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PILLOW LAVAS IN HOKKAIDO, JAPAN

by

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(with 4 Tables and 4 Figures)

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Abstract

Pillow lavas in Hokkaido are found from the following three different geologic units:
a) Central axial zone of Hokkaido. This zone is composed of thick geosynclinal pile of Triassic to Cretaceous sediments, in which, especially in the upper horizon, pillow lavas are intercalated. Well pillowed lavas from different depths are petrographically and chemically studied, and it was clarified that the pillow lava from the lower horizons are tholeiitic and those of the upper horizon alkaline.
b) Nemuro Peninsula. Geology of the peninsula is composed of alternation of shale and sandstone of the late Cretaceous period. Sheet-formed dolerites are found in the preceding formation. Two types of dolerite can be distinguished; one is characterized by the development of pillow structures associated with columnar joints and the other comprises very thick sheets which show distinct differentiation in situ. It is interpreted that the scheets have intruded into unconsolidated subaqueous sedimentary environments mainly composed of muds. The pillow lavas were derived from alkalic basaltic magma comparatively rich in K_2O.
c) Southwest Hokkaido. Pillow lavas occur as members of "Green Tuff Volcanism" of the Miocene and have recently been found in southwest Hokkaido. Localities, modes of occurrence, and textures of the pillow lavas are briefly reported in this paper. The chemistry of the pillow lavas has not been examined.

Introduction

The pillow lavas in Hokkaido, can be classified in terms of their distribution and age into the three groups:

1) Pillow lavas in the central axial zone, i.e. Triassic-Cretaceous sediments of the Hidaka geosyncline,
2) those of Upper Cretaceous age in the Nemuro district, eastern Hokkaido, and,
3) those in SW Hokkaido which are related to Miocene green tuff volcanism.

The first group is very well developed, sometimes attaining 1,000 m in

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thickness, and is associated with cherts, diabase-tuff, sandstones and slates, formed in a eugeosynclinal environment. The second group is characterized by the close association of pillow structure and columnar joints within the same sheet which intruded into the unconsolidated Cretaceous under deep water conditions. Pillow breccias or hyaloclastites are commonly associated with the pillow lavas of the third group, which are characteristics of shallow water conditions.

Chemically the pillow lavas range from tholeiitic through alkalic ("spilitic") basalts rich in Na_2O to alkali dolerites rich in potash. Their modes of occurrence, mechanism of formation and petrochemical features are discussed.

The data for the present paper are provided by Yagi (Nemuro district), Bamba (Central Axial Zone) and Suzuki (Green tuff region).

Pillow lavas from the Central Axial Zone

The central axial zone of Hokkaido is divided into the following three units from east to west:

1) Tokoro Belt
2) Hidaka Belt
3) Kamuikotan Belt.

Pillow lavas are observed in the Kamui Series up to the top of the Sorachi Series and especially predominant in the Sorachi Series.

The thickness of the pillow lava units generally ranges from ten to several tens of meters, occasionally attaining several hundred, or even, thousand meters. The above-mentioned pillow lavas are intercalated with sandstones or mudstones, accompanied by cherts or pyroclastic materials.

Each pillow generally shows spheroidal, ellipsoidal, or bowl-like forms, about 0.3–2 m in size. Frequently several kinds of pillow lavas occur together in an outcrop. Isolated pillows in the pyroclastic material or accumulated fragments of pillows have been identified as a variety of pillow lavas (Suzuki, 1974). Radial cracks are well-developed in the spheloidal pillows.

The margin of a unit pillow is generally composed of glassy material, whereas the core of the unit pillow is holocrystalline with variolitic or sub-ophitic textures between plagioclase and augite. In general, ilmenite is present as an accesory mineral. Chlorite epidote, sphene, pumpellyite and calcite are generally considered to have been formed as the products of alteration.

The chemistry of the pillow lavas ranges from tholeiitic to spilitic compositions. Pillow lavas from 13 localities are illastrated in Fig. 1 and are

regarded as being representatives of each of the tectonic belts. Petrographical and chemical characteristics of these pillow lavas are discussed with special reference to the change in chemical composition from the stratigraphical aspect.

Pillow lavas from Tokoro Belt

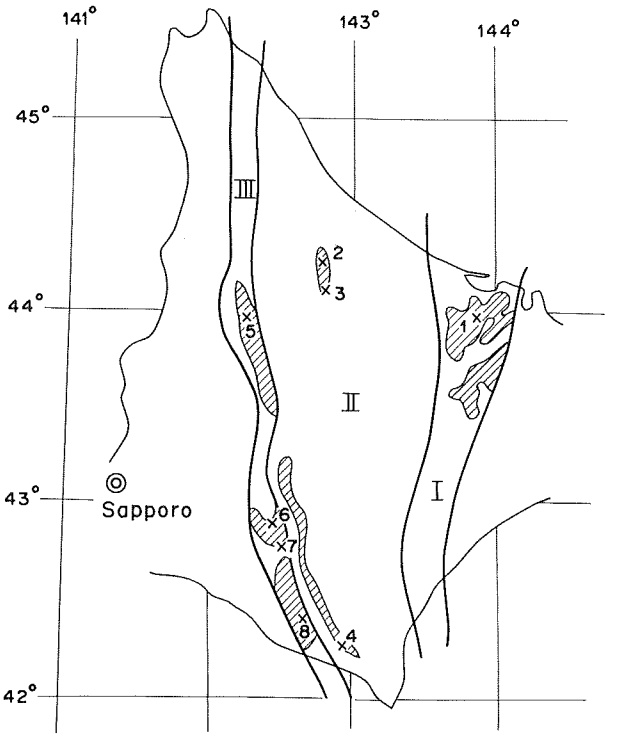

Fig. 1 Three geotectonic belts in the central axial zone of Hokkaido. The area occupied by oblique lines is composed of green rocks enclosing pillow lava.
I. Tokoro Belt
II. Hidaka Belt
III. Kamuikotan Belt
x1 Tokoro x2 Shimokawa x3 Nisama x4 Hidaka-Horobetsu
x5 Horokanai x6 Onitoge x7 Nukabira x8 Shizunai

The whole Jurassic system of this area is estimated to be about 6,000 m thick, being composed mostly of green pyroclastic layers such as pillow lava and diabasic tuff with intercalated chert together with slate, limestone and sandstone. Pillow lavas are made up of numerous rounded bodies of compact basaltic or diabasic rocks.

Petrographically pillow lavas can be classified into glassy, variolitic and subophitic parts with a continuous gradation between them.

The crystallinity varies from glassy to holocrystalline. Variolitic facies having a considerable amount of glass are predominant, and characterized by the presence of numerous varioles composed of radial aggregates of fibrous plagioclase.

Glassy Facies. This is made up of brownish glass with irregular cracks. Occasionally, tortoise-shell structure caused by the development of hexagonal cracks is observed, the areas bounded by the cracks being about 0.3 mm in diameter. Small amounts of fibrous crystallites of plagioclase can sometimes be seen.

Variolitic Facies. The varioles are composed of plagioclase and clinopyroxene, with or without a small amount of glass, showing a variolitic texture. The dimensions of varioles are commonly about 0.1 mm, rarely up to 0.3 mm. Clinopyroxene is very fine-grained and usually forms cedar-leaf aggregates. Plagioclase is fibrous or acicular. Amygdaloids, 0.1–0.2 mm of dimension filled up by pumpellyite attain about 1–5 vol.% in general.

Subophitic Facies. Clinopyroxene and plagioclase are the main components associated with a small amount of ilmenite. Clinopyroxene and ilmenite are granular, about 0.1 mm in size, and plagioclase is prismatic, 0.2 mm in length, forming a subophitic texture. The three rock facies described above are commonly recognized in an individual pillow. Their distribution therein, however, is irregular and no concentric arrangement is distinct.

Network veins, 1–3 mm in width, consisting of pumpellyite – calcite – quartz, are common in the pillow lavas from the mineralized zone running from the Hokko Mine to the Shibayama Mine. In diabasic tuff from the Hokko Mine at the northern end of the mineralized zone, epidote – pumpellyite association is found.

Keratophyre. A small amount of keratophyre is associated with pillow lavas in this belt, showing a flame-like shape or irregular network. However, the identification of keratophyre in the field is difficult because of its fine-grained appearance and greenish-grey colour which is similar to that of the diabase.

Judging from the modes of occurrence, the keratophyre is considered to be a kind of segregation. Prismatic plagioclase (0.1–0.3 mm) is a major component, arranged in subparallel rows. Subordinate green hornblende and chlorite occur as accessory minerals.

It is noticeable that the chemical compositions of the three rock facies are much alike, in spite of their differences in texture, except that the variolitic facies is comparatively rich in K_2O and the glassy facies is poor in MgO.

Pillow lavas from the Tokoro Belt are normal basalt or dolerite: Chemically

Table 1. Chemical composition of pillow lavas from the Tokoro Belt, central axial zone of Hokkaido, Japan.

	1	2	3	4
SiO_2	48.88	47.40	47.36	66.10
TiO_2	1.48	1.14	1.10	0.36
Al_2O_3	14.56	15.35	14.22	16.55
Fe_2O_3	3.55	3.11	3.88	4.65
FeO	7.52	6.29	6.78	0.78
MnO	0.19	0.15	0.19	0.06
MgO	6.31	8.53	8.07	0.56
CaO	10.80	11.18	12.05	3.01
Na_2O	2.82	1.82	2.05	6.19
K_2O	0.05	0.75	0.13	0.01
P_2O_5	0.08	0.08	0.08	0.06
$H_2O(+)$	3.06	3.70	3.52	1.40
$H_2O(-)$	0.42	0.44	0.40	0.26
Total	99.72	99.94	99.83	99.99

(1) Glassy facies from the outer shell of a unit pillow.
(2) Variolite facies from the core of a unit pillow.
(3) Subophitic facies from the core of a unit pillow.
(4) Keratophyre from the Tomioka area, Tokoro district.
(Bamba and Sawa, 1967).

they are poor in Al_2O_3 and K_2O, and rich in CaO and total Fe. Based on the mode and chemical composition, the primary magma from which the pillow lavas were derived is regarded as tholeiitic.

Pillow lavas from Hidaka Belt

Many localities of pillow lava are known along the Hidaka Belt. Analysis of pillow lavas from the Shimokawa and Nisama districts, in the northern part of the belt, and pillow lava from the upper stream of the Hidaka-Horobetsu River, southern end of the belt, are given in Table 2. The former belongs to Kamui Series, and the latter belongs to the top of Sorachi Series.

Pillowed diabase from Shimokawa district. A longitudinal swarm of diabase bodies associated with lenticular serpentinite striking in a N-S trend is present. The diabase bodies are commonly conformable to the strata and dip steeply to the east. Numerous lenticular bodies of diabase form swarm within a narrow belt. The width of the diabase swarm reaches about 1.6 km in the broadest part, and the length about 20 km. Typical pillow structure is found within the diabase swarm, though it occupies only less than 5% of the whole exposed diabase mass.

The dimensions of individual pillows of diabase from the Shimokawa district vary from 5 cm to 50 cm. The interstices between the pillows are filled by tuffaceous material containing a considerable amount of quartz. The outer shell of the pillows are composed of glassy material, about 2 mm thick.

The outer shell is composed of brownish vitrified glass including crystallites of plagioclase and microcrystalline quartz, while the interior of the body is composed of plagioclase and clinopyroxene or glass. Variolitic texture is observed in this part, but no ophitic texture has been seen in any pillows from the Shimokawa district. On the other hand, diabase in the area has a typical ophitic texture. This rock facies is predominant and no variation is observed in the interior part of any individual diabase body. The marginal part of a diabase body, is fine-grained but holocrystalline, and the texture is always ophitic. Amygdaloids, 1–2 mm of dimension, filled up by pumpellyite is observed in the diabase from the southern end of the Shimokawa diabase.

Specimens for chemical analysis were obtained from three localities in the diabase swarm. One is a pillow and the others are common diabase, (Table 2). No notable variation is observed in their chemical compositions. They are always poor in Al_2O_3 and alkalis, especially in K_2O, and rich in CaO and MgO,

Table 2. Chemical composition of pillow lavas from the Hidaka Belt, central axial zone of Hokkaido, Japan.

	1	2	3	4
SiO_2	48.04	47.44	49.02	49.06
TiO_2	1.12	1.15	1.15	2.31
Al_2O_3	16.04	18.68	15.38	18.50
Fe_2O_3	2.52	1.32	2.56	10.14
FeO	6.14	6.72	6.03	1.29
MnO	0.19	0.12	0.16	0.14
MgO	7.91	8.44	7.80	1.61
CaO	12.20	11.26	12.16	3.61
Na_2O	1.82	1.83	1.83	4.39
K_2O	0.17	0.21	0.25	2.95
P_2O_5	0.07	0.11	0.09	1.26
$H_2O(+)$	2.48	1.76	2.32	3.80
$H_2O(-)$	1.06	0.74	0.96	0.82
Total	99.76	99.78	99.71	99.88

(1) Variolite-textured diabase showing pillow form (sample for analysis is prepared as a total pillow) from Shimokawa Mine.
(2) Ophitic-textured diabase from the Shimokawa Mine.
(3) Pillow lava from the Nisama area in the southern part of the Shimokawa Mine.
(4) Pillow lava from the Hidaka-Horobetsu River

and are very similar to those of the Tokoro Belt.

Pillow lava from the Hidaka-Horobetsu River area. Many localities of pillow lave are known along the Hidaka-Horobetsu River, southern end of the Hidaka Belt. Among them, a pillow lava at the top of the Sorachi Series was obtained for the chemical analysis. This rock is characterized by high alkalis and low MgO and CaO contents (Table 2). It compares closely with rocks from the Shimokawa district (Fig. 2). It is clarified that these plots in the alkaline field and the, differentiation course of the magma was slightly deviated from the course of the tholeiitic magma investigated in the Tokoro Belt as given in Fig. 3.

Pillow lavas from Kamuikotan Belt

Pillow lavas from Horokanai, Onitoge and the middle stream of the Nukabira, Shizunai Rivers in the Kamuikotan belt were selected for the petrographical and petrochemical study.

Pillow lava from Horokanai District. This lava is stratigraphically correlated to the top of the Sorachi Series (Igi, 1956). The core of a pillow is mainly composed of partially chloritized clinopyroxene, and plagioclase 0.1 mm–1 mm in size, showing typical ophitic structure. This rock is rich in alkalis, especially Na_2O (Table 3).

Pillow lavas from Onitoge-Nukabira District. The petrography of this pillow lava is quite similar to that of the Horokanai district, i.e., the pillow lava is mainly composed of fine crystals of clinopyroxene and fresh, acicular albite, with subophitic structure. The rock is characterized by a high Na_2O content (5.73%) (Table 3). In this pillow lava, a greyish-white coloured facies, consisting mainly of albite is present. Albite crystals in this rock are comparatively large compared with those of the preceding spilite. Since this rock contains 6.8% Na_2O, it can be classified as a kind of keratophyre. This spilite-keratophyre suite is stratigraphically correlated to the top of the Sorachi Series (Bamba 1974).

A pillow lava from the bottom of the Sorachi Series, obtained at the middle stream of the Nukabira River, about 20 km south from Onigoge was studied for comparison. Epidote-bearing pillow lava with rhythmical banding in a pillow is observed here. The chilled margin of the pillow is glassy and the thickness of the glassy shell varies from 0.5 cm to 1 cm, showing a double or triple rhythmic band. Variolitic texture is distinct in the remainder, which is composed of albite, chlorite and a considerable amount of epidote. Occasionally, albite – muscovite – pumpellyite – epidote – quartz veins, 1 mm in width, are observable in above-stated pillow lava.

This pillow lava is poor in alkalis and rich in CaO and Al_2O_3 compared with the former (Table 3). The unique chemistry of this pillow lava is regarded as a product of strong epidotization which is probably restricted to a lower horizon of the Sorachi Series.

Table 3. Chemical composition of pillow lavas from the Kamuikotan Belt, central axial zone of Hokkaido, Japan.

	1	2	3	4	5	6
SiO_2	47.06	53.82	56.48	45.31	42.57	44.42
TiO_2	1.11	1.51	0.61	0.96	3.36	2.89
Al_2O_3	14.78	18.81	19.18	16.68	15.79	16.09
Fe_2O_3	4.29	2.55	3.03	4.46	7.03	7.27
FeO	5.44	4.60	3.16	6.90	4.60	4.67
MnO	0.24	0.05	0.06	0.16	0.20	0.14
MgO	7.34	4.49	2.80	7.49	3.69	4.82
CaO	10.78	2.04	1.32	13.28	11.48	6.86
Na_2O	4.17	5.73	6.80	2.28	2.56	4.04
K_2O	0.31	0.66	0.78	0.21	0.60	1.21
P_2O_5	0.09	0.26	0.15	0.11	0.52	0.45
$H_2O(+)$	3.69	4.58	3.84	2.00	5.32	4.47
$H_2O(-)$	0.45	0.78	0.88	0.15	0.60	0.38
CO_2	–	–	–	–	1.30	1.91
Total	99.75	99.88	99.09	99.99	99.62	99.62

(1) Spilitic pillow lava from the Horokanai district (Igi, 1956)
(2) Spilitic pillow lava from Onitoge.
(3) Keratophyre from Onitoge.
(4) Epidote-bearing pillow lava from the Nukabira River (Bamba, 1974).
(5) Pillow lava from the Shizunai River.
(6) Pillow lava from the Shizunai River.

Pillow lavas from Shizunai River area. Many localities of pillow lavas belonging to the Sorachi Series are known in the southern area of the Kamuikotan Belt, especially along the Shizunai River. Their modes of occurrence are quite similar to those from the preceding ones.

Two pillow lavas from the Shizunai River area were selected for analysis. Both of them belong to the middle to lower parts of the Sorachi Series. One of them is identified as a spilite-type due to the richness of alkalis and the other is tholeiitic as given in Table 3.

As above-mentioned, the pillow lavas from many localities of the central axial zone of Hokkaido were studied petrographically as well as chemically and

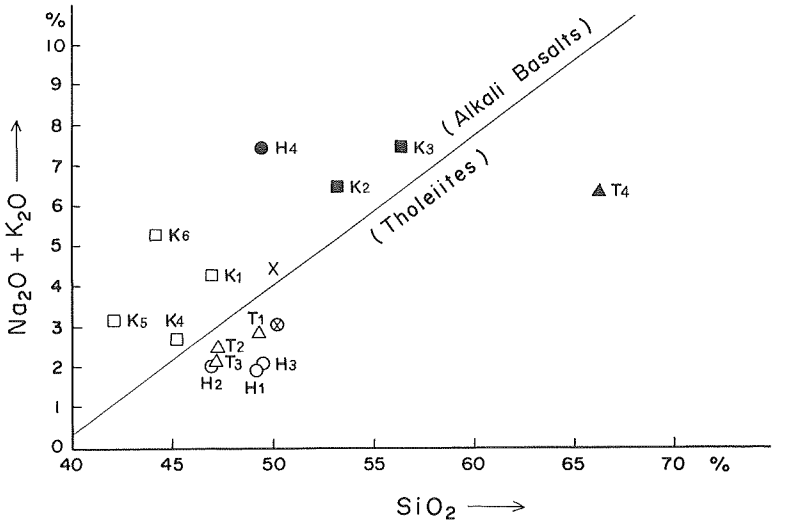

Fig. 2 Alkali-silica diagram for pillow lava rocks from the central axial zone of Hokkaido. Heavy line is Hawaii alkalic-tholeiitic division line, as defined by Macdonald and Katsura (1964)
○ Pillow lavas from the Tokoro Belt
△ Pillow lavas from the Hidaka Belt
□ Pillow lavas from the Kamuikotan Belt
× Average spilite from Poldervaart (1955)
⊕ Average oceanic tholeiite from Engel et al. (1965)
Black colored symbol shows that it is the final product of the volcanism in the Hidaka geosynclinal phase.

the present authors came to a conclusion that there exists various kinds of pillow lavas ranging from tholeiitic through spilitic to keratophyre and the change is closely related to the depth where these lavas were erupted. In other words, this change between the chemical compositions can be ascribed to the difference of intrusion phase of the magma which yielded each pillow lava: i.e., those of earlier phases are tholeiitic and those of later phase alkaline, and keratophyres might have been formed as final product.

Pillow lavas from the Nemuro Peninsula

In the Nemuro peninsula, Eastern Hokkaido, Occurrence of pillow lavas is known within the alternation of sandstone and shale of the Nemuro and Nokkamappu Formations of Upper Cretaceous (Yagi, 1958, 1969a, Fujiwara et al. 1959, Hasegawa et al. 1959, Mitani et al. 1958). Among the excellent exposures found on the cliffs along the sea coast of this peninsula, the pillow lavas of the Hanasaki Cape on the Pacific side are best developed.

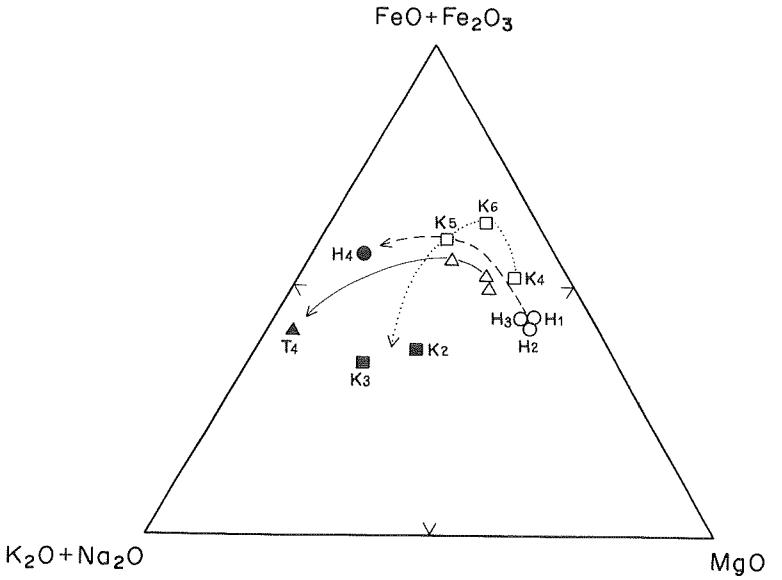

Fig. 3 FMA diagram showing pillow lavas from the Tokoro Belt, the Hidaka Belt and the Kamuikotan Belt, central axial zone of Hokkaido
△ Pillow lavas from the Tokoro Belt
○ Pillow lavas from the Hidaka Belt
□ Pillow lavas from the Kamuikotan Belt
Black colored symbol shows that it is the final product of the volcanism in the Hidaka geosynclinal phase.

Because of the remarkable radial joints which resemble spokes of wheels, these pillows at this locality are called "Kuruma-ishi" or wheel stones. They are concentrated in the central portion of the sheets, whereas columnar joints are developed in the upper and lower contact portions. The pillows rest one upon another with large vacant spaces between them sometimes filled with a yellow silty sediment. Examination shows that the pillowed and columnar parts are continuous with each other, and the columnar joints are gradually replaced by pillow structures in many places. Therefore, it is evident that these parts do not represent multiple intrusions but a single intrusive body, in spite of the distinct difference in their structures. The shales are slightly metamorphosed at the upper and lower contacts of the sheet.

A gradual change from columnar joints to pillow structures can be observed in many other localities near Nemuro City. Pillows in these dolerite sheets assume various shapes, of which ellipsoidal ones predominant. Most of them are 0.5–2.0 m in diameter, but sometimes attain as large as 5–8 m across. They show distinct zonal structure composed of an outermost glassy rim, through a fine-grained outer portion to a coarse-grained central portion. Sometimes

vesicules are developed in the central portion, in which crystals of analcite or natrolite are found. The total thickness of the sheets including both the columner jointed portion and central pillowed portion, rarely exceeds 20 or 30 m.

The constituent minerals are phenocrysts of plagioclase, olivine, augite, titaniferous magnetite, set in the crystalline groundmass composed of plagioclase, anorthoclase, augite, magnetite, apatite and ilmenite.

A different kind of pillow lava flows is found in the shale at Tosappu on the Okhotsk Sea coast. Here the pillows are not associated with the intrusive sheet, but with agglomeratic layer lying above, indicating that the pillow lava was contemporaneous with the deposition of the shale. Petrological features of these pillows are more or less similar to the one mentioned above, though the crystallinity is usually much lower.

Table 4. Chemical composition of various part of a pillow from Hanasaki Cape and of Dolerites from Nambuto, Japan.

	1	2	3	4	5	6	7
SiO_2	50.24	51.84	52.44	45.21	51.41	49.43	50.67
TiO_2	1.87	1.76	1.74	0.82	0.74	1.10	0.91
Al_2O_3	16.72	17.49	17.09	18.07	17.24	16.59	16.89
Fe_2O_3	5.14	2.36	2.61	5.40	5.74	4.69	2.75
FeO	4.46	4.44	4.72	4.70	2.58	4.79	5.74
MnO	0.23	0.21	0.18	0.30	0.12	0.26	0.24
MgO	3.02	2.58	2.69	2.89	3.19	2.59	2.25
CaO	5.63	6.31	5.33	4.04	4.76	6.25	4.28
Na_2O	4.76	4.73	4.98	7.03	4.31	2.97	3.59
K_2O	3.75	3.58	3.71	0.36	3.58	2.11	2.59
$H_2O(+)$	2.29	2.59	2.43	6.81	3.59	5.43	6.99
$H_2O(-)$	1.54	1.60	1.45	3.45	1.75	3.23	2.38
P_2O_5	0.60	0.52	0.58	0.63	0.57	0.59	0.77
Total	100.25	100.01	99.95	99.71	99.61	100.03	100.05

(1) Dolerite, No. 2707A, Center of a pillow, Hanasaki Cape. Analyst: H. Onuki.
(2) Dolerite, No. 2707B, Outer part of inner core of a pillow. Hanasaki Cape. Analyst: H. Onuki.
(3) Dolerite, No. 2707C, Inner part of outer rim of a pillow, Hanasaki Cape. Analyst: H. Onuki.
(4) Tachylite, No. 1707D, Outermost rim of a pillow, Hanasaki Cape. Analyst: T. Tiba.
(5) Dolerite, No. 801A, Nambuto, Analyst: K. Aoki.
(6) Tachylite, No. 801B, Nambuto. Analyst: H. Onuki.
(7) Glass of tachylite, No. 801B, Nambuto. Analyst: H. Onuki (Yagi, 1969).

In this connection it is worthy of note that many thicker sheets, about 100–300 m thick, show differentiation in situ, consisting of porphyritic dolerite, picritic dolerite, monzonite, and porphyritic dolerite enumerated from bottom to top. In addition numerous syenitic veinlets are found, cutting the central portion of the sheet. In such thick sheets no pillow lava structure has been found. On the other hand, the above-mentioned differentiation in situ, has never been observed in the thinner sheets with pillow structures (Yagi, 1969a).

Analyses of the various parts of a pillow collected at Hanasaki Cape and Nambuto, Nemuro City, indicate that they are derived from alkali dolerite magma high in alkalis and with a fairly high ratio of K_2O/Na_2O, compared to other alkalic rocks from Japan, (Table 4). The predominance of K_2O is more pronounced in the syenites of monzonites in the differentiated sheets.

From these features it is concluded that the pillow lavas in the Nemuro Peninsula were derived from alkalic basaltic magma, fairly high in K_2O, which was different from the alkalic magma of the Cenozoic time in other parts of Japan (Yagi, 1969a. 1969b, Ishikawa et al. 1971).

Pillow lavas from the green tuff region in southwest Hokkaido

Southwest and northeast Hokkaido are known for the green tuff volcanism. Reconnaissance surveys in recent time have yielded much new information on the pillow lavas of Miocene age related to the green tuff volcanism. The distribution of the pillow lava is, however, restricted to southwest Hokkaido. More than ten localities of pillow lavas have been found there. Though the pillow lavas occur in Miocene formations, the horizons in which pillow lavas appear are not fixed. The pillow lavas from the upper Miocene formation are found in the Kunitomi area and central part of the Kameda Peninsula. These pillow lavas occur in the green tuffs intercalated with mudstone, and are generally small in scale: e.g., the thickness of a unit pillow lava flow is generally 5 to 10 m.

Besides pillows of doleritic rock with ellipsoidal, or partially bowl-like form, a kind of pillow breccia is sometimes found at the top of the lava flow, especially near the boundary with the overlying mudstone. This was probably formed by explosive shattering during the consolidating process of the pillow lava. The dimension of the pillows ranges from 0.3 m to 1.0 m, and no radial cracks are observed, though many irregular cracks are developed.

Amygdaloidal structure represented by aggregates of chlorite ranging from 1 mm to 5 mm is found in the rock. The chlorite is frequently accompanied by epidote, calcite or quartz. The amygdaloid is generally dark green, displaying

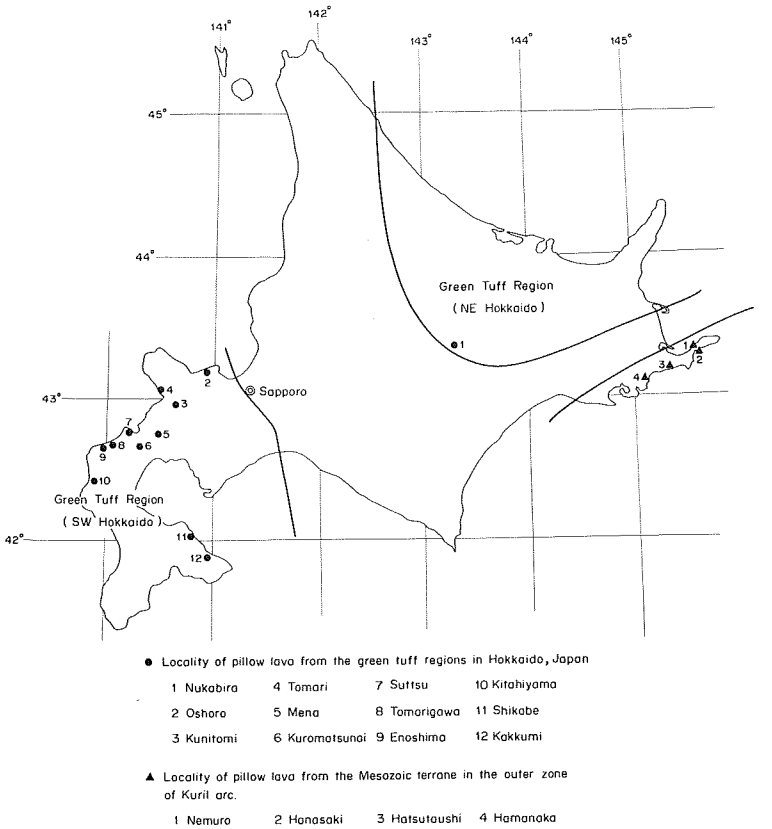

Fig. 4 Map showing the distribution of pillow lavas in Hokkaido except those of central axial zone.

rhythmical banding within a pillow. The ratio of these amygdaloids to the pillow is 10–20% in general, but attains a maximum of 30%. The outer shell of a unit pillow is composed of glassy materials accompanied by chlorite, while variolitic texture is commonly observed in the interior of a pillow or around the amygdaloids. The core of a pillow is composed of subophitic textured facies consisting of ceder-leave form clinopyroxene and plagioclase, associated with small amount of analcime.

Distinct alteration of the pillow lava is characterized by the presence of chlorite, calcite, epidote, quartz and prehnite. Though this makes the identification of the original rocks difficult, it seems likely that the pillow lavas have been formed from a tholeiite magma due to the mineral assemblage and mode. The mode of occurrence of the pillow lava from Kitahiyama district, central part of southwest Hokkaido, is worthy of special note. Here a horizontal sheet lying conformably with the sediments of the Kuromatsunai

Series has a feeder dyke which truncates the sediments vertically at one end, and grades into aggregates of pillow lavas on the other end. The pillows are composed of porous doleritic rock, and the space between the pillows is filled with glassy material and/or fragments of the tuffaceous rock. The outer shell of a pillow is generally composed of glassy materials, with many lenticular pores showing rhythmic banding parallel to the outer shell. Prismatic plagioclase and clinopyroxene are major components, these are arranged in subparallel rows, while hyalo-ophitic texture enclosing some phenocrysts of augite and plagioclase is observed in the core of a pillow.

It is one of the most notable characters of the pillow lavas from the southwest Hokkaido of Miocene age that they are much more porous compared with those from the central axial zone of Hokkaido. This suggests that these pillow lavas have been formed in shallower water conditions than in other districts.

Genetic Considerations

Moore (1965) showed a distinct relation between the porocity of the pillow lavas and the depth at which the pillows were formed. According to his diagram the pillow lavas in the southwestern Hokkaido were formed at shallow sea, those in the Nemuro peninsula at deep sea, and those in the central axial zones were formed at various depths.

Slumping phenomena sometimes observed in the shale lying above the Nemuro Formation may suggest that the pillow lavas have been formed on the slopes of the continental shelf rather than on the deep ocean bottom.

The presence of pillow structures associated with the intrusive sheets has been mentioned in several cases (Snyder and Fraser, 1963a, 1963b), but no satisfactory explanation has been presented for the close association of columnar joints with pillow structures. From the field observations in the Nemuro Peninsula the following conclusion was obtained (Yagi, 1969a).

Extremely fluidal basalt magma was intruded into the layers of unconsolidated silty and sandy sediments on the sea bottom. The upper and lower contacts of the sheet with sediments were quenched, and stopped the movement, resulting in the formation of columnar joints, whereas the hotter central portion maintained its forward movements just like a lava tunnel. When the quenched frontal portion was broken, hot liquid lava came into direct contact with the sea water in the voids of unconsilidated sediments, and thus the pillow structures were formed in the central portion.

Paleomagnetic study shows that all the individual pillows have the same magnetic orientation, and therefore they were above the Curie point

temperature when formed (Fujiwara and Nagase, 1965).

This type of close association of pillow and columnar structures has not been found in other localities in Hokkaido. Pillow lavas in other localities belong to ordinary pillow lavas which can be explained as lava flows erupted on the surface of the sea bottom, but no satisfactory interpretation has been presented for the origin of pillows associated with the Shimokawa diabase swarm.

In the following the characteristic features and the original magmas of the pillow lavas in Hokkaido are summarized.

The pillow lavas in the central axial zone are associated with monotonous geosynclinal deposits, sometimes intercalated with chert and limestone layers. They are usually non-porous and range from subophitic, variolitic to ophitic in texture. Petrochemically the pillow lavas of the earlier stages are tholeiitic, rather rich in Mg and Ca, and poor in alkalis and Al, while those of the later stages are enriched in alkalis, especially Na, sometimes showing keratophyric features.

In the Kamuikotan belt of this axial zone pillow breccias are well-developed, subjected to intense shearing stress. Petrochemically they are rich in alkalis, especially Na, and spillitic in composition. Thus in the central axial zone, most of the pillow lavas were derived from the tholeiitic magmas in the early stages of activity, while some later ones might have originated from differentiated magma rich in alkalis.

On the contrary the pillow lavas of the Nemuro district are fairly uniform. It is considered that they were produced from alkali basaltic magma rich in K_2O, which was probably derived from the partial melting of the phlogopite-bearing peridotite in the upper mantle.

The pillow lavas in the green tuff regions are associated with the green tuff formations in the lower horizon, while those in the upper horizon are associated with alternation of mudstone, sandstone and pyroclastic formations. The pillow lavas of the lower horizon are variolitic in texture, rather rich in amygdules, while those of the upper horizon are porous, rich in vesicles, and non-variolitic. Probably the later pillow lavas formed in much more shallow sea condition than the earlier ones. Strong alteration of the pillow lavas, such as formation of chlorite and epidote, makes it difficult to estimate the primary magma from the original mineralogical compositions, however, it is estimated that it was probably tholeiitic.

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