite because of higher contents of K_2O, TiO_2, and P_2O_5 (Myers *et al.*, 1976; Shibata *et al.*, 1979). The chemical traits of the dolerite intrusives from this area are conspicuously different from such alkali basalts.

An inference of magma type from the amounts of Al and Ti entering clinopyroxenes has been attempted (e.g., Kushiro, 1960; LeBas, 1962). Most of the clinopyroxene analyses from the dolerite intrusives fall into the overlapped field between the alkaline and non-alkaline ones of Maruyama's diagram (1976), whereas some clinopyroxenes are plotted in the alkaline field (Text-fig. 11). In addition, the Al_2O_3 content in the clinopyroxene tends to increase with decreasing in the Mg/Mg+Fe ratio, as shown in the Al_2O_3 – Mg/Mg+Fe diagram (Text-fig. 12). It is suggested from this trend that the dolerite magma became low in SiO_2 activity with the proceeding of crystallization. The plots on the Al_2O_3 – Mg/Mg+Fe diagram, however, show a considerable deviation. This compositional deviation is considered to be caused by sector zoning of clinopyroxenes as well as probably by a rapid cooling rate. The latter cause also give rise to an unusual Cr_2O_3 concentration in the clinopyroxenes. It is inferred that the dolerite intrusives belong to a tholeiitic suite, because the clinopyroxenes have high contents in Cr_2O_3 and low in TiO_2 as suggested by Schweizer *et al.* (1979).

The presence of dolerite dyke swarms characterizes ophiolites (Coleman, 1977). However, it has not been reported in ophiolites, that dolerite intrudes into tectonites. The Western Ophiolite Zone of the Hidaka Metamorphic Belt has a pseudostratigraphy of about 5.5 km in thickness. Numerous metamorphosed dolerite dykes up to a few hundred were found from the intermediate to the upper horizon of the Western Zone. Bulk chemical compositions of the metamorphosed dolerite dykes are different from those of the dolerite intrusives now investigated and correspond well with those of typical oceanic ridge tholeiites (Miyashita, in preparation). The presence of chilled margin and the chemical characteristics of the clinopyroxenes of the dolerite intrusives indicate that the dolerite magma intruded after complete cooling of the whole ophiolite succession. At the time of the intrusion, mylonitization of the ultramafic tectonites had already advanced. Thus the intrusion of the dolerite was a later episode following the completion of the ophiolite succesion.

It is important to know when and where the dolerites now studied intruded and what genetic relation the dolerites have with that of the ophiolite of the Western Zone of the Hidaka Metamorphic Belt.

Concluding Remarks

1) Large numbers of metamorphosed dolerite intrusives were found in the Western Ophiolite Zone of the Hidaka Metamorphic Belt. The intrusives distribute to the extent of the lower half of the ophiolite succession which is composed of ultramafic tectonites, cumulates, and metagabbros. The dolerite intrusives range from a few cm to 30 m in thickness and occur as dykes or sheets which generally contact parallel to the schistosity of the host rocks. In some cases the dolerite cuts the host rocks.
2) The dolerites intruded into the cumulate and metagabbros which were already consolidated and considerably cooled. Moreover, in the ultramafic tectonite the dolerite intrusion took place after the mylonitization of dunite and harzburgite.
3) The dolerite intrusives are metamorphosed into amphibolite in various degrees. The metamorphic grade becomes higher toward the eastern part of the Western Zone. In the ultramafic tectonites it reaches up to the higher grade of amphibolite facies, and partly to the hornblende granulite facies. Nevertheless, original textures and minerals are notably preserved in some intrusives.
4) Petrochemistry and mineralogy indicate that all of the dolerite intrusives are co-magmatic. The K_2O contents in the dolerite intrusives are characteristically low. The SiO_2 – alkali relation indicates that the nature of the dolerite magma is non-alkaline, but that the alkali contents are rather high. The dolerites contain large amounts of normative olivine as well as small amounts of normative nepheline or hypersthene. Accordingly, the dolerite intrusives are considered to be formed by crystallization of olivine tholeiite magma which is highly undersaturated in silica and less differentiated.

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