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PETROCHEMISTRY OF THE QUATERNARY VOLCANIC ROCKS OF HOKKAIDO, NORTH JAPAN

by

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(with 16 text-figures and 7 tables)

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Abstract

The Kurile and north Honshu island areas, which join in Hokkaido, are divided into an outer (Pacific) arc and an inner (Okhotsk or Japan Sea) arc. Quaternary volcanism has been taking place only in the inner arcs.

The Quaternary volcanic rocks are composed of a basalt – andesite – dacite – rhyolite suite, of which andesite and dacite of the calc-alkali series are predominant. The rocks vary markedly from the Pacific side to the marginal sea side, and are associated with basalts which vary from tholeiitic to alkalic basalt types, as follows:

Pacific side .... *Marginal sea side*
Tholeiite series(T) High-Al basalt ser.(H) Alkali rock series(A)
Calc-alkali ser.(C_T) Calc-alkali series(C_H) Calc-alkali series(C_A)

183 major element chemical analyses of the Quaternary volcanic rocks of Hokkaido are now available. Spatial zonation of the rocks is well represented in alkali - silica relations. Marked iron enrichment in the intermediate rocks is found in the tholeiite series.

Trace elements were determined on 42 selected rocks. The contents of REE, Ba, U, Th and Hf increase with silica. The rocks of the marginal sea side are particularly enriched in these elements. The abundance of Sc, Cr, V and Co decreases with increasing silica content. It is noted that Sc and V behave as iron. The three groups, T & C_T, H & C_H and A & C_A, are well distinguished from each other in the chondrite-normalized REE pattern, i.e. T & C_T has distribution patterns vary similar to the ocean ridge tholeiite, showing a tendency toward depletion or equality of light REE over heavy REE, whereas A & C_A has a marked enrichment of light REE over heavy REE. There is no essential difference in the REE pattern between the calc-alkali rocks and the associated basaltic rocks in each group, suggesting a common source for them. A negative Eu anomaly is a characteristic feature of the calc-alkali rocks, though this anomaly does not always appear.

$^{87}Sr/^{86}Sr$ ratios were determined on 49 samples. The ratios of the rocks of the Kurile are extremely low (0.7028 – 0.7039), and those of the north Honshu arc are also low (0.7026 – 0.7057). The Sr-isotope ratios of basalt to dacite in a single volcano are almost identical and exhibit a small range of variation without systematic change. This implies that

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the igneous magmas have been produced from a relatively homogeneous mantle material and not modified by contamination with the older continental crust.

Introduction

Two younger island arcs, the Kurile and the north Honshu, are joined together in Hokkaido (Fig. 1). As has been mentioned by many geologists, these two island arcs are divided into the outer (Pacific side) and the inner (Okhotsk or Japan sea side) arcs, respectively. The inner arcs are called the "Green-tuff region" (Minato *et al.*, 1956) where intense volcanic activity has been taking place since early or middle Miocene. Volcanism in the Quaternary period also occurs only in the inner arcs (Fig. 2). This situation, together with the existence of a deep-sea trench and active seismicity, the focal plane of which dips under the marginal sea, indicates that Hokkaido has a similar tectonic feature to the double island arcs of the circum-Pacific belt (Fig. 3). It is noticed here that the active volcanic zones in Hokkaido are located 250 – 350 m from the trench axis, and its location coincides with the zone of epicenters with focal depth 100 – 200 km.

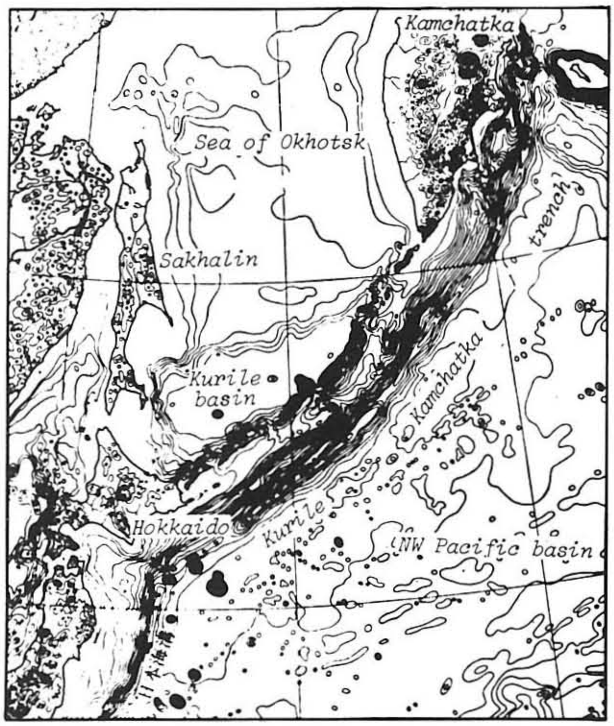

Fig. 1 Bathymetric chart of the surrounding regions of Hokkaido. (Hydrographic Department, Japan Maritime Safety Agency, 1971).

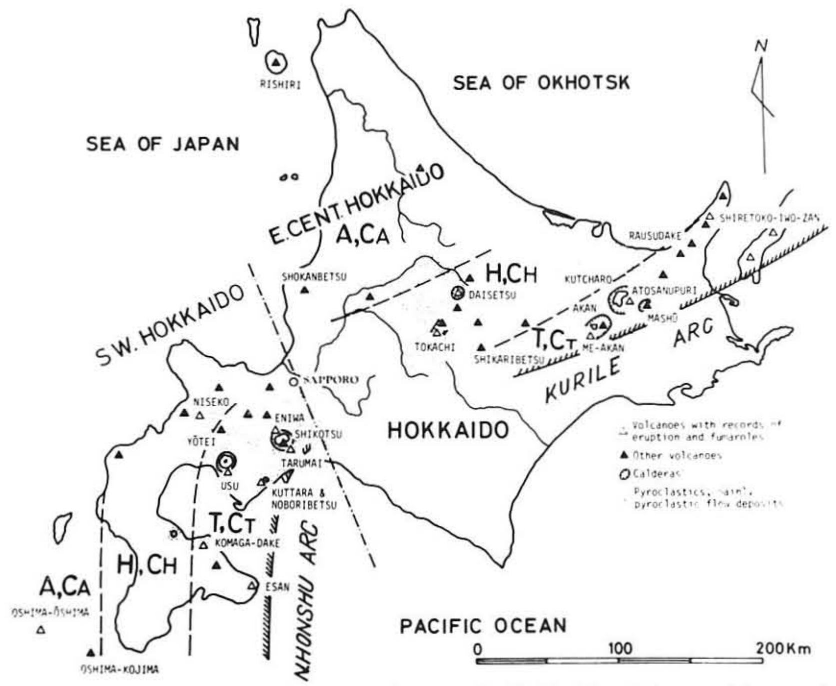

Fig. 2 Distribution of the Quaternary volcanoes in Hokkaido. Petrographic provinces are shown by the symbols of rock series, T & C_T, H & C_H, and A & C_A (see Table 2).

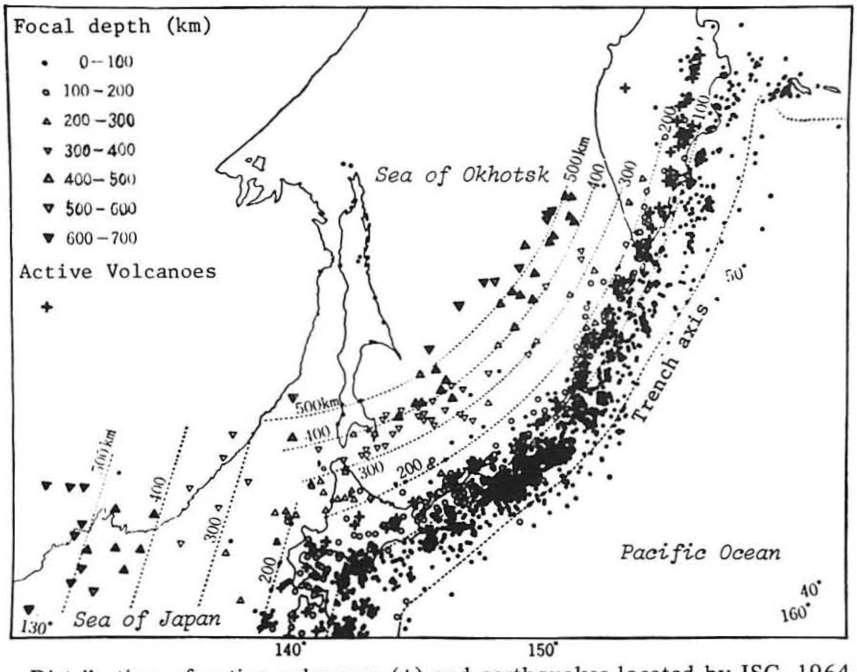

Fig. 3 Distribution of active volcanoes (+) and earthquakes located by ISC, 1964–1967 with addition of 20 earthquakes (depth > 200 km, 1926–1963) (Utsu *et al.* 1972).

As shown in Fig. 2, the Quaternary volcanoes in Hokkaido are divided into two major zones; one comprises those along the Kurile arc, and the other those along the north Honshu arc. The junction of the two major volcanic zones is located in the Sapporo-Tomakomai lowland which separates the island into east-central and southwestern parts. It is worthly of note that the two inclined seismic zones along the Kurile and the north Honshu arcs are also joined together at the Sapporo-Tomakomai lowland, as shown in Fig. 3.

During the Quaternary period, 45 volcanoes (or volcano groups) have erupted along the inner zones of the Kurile and the north Honshu arcs (Fig. 2). Of these 8 volcanoes have records of activity in historic times (Shiretoko-iwo-zan, Me-akan-dake, Tokachi-dake, Tarumai, Usu, Komaga-dake, Esan, and Oshima-oshima), and 5 volcanoes retain vigorous solfataric activity (Atosa-nupuri, Daisetsu, Eniwa, Niseko, and Noboribetsu). Most of the volcanoes in Hokkaido are stratovolcanoes formed though central eruption, and lava-domes and pyroclastic cones are associated. Some of them built gigantic calderas of the Krakatau type as a result of large scale eruptions of pyroclastic flows, i.e. Kutcharo, Mashu, Akan, Daisetsu, Tokachi, Shikotsu, Tōya, Kuttara, and Nigorikawa. Around these calderas felsic pyroclastic deposits of Pleistocene to Holocene age are widely developed, forming extensive pyroclastic plateaux.

Petrographically speaking, the Quaternary volcanic rocks of Hokkaido are grouped in a basalt – andesite – dacite – rhyolite suite, of which andesite and dacite of the calc-alkali series are abundant rocks as in other island arcs. These rocks vary markedly in nature from the Pacific side (calcic) to the marginal sea side (more alkalic), and considerable amounts of tholeiite, high-alumina basalt or alkali olivine basalt are associated with the calc-alkali rocks in many volcanoes.

This report concerns the spatial zonal arrangement of the rocks and origin of the calc-alkali rocks, on the basis of mode of occurrence of the rocks and their major element chemistry, trace element abundances, and Sr-isotopic ratios.

Rock Types and Rock Series

All of the Quaternary volcanic rocks in Hokkaido are included in a wide range of basalt – andesite – dacite – rhyolite. Their mineral compositions, rock types, and rock series are shown in Tables 1, 2 and 3.
Of these, andesite and dacite of the calc-alkali series are predominant rocks in most of the volcanic fields in Hokkaido. The term calc-alkali series is used here for the hypersthenic rock series (Kuno, 1968) which is characterized by the presence of groundmass orthopyroxene. Appearance of hornblende and/or

biotite as phenocrysts which are normally absent in the other series, is another mineralogical feature of the calc-alkali series.

Table 1 Rock types of the Quaternary volcanic rocks of Hokkaido.

Groundmass / Phenocryst	Ol Cpx Opx	Ol Cpx	Cpx	Cpx Opx	Opx	glassy	+ Biot. phenocryst
none	a	b	c ϕ	d	e		
Cpx	Ia	Ib	Ic ϕ	Id	Ie ○ +	I	XI
Ol Opx	IIa	IIb	IIc	IId	IIe	II	XII
Ol	IIIa	IIIb	IIIc	IIId	IIIe	III	XIII
Ol Cpx	IVa	IVb + → Φ	IVc ϕ ← ϕ	IVd +	IVe	IV	XIV
± Ol Cpx Opx	Va	Vb	Vc Φ ϕ ϕ/●	Vd ○ ● +	Ve ○	V ○	XV
± Ol Cpx & Opx Hor	VIa	VIb	VIc	VId ● +	VIe	VI ○	XVI ● +
± Ol Opx Hor	VIIa	VIIb	VIIc	VIId	VIIe	VII ○	XVII ●
± Ol Hor	VIIIa	VIIIb	VIIIc	VIIId	VIIIe	VIII	XVIII ● +
± Ol Cpx Hor	IXa	IXb	IXc	IXd	IXe	IX	XIX +
Cpx	Xa	Xb	Xc	Xd	Xe	X	XX

Rock types are classified by the ferromagnesian silicate mineral assemblage which was proposed by Kuno (1950). Rock types enclosed in bold lines indicate those occurred in Hokkaido, and their rock series are shown by symbols (see Table 2).

Table 2 Rock series of the Quaternary volcanic rocks of Hokkaido.

Zone	Basaltic rock series		Associated Calc-alkali series	
Pacific side	T (ϕ) Tholeiite series (mostly low alkali tholeiite)	*basalt* IVc, Vc *andesite* IVc, Vc, Ic Vd→ c, c	C_T (○)	*andesite* Vd, V *dacite* Vd, Vd→e, Ie & VI(pumice) *rhyolite (rare)* VI, VII(pumice)
↕	H (⬤ with line) High-alumina basalt series	*basalt* IVb→ c *andesite* Vc	C_H (●)	*andesite* Vc– d, Vd, VId, XVId, XVI *dacite* - *rhyolite* XVII, XVIII(pumice)
Marginal Sea side	A (+) Alkali series	*basalt* IVb [IIIb, IVd IIIb→ c, IVb→ c IIIc, IVc, Xc]	C_A (+)	*andesite* IVd, Vd, VId, Ve, Ie XVId, XVIII, XIX [IIIa→ d, IVa→ d IIId, IVd, Vd, IXd]

( ) symbols of the rock series.

[ ] Late Pliocene basalt - andesite (Ōba, 1972)

Table 3 Essential mineral composition of the Quaternary basalt and andesite of Hokkaido.

Rock series	T [C_T]	H [C_H]	A [C_A]
Pheno-cryst	Anorthite* – bytownite Olivine with pyroxene rim Augite, rarely pigeonite in T Hypersthene Magnetite (*sometimes large pheno-cryst > 1 cm in size)	Bytownite – labradorite Olivine Augite Hypersthene Magnetite [Hornblende]	Labradorite – andesine Olivine Augite, Ti-augite in A Magnetite [Hypersthene] [Hornblende] [Biotite]
Ground-mass	Bytownite – labradorite Augite, pigeonite in T Olivine (rare) usually with reaction rim Silica minerals Magnetite [Hypersthene] [Alkali feldspar]	Labradorite – andesine Augite Olivine (rare) with or without reaction rim in H Silica minerals Alkali feldspar Magnetite [Hypersthene]	Andesine – oligoclase Augite Olivine without reaction rim in A Alkali feldspar Magnetite Apatite [Hypersthene] [Silica minerals]

[ ] included only in calc-alkali rocks.

The nature of the calc-alkali rocks as defined above, however, varies in petrographic character, showing spatial zonation from the Pacific side toward the marginal sea, i.e. the rocks of the Pacific side consist of pyroxene-andesite and -dacite with a little rhyolite, which are poor in alkalies and rich in lime and iron oxides, whereas toward the marginal sea they are composed of andesite, dacite •and rhyolite, which are high in alkalies and magnesia, and carry commonly hornblende and biotite phenocrysts. Such spatial zonation of calc-alkali rocks has been noticed with special interest (Katsui, 1961; Kuno, 1959, 1966 and 1968).

Although andesite and dacite of the calc-alkali series are predominant rocks in the Quaternary volcanic fields, substantial amounts of basaltic rocks occur in many volcanoes, being intimately associated with the calc-alkali rocks (Fig. 2 and Table 2). In the Akan-Kutcharo volcano group in eastern Hokkaido, for example, tholeiitic basalt and andesite (T) erupted in the early stage of each volcano. This was followed by eruption of andesite and dacite of the calc-alkali series (C_T). Repetition of the T → C_T sequence is also found in the Kutcharo area, as follows:

Pleisto-cene	Kutcharo	basalt & andesite (T) → dacite pumice (C_T)
	Atosanupuri	andesite (T) → dacite pumice & dome (C_T)
Holocene ↓	Mashu	andesite (T) → felsic andesite pumice and dome (C_T)

Oshima-oshima, a volcanic island in the Japan Sea, consists of a triple stratovolcano, showing a more complicated history as follows;

Pleisto-cene	Higashi-yama	andesite (C_A) → basalt (A)
	Nishi-yama	basalt (A) → andesite (C_A) → basalt (A)
Holocene ↓	Central cone	basalt (A)

The mode of occurrence mentioned above strongly suggests a genetic consanguinity between the calc-alkali rocks and associated basaltic rocks in each volcano or volcanic region.

Major Elements

About 180 major-element chemical analyses are available of the Quaternary volcanic rocks of Hokkaido, of which 74 selected ones are listed in Tables 4 and 5.

Table 4 Chemical composition of the Quaternary volcanic rocks of east - central Hokkaido (Kurile arc)

Volcano	Shiretoko-iwo-zan	Rausudake	Kutcharo		Atosanupuri	Mashū	
No.	K-1	K-2	K-3	K-4	K-5	K-6	K-7
Rock series*	C_T	C_T	T	C_T	T	T	T
Type of mineral assemblage**	Vd	Vd	Vc	V	c	Vc	Ic
SiO_2	60.69	61.76	54.14	71.25	64.26	55.08	52.78
TiO_2	.71	.80	1.21	.50	.91	1.19	.77
Al_2O_3	16.72	16.38	15.71	14.31	14.87	15.92	19.01
Fe_2O_3	3.60	3.14	3.41	1.22	2.18	3.83	2.48
FeO	3.96	4.04	9.19	1.48	5.03	8.16	7.15
MnO	.09	.12	.22	.10	.14	.22	.18
MgO	2.44	2.08	3.26	.89	1.76	3.19	3.78
CaO	5.83	5.81	8.93	3.13	5.49	9.02	11.08
Na_2O	3.51	3.40	2.31	4.06	3.70	2.48	2.21
K_2O	1.57	1.39	.41	1.91	.83	.44	.30
P_2O_5	.15	.18	.08	.11	.20	.21	.25
H_2O (+)	.27	.34	.48	.68	.25	.25	.19
H_2O (−)	.19	.13	.41	.16	.36	.14	.18
Total	99.73	99.57	99.76	99.80	99.98	100.13	100.36
Analyst	Katsui	Katsui	Katsui	Katsui	Katsui	Katsui	Katsui

* cfr. Table 2.

** Symbols of Kuno's classification by the ferromagnesian silicate mineral assemblage (Kuno, 1950).

K-1 Augite hypersthene andesite, Naka-dake lava of the Shiretoko-iwo-zan volcano. Loc., summit of Naka-dake. (Katsui, 1961)

K-2 Augite hypersthene andesite, a dome lava of the Rausu-dake volcano. Loc., summit of Rausu-dake. (Katsui, 1961)

K-3 Augite hypersthene basalt, a somma lava of the Kutcharo volcano. Loc., south of Kamisattsuru. (Katsui, 1958)

K-4 Augite-bearing hypersthene dacitic welded tuff, a welded part of the first pumice-flow deposit of the Kutcharo volcano. Loc., a quarry of Furume, south of Bihoro. (Katsui, 1958)

K-5 Aphyric andesite, a somma lava of the Atosanupuri volcano. Loc., eastern part of the Atosanupuri caldera-wall. (Katsui, 1958)

K-6 Augite-bearing hypersthene andesite, a somma lava of the Mashū volcano. Loc., foot of the western part of the Mashū caldera. (Katsui, 1955)

K-7 Hypersthene andesite, a somma lava of the Mashū volcano. Loc., foot of the western part of the Mashū caldera. (Katsui, 1955)

Table 4 (Kurile arc) continued

Volcano	Mashu		Akan		Me-akan	Shikaribetsu	
No.	K-8	K-9	K-10	K-11	K-12	K-13	K-14
Rock series	C_T	C_T	T	C_T	C_T	C_H	C_H
Type of mineral assemblage	V	Vd	IVc	V	Vd	Vd	VId
SiO_2	65.73	72.96	52.43	65.87	57.54	59.16	61.26
TiO_2	.62	.33	1.01	.78	.81	.70	.63
Al_2O_3	15.29	12.54	17.67	14.53	18.37	16.84	17.51
Fe_2O_3	2.15	2.01	3.08	2.43	2.07	1.75	2.76
FeO	3.25	2.09	7.28	3.51	5.54	5.54	3.60
MnO	.13	.08	.19	.13	.11	.06	.07
MgO	1.99	.99	3.86	1.38	3.21	3.19	2.50
CaO	4.74	3.29	10.34	4.75	7.55	6.90	5.92
Na_2O	4.10	3.66	2.22	3.51	2.66	2.91	3.64
K_2O	.75	1.07	.51	1.46	1.07	1.26	1.39
P_2O_5	.25	.29	.11	.34	.09	.12	.10
H_2O (+)	.40	.41	.42	.75	.64	.25	.30
H_2O (−)	.33	.30	.32	.44	.43	.84	.06
Total	99.73	100.02	99.44	99.88	100.09	99.52	99.74
Analyst	Katsui	Katsui	Katsui	Katsui	Katsui	Katsui, Ōba, Fujita	Katsui, Ōba, Fujita

K-8 Augite hypersthene andesite, pumice from the Ma-f pumice-flow deposit, Loc., Nijibetsu, east of the Mashū caldera. (Katsui, 1963)

K-9 Augite hypersthene dacite, Kamuishu dome lava of the Mashū caldera. Loc., Kamuishu island. (Katsui, 1955)

K-10 Augite-bearing olivine basaltic andesite, a somma lava of the Akan volcano. Loc., Senpoku-tōge. (Katsui, 1958)

K-11 Augite hypersthene andesitic welded tuff, a pyroclastic flow deposit of the Akan volcano. Loc., north of the Akan caldera. (Katsui, 1958)

K-12 Augite hypersthene andesite, a lava of Ponmachineshiri, one of the strato-cones of the Me-akan-dake volcano. Loc., Northwest of the summit of Ponmachineshiri. (Katsui, 1958)

K-13 Hypersthene andesite, Yambetsu-gawa lava, an older lava of the Shikaribetsu volcano. Loc., north of Lake Shikaribetsu. (Fujita, 1972)

K-14 Hornblende hypersthene augite andesite, Tembo-zan dome lava, Shikaribetsu volcano. (Fujita, 1972)

Table 4 (Kurile arc) continued

Volcano	Daisetsu					Tokachi	
No.	K-15	K-16	K-17	K-18	K-19	K-20	K-21
Rock series	C_H	C_H	C_H	C_H	C_H	C_H	H
Type of mineral assemblage	Vd	VId	VId	Vd	Vd	XVI	IVb·c
SiO_2	56.99	60.44	64.67	56.72	54.73	71.57	46.79
TiO_2	.75	.55	.62	.64	.91	.29	1.61
Al_2O_3	17.01	15.67	16.24	16.58	17.84	13.11	18.03
Fe_2O_3	3.73	2.80	2.62	3.27	2.79	2.62	4.98
FeO	4.28	4.08	2.60	4.84	6.02	.78	7.52
MnO	.07	.08	.09	.10	.11	.07	.19
MgO	3.59	3.12	2.10	3.94	4.70	.64	5.76
CaO	8.21	6.50	4.80	7.28	8.13	2.19	10.55
Na_2O	2.72	3.31	3.77	3.03	2.86	3.89	2.67
K_2O	1.47	1.73	1.97	1.65	1.45	3.39	.79
P_2O_5	.17	.17	.12	.24	.17	.06	.08
H_2O (+)	.56	.75	.46	.64	.35	.60	.55
H_2O (−)	.39	.51	.15	.96	.12	.42	.38
Total	99.94	99.71	100.21	99.89	100.18	99.63	99.90
Analyst	Katsui	Katsui	Katsui	Katsui	Katsui	Takahashi	Katsui & Takahashi

K-15 Augite hypersthene andesite, a lava of Chuo-kako, the central crater of the Daisetsu volcano. Loc., west of the crater wall. (Katsui and Takahashi, 1960)

K-16 Quartz- and olivine-bearing hornblende augite hypersthene andesite, Keigetsu-dake dome lava of the Daisetsu volcano. Loc., summit of Keigetsu-dake. (Katsui and Takahashi, 1960)

K-17 Quartz-bearing augite hypersthene hornblende andesite, a dome lava of Kuro-dake of the Daisetsu volcano. Loc., southern flank of Kuro-dake. (Katsui and Takahashi, 1960)

K-18 Olivine-bearing augite hypersthene andesite, Mikura-sawa lava, a younger lava of the Daisetsu volcano. Loc., Mikura-sawa. (Katsui and Takahashi, 1960)

K-19 Olivine-bearing augite hypersthene andesite, a spindle-shaped bomb of Asahi-dake, a young strato-cone of the Daisetsu volcano. Loc., summit of Asahi-dake (Katsui and Takahashi, 1960)

K-20 Augite- and hypersthene-bearing hornblende biotite rhyolitic welded tuff, a lower welded tuff (Tokachi welded tuff) of the Tokachi-dake volcano. Loc., east of Kamifurano. (Katsui and Takahashi, 1960)

K-21 Augite olivine basalt, a lava of Furano-dake, one of the strato-cones of the Tokachi-dake volcano. Loc., summit of Furano-dake. (Katsui and Takahashi, 1960)

Table 4 (Kurile arc) continued

Volcano	Tokachi		Shokan -betsu	Rishiri			Me-akan
No.	K-22	K-23	K-24	K-25	K-26	K-27	K-28
Rock series	C_H	C_H	C_A	C_A	A	A	T
Type of mineral assemblage	XVId	Vd	VId	Vd	IVb	IVb	Vc
SiO_2	60.67	53.41	55.41	63.48	50.69	50.78	50.62
TiO_2	.79	1.23	.64	.56	1.28	1.09	.77
Al_2O_3	15.44	17.98	17.38	16.89	16.59	15.55	17.73
Fe_2O_3	4.72	2.77	3.36	2.82	4.06	3.90	4.34
FeO	2.67	6.52	4.16	2.77	5.01	7.02	6.94
MnO	.10	.20	.15	.10	.10	.12	.21
MgO	2.53	4.31	4.52	2.54	7.34	7.06	5.78
CaO	5.45	9.07	8.62	6.21	10.00	9.82	9.40
Na_2O	3.35	2.52	2.67	4.04	3.49	3.75	2.25
K_2O	2.93	1.31	1.34	.97	1.03	.59	.43
P_2O_5	.12	.19	.24	.14	.14	.07	.13
H_2O (+)	.79	.11	.57	.20	.43	.30	.63
H_2O (−)	.32	.10	.55	.05	.18	.20	.20
Total	99.88	99.72	99.61	100.77	100.34	100.25	99.43
Analyst	Takahashi	Katsui	Katsui	Katsui	Katsui	Katsui	Ando

K-22 Biotite- and hornblende-bearing augite hypersthene andesite, a dome lava of the Tokachi-dake volcano. Loc., summit of Tokachi-dake. (Katsui and Takahashi, 1960)

K-23 Olivine-bearing hypersthene augite andesite, 1962 bomb of the Tokachi-dake volcano. Loc., near the 1962 crater of the volcano. (Katsui and others, 1963)

K-24 Hornblende- and quartz-bearing olivine augite hypersthene andesite, a lava of the Shokanbetsu volcano. Loc., summit of Shokanbetsu-dake. (Katsui, 1961)

K-25 Augite hypersthene andesite, a lava of the 1st ejecta of the Rishiri volcano. Loc., eastern ridge of Rishiri. (Katsui, 1953)

K-26 Olivine augite basalt, a lava of the 2nd ejecta of the Rishiri volcano. Loc., eastern side of the top of Rishiri. (Katsui, 1953)

K-27 Olivine augite basalt, Motodomari lava of the Rishiri volcano. Loc., northern coast of Rishiri island. (Katsui, 1953)

K-28 Hypersthene-bearing augite olivine andesite, Nishi-yama lava of the Me-akan volcano. Loc., western flank of Me-akan-dake (Andō, unpublished)

Table 5 Chemical composition of the Quaternary volcanic rocks of southwestern Hokkaido (north Honshu arc)

Volcano	Usu						
No.	H-1	H-2	H-3	H-4	H-5	H-6	H-7
Rock series*	T	T	T	T	T	T	C_T
Type of mineral assemblage**	Vc	Vc	Vc	Vc	Vc	Vc	Ie
SiO_2	49.36	51.80	52.81	53.02	53.21	53.36	68.89
TiO_2	.69	.83	.86	.79	.87	.86	.47
Al_2O_3	16.07	16.79	16.47	16.42	19.22	17.27	14.92
Fe_2O_3	3.79	4.14	3.54	3.22	2.34	3.81	3.01
FeO	7.68	6.74	6.91	7.09	6.33	7.47	1.78
MnO	.21	.17	.17	.17	.13	.09	.16
MgO	8.92	6.01	6.23	4.95	4.21	3.63	.90
CaO	10.75	10.20	9.95	10.24	10.43	9.41	4.10
Na_2O	2.03	1.93	2.46	2.80	2.76	2.67	4.00
K_2O	.18	.46	.43	.58	.53	.51	1.03
P_2O_5	.12	.33	.23	.16	.11	.31	.24
H_2O (+)	.37	.26	.20	.17	.13	.28	.12
H_2O (−)	.10	.32	.09	.18	.19	.11	.32
Total	100.27	99.98	100.35	99.79	100.46	99.78	99.94
Analyst	Oba	Oba	Oba	Oba	Oba	Oba	Oba

* Cfr. Table 2.
** Symbols of Kuno's classification by the ferromagnesian silicate mineral assemblage (Kuno, 1950).

H-1 Augite-bearing hypersthene olivine basalt, I type somma lava of the Usu volcano. Loc., lake side of Nishi-maruyama. (Ōba, 1966)

H-2 Augite-bearing olivine hypersthene basalt, II type somma lava of the Usu volcano. Loc., south of Nishi-yama. (Ōba, 1966)

H-3 Olivine-bearing augite hypersthene basalt, IV type somma lava of the Usu volcano. Loc., south of Nishi-yama. (Ōba, 1966)

H-4 Hypersthene-bearing augite olivine basalt, III type somma lava of the volcano. Loc., a cliff of Sonkai-zawa. (Ōba, 1966)

H-5 Pigeonite hypersthene andesite, VII type somma lava of the Usu volcano. Loc., the roof-mountain of Showa-shinzan. (Ōba, 1966)

H-6 Augite hypersthene andesite, VI type somma lava of the Usu volcano. Loc., western foot of Konpirayama. (Ōba, 1966)

H-7 Hypersthene dacite, dome lava of Showa-shinzan, the youngest lava dome of the Usu volcano. Loc., northern side of Showa-shinzan. (Ōba, 1966)

Table 5 (north Honshu arc) continued

Volcano	Usu			Yōtei			
No.	H-8	H-9	H-10	H-11	H-12	H-13	H-14
Rock series	C_T	C_T	C_T	T	C_T	C_T	C_T
Type of mineral assemblage	Ie	Ie	VII	Vd→c	Vd	Vd	Vd
SiO_2	68.26	71.25	73.04	57.84	57.89	58.25	63.45
TiO_2	.36	.43	.26	.82	.89	1.01	.67
Al_2O_3	15.77	13.21	12.95	17.48	18.33	15.98	15.97
Fe_2O_3	1.91	3.19	1.11	2.72	2.36	3.60	2.58
FeO	2.15	1.96	1.54	5.74	5.11	5.76	4.28
MnO	.31	.27	.06	.12	.10	.14	.10
MgO	.99	.84	.36	3.14	2.65	3.32	1.95
CaO	4.37	3.10	2.41	7.77	7.97	7.65	5.08
Na_2O	3.83	4.02	5.07	3.13	3.30	2.89	3.75
K_2O	1.29	1.15	1.14	.99	1.07	1.01	1.34
P_2O_5	.18	.46	.43	.20	.17	.17	.18
H_2O (+)	.51	.50	1.02	.11	.20	.12	.21
H_2O (−)		.25	.21	.05	.04	.06	.11
Total	99.93	100.63	99.60	100.11	100.08	99.96	99.67
Analyst	G.S.Japan	Yagi	Oba	Katsui	Katsui	Katsui	Katsui

H-8 Hypersthene dacite, dome lava of O-Usu, a lava dome of the Usu volcano. (Tanakadate, 1930)

H-9 Hypersthene dacite, dome lava of Ko-Usu, a lava dome of the Usu volcano. (Yagi, 1949; Minakami et al, 1950)

H-10 Hornblende-bearing hypersthene rhyolitic pumice, pumice of the Us-b pumice fall deposits. Loc., north of Showa-sinzan. (Ōba, 1966)

H-11 Olivine-bearing augite hypersthene andesite, the 2nd stage lava of the Yōtei volcano. Loc., western slope of Yōtei. (Katsui, 1956)

H-12 Augite hypersthene andesite, the 1st stage lava of the Yōtei volcano. Loc., western foot of Yotei. (Katsui, 1956)

H-13 Olivine-bearing augite hypersthene andesite, the 3rd stage lava of the Yōtei volcano. Loc., southern rim of the younger crater, summit of Yōtei. (Katsui, 1956)

H-14 Augite-bearing hypersthene andesite, a lava of Minami-kako, one of the parasitic cones of the Yōtei volcano. Loc., southwestern foot of Yōtei. (Katsui, 1956; Katsui, 1961)

Table 5 (north Honshu arc) continued

Volcano	Niseko			Oshima-ōshima			
No.	H-15	H-16	H-17	H-18	H-19	H-20	H-21
Rock series	C_H	C_H	C_H	A	A	C_A	C_A
Type of mineral assemblage	VId	Vd	VId	IVb	IVb	VId	VId
SiO_2	58.20	59.93	60.35	48.89	49.90	55.56	61.72
TiO_2	.75	.86	.83	1.02	1.09	.61	.37
Al_2O_3	16.01	18.50	15.77	15.00	16.05	18.28	17.71
Fe_2O_3	4.67	3.09	5.01	2.92	5.03	2.46	1.12
FeO	2.73	2.84	2.78	6.41	5.55	5.11	4.33
MnO	.12	.06	.19	.25	.14	.19	.10
MgO	4.43	3.21	3.39	10.60	7.03	4.05	1.83
CaO	6.79	6.13	5.68	10.91	10.51	8.57	5.19
Na_2O	4.05	3.90	2.85	1.95	2.15	2.62	3.21
K_2O	1.20	1.80	1.61	1.13	1.92	1.80	3.28
P_2O_5	tr	.03	.22	.05	.23	.22	.20
H_2O (+)	1.24	.40	1.21	.64	.26	.62	.83
H_2O (−)	.41	.22	.19	.12	.06	.13	.16
Total	100.60	100.97	100.08	99.89	99.92	100.27	100.05
Analyst	Ōba	Ōba	Ōba	Katsui	Katsui	Katsui	Katsui

H-15 Quartz, hornblende- and olivine-bearing augite hypersthene andesite, dome lava of Chisenupuri, one of the lava domes of the Niseko volcano. Loc., near of the top of Chisenupuri. (Ōba, 1960)

H-16 Hypersthene augite andesite, lava of Nisekoannupuri, a lava cone of the Niseko volcano. Loc., near of the top of Nisekoannupuri. (Ōba 1960)

H-17 Quartz-bearing hypersthene augite andesite, dome lava of O-iwaonupuri, one of the lava domes of the Niseko volcano. Loc., near the top of O-iwaonupuri. (Ōba, 1960)

H-18 Augite olivine basalt, a lava of the younger somma (Nishi-yama) of the Oshima-ōshima volcano. Loc., Yamasedomari, southern coast of the Oshima-ōshima island. (Katsui, 1953)

H-19 Olivine augite basalt, a central cone lava of the Oshima-ōshima volcano. Loc., Yakekuzure peninsula, north of the Oshima-ōshima island. (Katsui, 1953)

H-20 Olivine- and hornblende-bearing augite hypersthene andesite, a lava of the younger somma (Nishi-yama) of the Oshima-ōshima volcano. Loc., Aidomari, southern coast of the Oshima-ōshima island. (Katsui, 1960).

H-21 Hornblende augite hypersthene andesite, a lava of the older somma (Higashi-yama) of the Oshima-ōshima volcano. Loc., Aidomari, Oshima-ōshima island. (Katsui, 1953)

Table 5 (north Honshu arc) continued

Volcano	Oshima-kojima	Shikotsu					Tarumai
No.	H-22	H-23	H-24	H-25	H-26	H-27	H-28
Rock series	C_A	C_T	C_T	C_T	C_T	C_T	C_T
Type of mineral assemblage	XVId	Vd	V	VI	VI	VI	Vd
SiO_2	60.46	51.40	64.92	69.05	69.63	72.41	57.40
TiD_2	.57	.92	.52	.42	.10	.31	.53
Al_2O_3	16.30	19.20	15.08	14.76	14.33	12.83	18.27
Fe_2O_3	3.16	3.96	1.81	1.87	2.08	1.36	3.50
FeO	2.83	5.82	2.24	1.27	1.90	1.20	6.01
MnO	.14	.27	.07	.09	.15	.05	.15
MgO	3.31	3.84	.81	.68	1.12	.45	3.89
CaO	7.11	9.94	3.98	3.19	3.20	2.04	7.30
Na_2O	3.04	2.67	3.40	3.91	3.09	3.35	2.12
K_2O	1.87	.65	1.71	2.45	1.88	3.50	.70
P_2O_5	.22	.20	.10	.11	.19	.13	n.d.
H_2O (+)	.39	.83	4.20	2.57	2.46	2.64	.43
H_2O (−)	.21	.27	.94	.28		.19	
Total	99.61	99.97	99.78	100.65	100.13	100.46	100.30
Analyst	Katsui	Katsui	Katsui	Katsui	average of 6	Katsui	Nakae

H-22 Biotite- and quartz-bearing hornblende hypersthene augite andesite, a lava of the Oshima-kojima volcano. Loc., western coast of Oshima-kojima island. (Katsui, 1963)

H-23 Olivine augite hypersthene andesite, a scoria of the Shikotsu scoria-fall deposit. Loc., Hayakita. (Katsui, 1963)

H-24 Augite hypersthene dacite, a pumice from the Shikotsu pumice-fall deposit (Spfa 2). Loc., Hayakita. (Katsui, 1959)

H-25 Hornblende augite hypersthene dacite, a pumice from the Shikotsu pumice-flow deposit (Spf 1). Loc., Shimamatsu, north of Chitose. (Katsui, 1963)

H-26 Hornblende augite hypersthene dacitic welded tuff, a welded part of the Shikotsu pumice-flow deposit (Spfl). Average of 6 analyses. (Sato & Kagawa, 1959)

H-27 Augite hornblende hypersthene rhyolite, a pumice from the Shikotsu pumice-fall deposit (Spfa 1). Loc., Bibi, south of Chitose. (Katsui, 1963)

H-28 Augite hypersthene andesite, a lava block of the central cone of the Tarumai volcano. Loc., eastern foot of the lava dome, summit of Tarumai. (Ishikawa, 1935)

Table 5 (north Honshu arc) continued

Volcano	Tarumai			Eniwa			Kuttara and Noboribetsu
No.	H-29	H-30	H-31	H-32	H-33	H-34	H-35
Rock series	C_T	C_T	C_T	C_T	C_T	C_T	T
Type of mineral assemblage	Vd	V	Vd	Vd	V	V	Vc
SiO_2	57.88	58.38	59.17	58.98	60.47	64.32	56.74
TiO_2	.49	.62	.48	.58	.97	.52	.60
Al_2O_3	19.42	17.84	18.60	17.02	17.36	16.92	16.71
Fe_2O_3	2.25	3.33	2.78	2.72	1.47	3.06	3.76
FeO	6.76	5.21	5.84	4.86	3.94	1.56	5.85
MnO	.87	.22	1.03	.11	.14	.09	.17
MgO	3.29	3.42	3.12	3.70	2.94	1.81	4.20
CaO	6.75	7.38	6.61	7.97	6.70	5.50	8.34
Na_2O	2.20	2.46	1.88	2.56	3.10	3.42	2.13
K_2O	1.00	.72	.98	.89	1.23	1.47	.57
P_2O_5	n.d.	n.d.	.21	.11	.16	.15	.06
H_2O (+)	.02	.97	.19	.08	1.40	1.34	.12
H_2O (−)				.30			.39
Total	100.93	100.55	100.95*	99.88	99.88	100.16	99.64
Analyst	Average of 3	Average of 6	Average of 5	Ōba & Nakamura	Nakamura	Nakamura	Ōba & Koike

* including 0.06%S.

H-29 Augite hypersthene andesite (with large anorthite), 1909 bread-crust bombs and lava block of the Tarumai volcano. Loc., summit of Tarumai. Average of 3 analyses. (Ishikawa, 1952)

H-30 Augite hypersthene andesitic welded tuff, welded part of the Tarumai pumice-flow deposit (lavas of Kuchawakkanai, Oppopu, Nishi-yama and Shishamonai according to Ishikawa) Average of 6 analyses. (Ishikawa 1952)

H-31 Augite hypersthene andesite (with large anorthite), 1909 dome lava of the Tarumai volcano. Loc., summit of Tarumai. Average of 5 analyses. (Ishikawa, 1952)

H-32 Olivine-bearing hypersthene augite andesite, a lava of the latest stage of the Eniwa volcano. Loc., northern wall of the crater. (unpublished)

H-33 Augite hypersthene andesite, Marukoma lava, a lava of the southern slope of the Eniwa volcano. Loc., near Marukoma hot spring. (unpublished)

H-34 Augite hypersthene andesitic pumice, a pumice from the En-a pumice-fall deposit erupted in the early stage of the Eniwa volcano. Loc., Poropinai, northern lake side of the Shikotsu. (unpublished)

H-35 Olivine-bearing hypersthene augite andesite, a somma lava f the Kuttara caldera. Loc., southern part of the caldera wall. (unpublished)

Table 5 (north Honshu arc) continued

Volcano	Kuttara and Noboribetsu		Komaga-dake				
No.	H-36	H-37	H-38	H-39	H-40	H-41	H-42
Rock series	C_T	C_T	C_T	C_T	C_T	C_T	C_T
Type of mineral assemblage	V	VId	V	V	V	V	V
SiO_2	63.34	67.08	58.03	59.08	59.50	59.86	60.68
TiO_2	.20	.37	.61	.57	.29	.75	.70
Al_2O_3	15.73	15.27	18.04	17.80	16.46	16.34	15.95
Fe_2O_3	4.48	3.19	2.63	2.92	3.48	2.73	2.65
FeO	2.28	1.80	5.36	5.22	5.62	5.33	4.86
MnO	.40	.06	.18	.12	tr.	.09	.06
MgO	1.76	1.64	3.17	3.10	3.16	3.04	2.51
CaO	6.10	4.32	7.95	7.83	7.52	7.03	6.84
Na_2O	3.35	3.33	2.99	2.20	2.87	3.67	4.28
K_2O	1.54	1.43	.65	1.03	.89	.97	1.04
P_2O_5	.21	.08	.18	.16	.32	.09	.08
H_2O (+)	1.04	.44	.19	.58	.39	.30	.63
H_2O (−)		.56	.04	.06	.06		
Total	100.43	99.57	100.02	100.67	100.56	100.20	100.28
Analyst	Sato & Kagawa	Ōba & Koike	Tanaka	Seto	Seto	average of 3	average of 3

H-36 Augite hypersthene andesitic welded tuff, Noboribetsu welded tuff. Loc., a quarry along the Noboribetsu coast. (Sato and Kagawa, 1956)

H-37 Hornblende-bearing augite hypersthene dacite, Hiyori-yama dome lava of the Noboribetsu volcano. Loc., summit of the dome. (unpublished)

H-38 Augite hypersthene andesite, 1929 scoria of the Komaga-dake volcano. Loc., southwest slope of Komaga-dake. (Tsuya, 1930)

H-39 Augite hypersthene andesitic welded tuff (andesite according to Seto), a part of the Kurumisaka agglomeratic lava (named by Kato) of the Kamaga-dake volcano. Loc., Shinogawa station. (Seto 1931)

H-40 Augite hypersthene andesitic welded tuff (andesite according to Seto), a part of the Sahara-dake lava (named by Kato) of the Komaga-dake volcano. Loc., western summit of Sahara-dake. (Seto 1931)

H-41 Augite hypersthene andesite, 1929 lava blocks of the Komaga-dake volcano. Loc., southeastern slope of Komaga-dake and summit of Sumidamori. Average of 3 analyses. (Tsuya, 1930; Seto & Yagi, 1931)

H-42 Augite hypersthene andesite, 1929 pumice f the Komaga-dake volcano. Loc., Yakeyama slope and Akaigawa. Average of 3 analyses. (Tsuya, 1930; Seto, 1932; Seto & Yagi, 1931)

Table 5 (north Honshu arc) continued

Volcano	Komaga-dake	Esan		
No.	H-43	H-44	H-45	H-46
Rock series	C_T	C_T	C_T	C_T
Type of mineral assemblage	V	Vd	V	V
SiO_2	60.74	57.75	61.51	62.21
TiO_2	.67	.55	.42	.33
Al_2O_3	15.89	16.81	16.88	16.13
Fe_2O_3	3.01	4.87	2.33	4.09
FeO	5.26	5.06	4.10	3.37
MnO	.10	.08	.07	.01
MgO	2.65	3.36	2.82	1.71
CaO	6.83	7.17	6.65	6.55
Na_2O	3.96	2.23	2.65	3.06
K_2O	.76	.46	.90	.89
P_2O_5	.12	.10	tr.	tr.
H_2O (+)	.43 (total of H_2O (+) and H_2O (–))	.52	.82	.83
H_2O (–)		.30	.79	.54
Total	100.42	99.26	99.94	99.72
Analyst	average of 2	Andō	Andō	Andō

H-43 Augite hypersthene andesite, 1929 bread-crust bombs of Komaga-dake volcano. Loc., near the summit of Komaga-dake. Average of 2 analyses. (Tsuya, 1930; Seto & Yagi, 1931)

H-44 Augite hypersthene andesite, a somma lava of the Esan volcano. Loc., northern part of the somma. (Andō, in prep.)

H-45 Qartz-bearing augite hypersthene andesite, Misaki lava, a lava tongue of the younger stage of the Esan volcano. Loc., southeast foot of the volcano. (Andō, in prep.)

H-46 Quartz-bearing qugite hypersthene andesite, a dome lava of the Esan volcano. Loc., summit of the Esan lava dome (Andō, in prep.)

Lateral variation of the nature of rocks across the island from the Pacific to marginal sea side is well represented in variation diagrams for total alkali plotted against silica (Fig. 4). The rocks of the Pacific side are generally poor in alkalis, whereas toward the marginal sea those become more alkalic. Similar

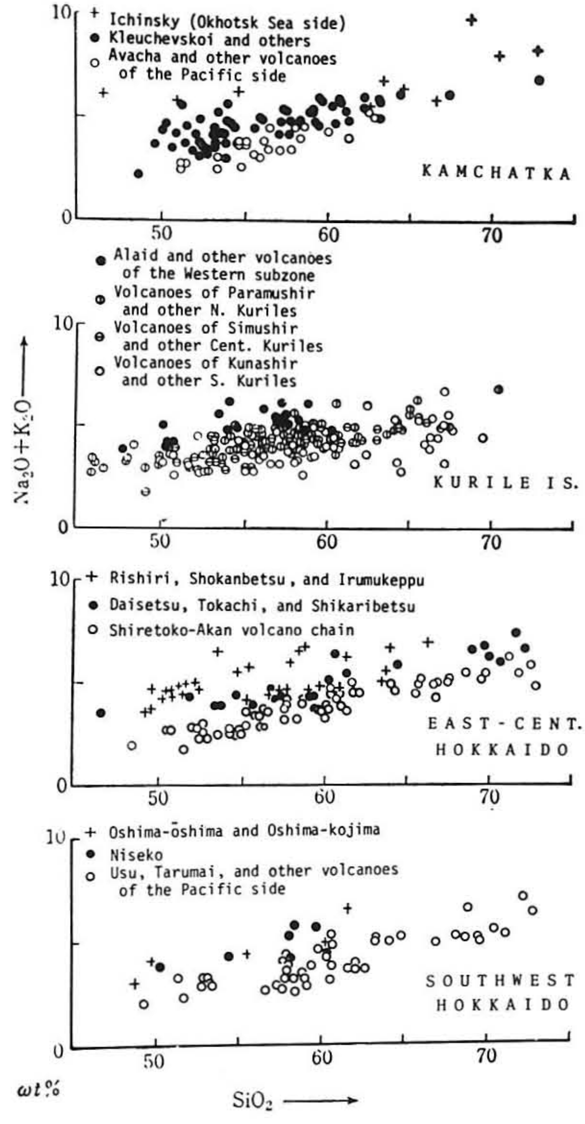

Fig. 4 Silica – alkali diagram. Source of data: *East–Cent. Hokkaido* Andō (unpubl.), Fujita (1972), Katsui (1961, 1963), Katsui, Ando and Inaba (unpubl.), Matsui *et al.* (1967), Katsura (1956), Satoh (1965); *Southwest Hokkaido* Andō (unpubl.), Katsui (1961, 1963), Nakamura (unpubl.), Ōba (1960, 1966, 1969), Sato and Kagawa (1956); *Kamchatka and Kurile Is.* Vlodavetz and Piip (1959), Gorshkov (1970).

variation is also traceable in the continuation to the Kuriles and Kamchatka, as mentioned by Gorshkov (1970).

A correlation exists between the alkali content and distance of the volcano from the trench axis, e.g. K_2O content generally increases with the focal depth of earchquakes beneath the volcano (Dickinson, 1968). An exception is the Rishiri volcano which is situated far from the trench axis. Both alkali olivine basalt and calc-alkali andesite of Rishiri are rather poor in K_2O, but rich in Na_2O (Katsui, 1953; Matsui, *et al.* 1967).

Degree of iron enrichment of each rock series is represented in triangular diagrams for MgO – $FeO+Fe_2O_3$ – Na_2O+K_2O (Fig. 5). The rocks of the T series demonstrate the strongest iron-rich trend, compared with those of the H and A series. Also, the calc-alkali rocks of the C_T series are relatively richer in iron than those of the C_H and C_A series.

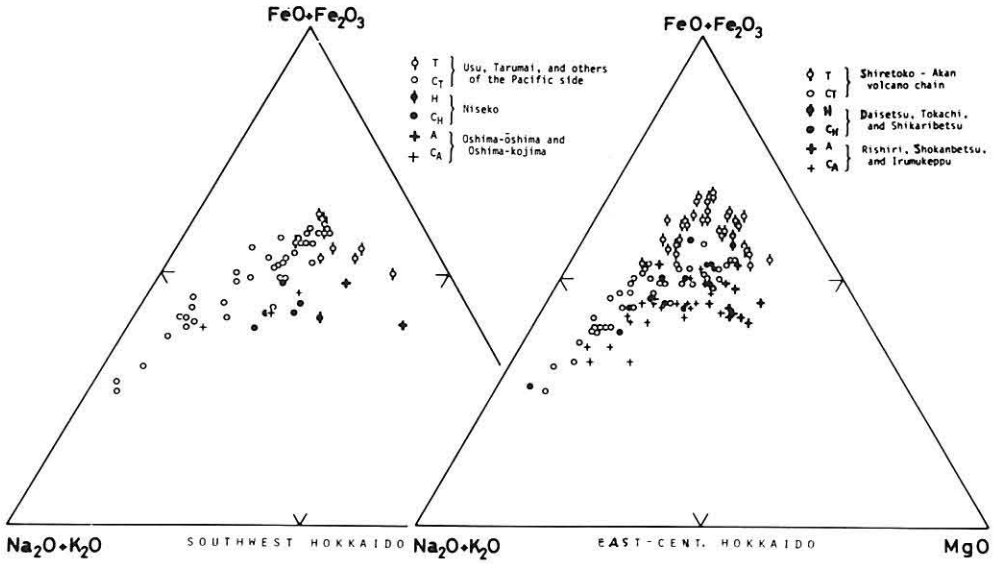

Fig. 5 MgO – $FeO+Fe_2O_3$ – Na_2O+K_2O diagram.

In the volcanoes of the Pacific side tholeiitic basalt and mafic andesite are relatively dominant, and eruptions of the rocks of the T series followed by those of the C_T series are the most common sequence. Mode of occurrence and chemical similarity mentioned above suggest that the rocks of the C_T series were derived from tholeiitic magma probably through fractional crystallization involving separation of magnetite under higher Po_2 towards the later stage of the crystallization, as interpreted by Ōba (1966) at Usu volcano (Fig. 6).

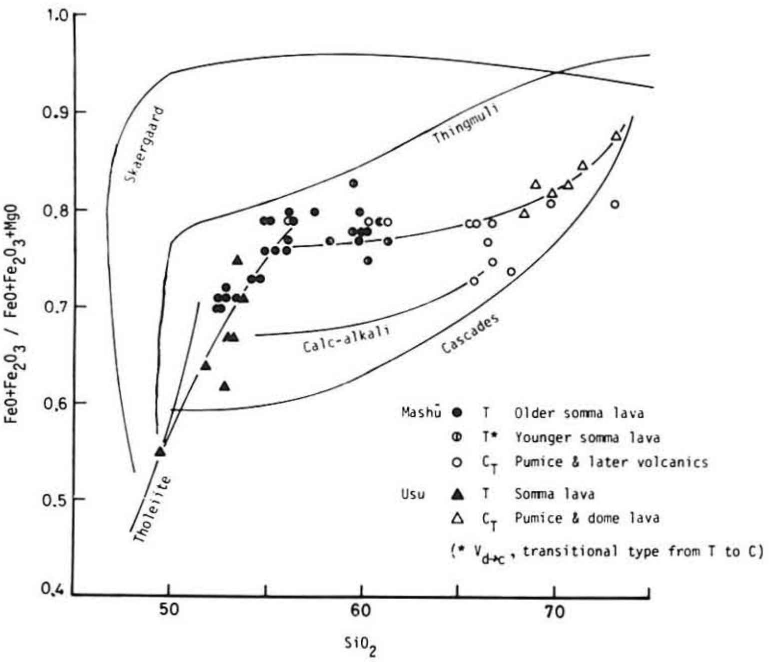

Fig. 6 $FeO+Fe_2O_3$ / $FeO+Fe_2O_3+MgO$ – Silica.

The calc-alkali andesite which is the most predominant rock in the C_H and C_A series, commonly carries hornblende and/or biotite phenocrysts (sometimes megacrysts) which are scarcely found in the C_T series (Katsui, 1961). It seems certain that early separation of hornblende from basaltic magma results in a trend of non-iron enrichment, as discussed by Allen *et al.* (1972).

Trace Elements

Trace elements were determined on 42 selected rocks. Aliquots of the samples which were prepared for major element analysis, were used. Uranium contents in samples were determined by means of a conventional fission-track method (Nishimura, 1970a). Io(^{230}Th) was determined by alpha-ray spectrometry with decomposed sample (Nishimura, 1970b). Seven rare-earth elements (REE: La, Ce, Sm, Eu, Tb, Yb and Lu), Th, Co, Sc, Ba and Hf were analysed by instrumental neutron activation analysis (Masuda *et al.*, 1972), which is essentially the same method as that of Gordon *et al.* (1968). For the standards such as BCR – 1 and JB – 1 were used. Analytical data are listed in Table 6, and illustrated in Figs. 7 to 13.

Table 6 Analytical data for trace elements. All values in ppm except SiO_2 and K_2O.
Analysts: S. Nishimura and Y. Masuda

Sample	K-1	K-2	K-3	K-4	K-5	K-6	K-7	K-8	K-9	K-10	K-11
SiO_2%	60.69	61.76	54.14	71.25	64.26	55.08	52.78	65.73	72.96	52.43	65.87
K_2O%	1.57	1.39	0.41	1.91	0.83	0.44	0.30	0.75	1.07	0.51	1.46
Co	20.7	17.1	23.6	5.0	10.8	20.6	21.7	4.1	2.2	28.9	7.2
Cr	22.1	9.8	5.7	3.5	7.8	3.2	9.9	5.2	5.7	132.3	4.8
Sc	23.0	23.8	46.6	7.6	26.2	45.3	35.6	23.4	19.0	34.5	23.0
Ba	538	493	212	530	513	184	105	270	383	224	540
Hf	4.5	4.1	1.1	5.6	3.6	0.9	0.4	3.0	3.7	0.9	3.6
Th	7.56	6.57	0.44	8.56	3.96	0.57	0.28	1.37	1.59	1.04	4.61
U	1.46	1.54	0.42	1.98	0.86	0.31	0.20	0.41	0.41	0.38	1.24
Io/U		1.2								1.3	
La	13.7	13.2	2.1	13.7	11.9	2.5	1.6	6.3	7.4	4.6	12.0
Ce	38.9	37.9	6.6	33.3	35.9	9.1	6.4	21.7	24.0	11.6	34.9
Sm	5.8	6.0	2.3	3.2	6.0	2.5	1.7	5.1	5.7	2.1	6.1
Eu	1.62	1.46	0.83	0.86	1.92	1.02	0.67	1.57	1.95	0.72	1.58
Tb	0.96	1.08	0.59	0.50	1.11	0.78	0.58	1.21	1.39	0.56	1.29
Yb	4.7	3.8	2.5	2.0	5.1	2.6	2.4	5.2	6.0	2.1	3.9
Lu	0.73	0.68	0.43	0.43	0.77	0.45	0.31	0.82	0.94	0.29	0.69

Sample	K-12	K-13	K-14	K-15	K-16	K-17	K-18	K-19	K-20	K-21	K-22
SiO_2%	57.54	59.16	61.26	56.99	60.44	64.67	56.72	54.73	71.57	46.79	60.67
K_2O%	1.07	1.26	1.39	1.47	1.73	1.97	1.65	1.45	3.39	0.79	2.93
Co	27.1	17.1	13.4	17.5	16.3	10.4	16.5	18.2	6.4	29.5	
Cr	41.8	34.1	7.7	8.0	21.9	11.5	18.6	44.2	2.2	8.7	
Sc	32.1	28.3	16.8	20.6	20.2	16.5	19.9	21.0	5.6	34.2	
Ba	268	330	325	322	503	538	356	383	504	171	
Hf	1.0	2.5	3.5	2.9	3.7	5.7	2.7	2.7	3.3	1.6	
Th	0.88	3.51	4.31	4.52	7.59	9.54	5.71	3.48	16.57	1.74	
U	0.39	1.06	1.11	1.21	1.67	2.11	1.49	0.93	3.73	0.39	1.78
Io/U										1.1	
La	3.9	7.7	10.1	18.3	15.5	15.7	13.1	10.1	20.5	7.7	
Ce	12.0	23.6	26.4	41.7	37.5	38.4	33.7	26.9	50.8	25.5	
Sm	2.2	3.3	3.3	6.5	4.1	4.3	4.0	3.6	3.9	4.3	
Eu	0.83	1.10	0.96	1.55	1.25	1.02	1.12	1.14	0.53	1.36	
Tb	0.61	0.66	0.46	1.10	0.75	0.58	0.80	0.62	0.48	0.77	
Yb	2.1	2.3	1.8	3.1	3.1	2.3	2.1	2.0	2.3	2.5	
Lu	0.28	0.35	0.36	0.46	0.44	0.48	0.32	0.35	0.51	0.34	

Table 6 -(continued)

Sample	K-23	K-24	K-25	K-26	K-27	H-1	H-3	H-5	H-8	H-11
SiO_2%	53.41	55.41	63.48	50.69	50.78	49.36	52.81	53.21	68.26	57.84
K_2O%	1.31	1.34	0.97	1.03	0.59	0.18	0.43	0.53	1.29	1.07
Co	22.4	20.1	11.3	29.0	28.4	40.8	33.1	25.7	5.2	12.5
Cr	10.2	97.9	28.4	144	116	30.6	31.1	13.0	8.6	4.3
Sc	28.6	20.2	9.0	24.5	23.5	33.4	35.5	30.1	10.3	21.7
Ba	261	733	405	235	255	139	167	199	284	643
Hf	2.6	2.6	3.4	2.6	2.3	0.9	1.1	1.5	2.8	2.7
Th	4.08	11.35	5.29	2.55	1.20	1.53	0.99	1.14	2.43	3.22
U	1.15	2.64	1.46	0.66	0.31	3.03	4.12	0.67	0.94	2.73
Io/U				1.2		1.0				
La	10.2	18.6	20.7	13.3	8.9	2.3	4.1	5.8	9.5	13.0
Ce	30.6	44.1	40.7	36.5	25.1	7.6	15.3	18.8	27.5	37.5
Sm	4.9	4.6	3.1	4.6	3.8	1.7	2.4	3.2	4.4	6.1
Eu	1.32	1.34	0.98	1.39	1.27	0.64	0.84	1.12	1.35	2.02
Tb	0.94	0.58	0.46	0.73	0.80	0.40	0.50	0.57	0.86	1.14
Yb	3.0	1.5	1.5	2.4	2.4	1.6	1.9	2.5	3.0	3.5
Lu	0.45	0.29	0.25	0.37	0.35	0.28	0.35	0.41	0.52	0.58

Sample	H-12	H-13	H-14	H-16	H-17	H-18	H-19	H-20	H-21	H-22
SiO_2%	57.89	58.23	63.45	59.93	60.35	48.89	49.90	55.56	61.72	60.46
K_2O%	0.99	1.01	1.34	1.80	1.61	1.13	1.92	1.80	3.28	1.84
Co	13.3	16.8	5.8	16.8	18.4	45.7	32.5	18.0	8.2	14.1
Cr	5.7	8.2	5.5	5.7	2.3	690	180	17.6	6.3	8.2
Sc	23.5	27.4	20.5	19.6	20.4	43.5	35.3	14.2	5.7	15.2
Ba	730	874	1045	713	697	401	571	853	1381	846
Hf	3.4	3.6	4.8	2.6	3.0	0.9	2.4	2.9	3.7	3.2
Th	4.43	5.17	6.26	6.45	6.61	2.24	5.95	6.95	16.66	10.71
U	1.18	2.92	2.61	4.12	1.75	0.83	2.30	1.28	2.90	2.62
Io/U						0.9	0.9			
La	16.8	16.0	21.4	13.3	10.8	11.1	19.8	21.7	32.7	19.7
Ce	53.1	43.4	58.6	33.8	32.6	30.4	50.8	52.4	73.3	46.2
Sm	7.8	7.1	9.4	4.8	3.5	4.6	6.2	5.5	6.6	4.4
Eu	2.20	2.16	2.57	1.37	1.07	1.51	2.02	1.48	1.38	1.43
Tb	1.24	1.21	1.54	0.82	0.75	0.90	1.09	0.88	0.93	0.82
Yb	4.8	4.3	5.5	3.3	2.0	2.8	2.8	2.4	2.5	2.5
Lu	0.73	0.70	0.92	0.52	0.38	0.47	0.47	0.40	0.53	0.45

The contents of Ba, Th, Hf and REE increase with silica, as shown in Figs. 7 and 11. There is a notable tendency for the rocks of the marginal sea side to be enriched in these trace elements. This pattern closely resembles that of K, as expected from a similarity in their large ionic radii. The rocks of Mashū and Usu are included in the low-potassic T and C_T series, and represent the lowest

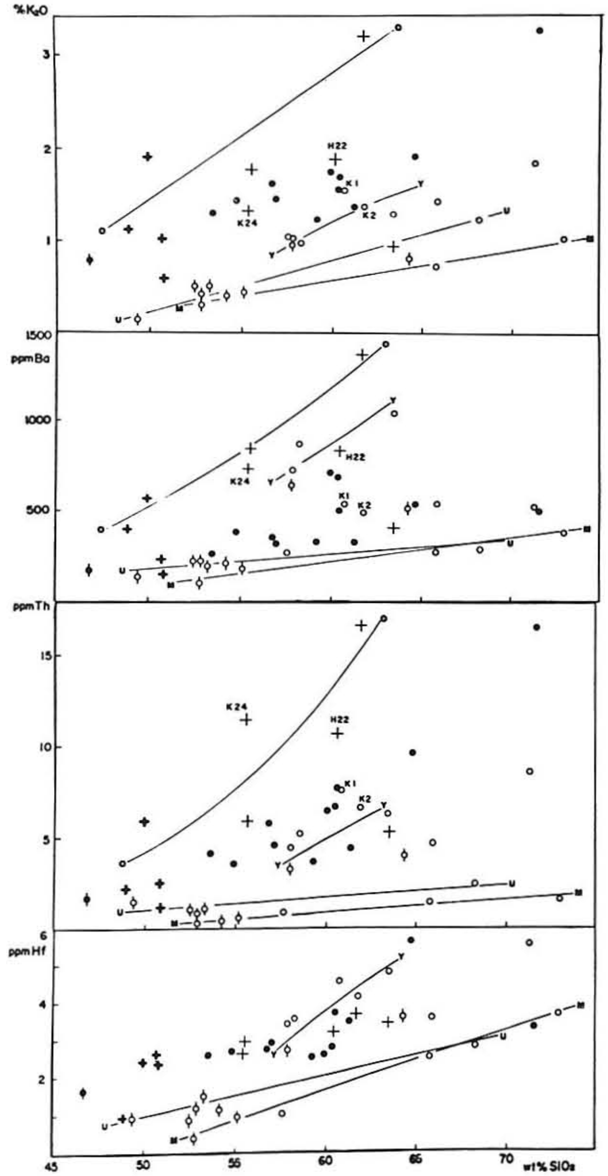

Fig. 7 K_2O, Ba, Th and Hf vs. SiO_2. M-M: Mashū, U-U: Usu, Y-Y: Yōtei, O-O: Oshima-oshima.

level in these trace element abundances. Towards the boundary between the T & C_T and H & C_H provinces, the abundances increase markedly. Thus, the rocks of Yōtei and Shiretoko-iwo-zan are rich in these elements, although they are classified into the T and C_T series from their mineralogy.

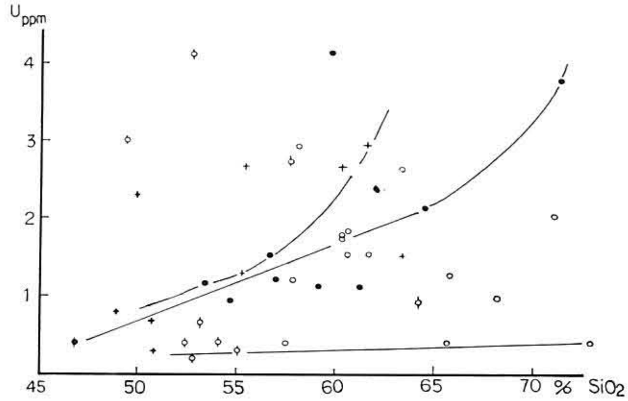

Fig. 8 Uranium vs. SiO_2.

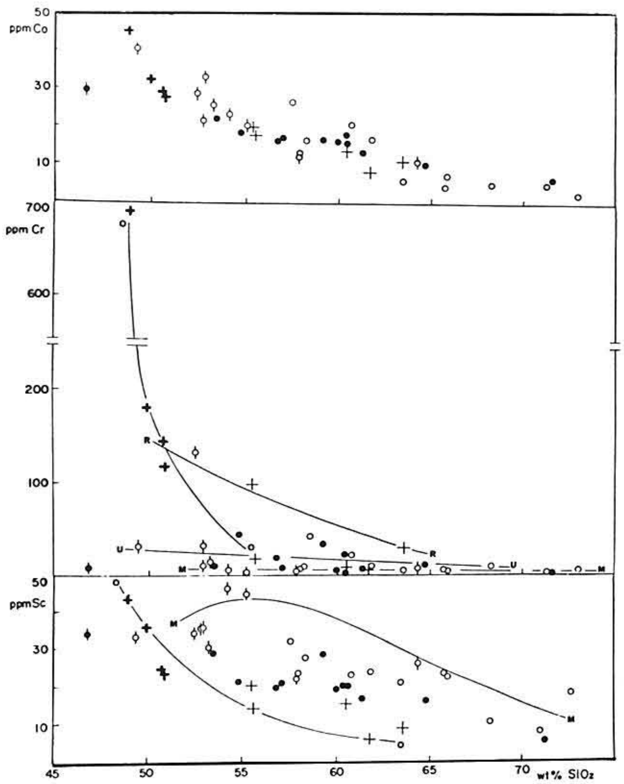

Fig. 9 Co, Cr and Sc vs. SiO_2.

The pattern of uranium content is essentially the same as above, because during the magmatic process uranium behaves as thorium, since they are in the tetravalent state and similar in ionic radius (Fig. 8). However, uranium is easily oxidized to the hexavalent state and dissolved in water or hydrothermal solutions. Exceptionally high values in uranium content, shown by some of the

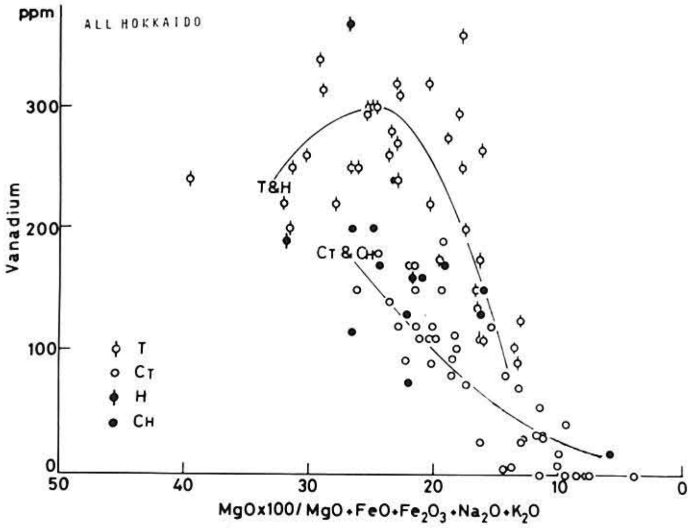

Fig. 10 Vanadium – MgO×100 / MgO+FeO+Fe_2O_3+Na_2O+K_2O diagram (Andō, 1971 and 1972, with unpublished data). Analysis made by means of emission-spectroscopy.

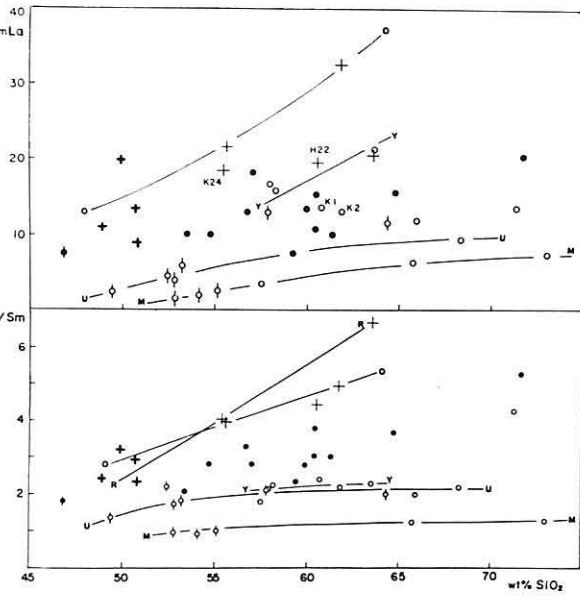

Fig. 11 La and La/Sm vs. SiO_2.

Usu rocks (Nos. H-1 and -2 in Fig. 8) for example, are probably interpreted as a result of secondary enrichment.

The contents of Co, Cr, Sc and V decrease with increasing silica content (Fig. 9). There is an intimate relation between abundances of Cr and modal olivine. Alkali olivine basalt and its allied rocks (A and C_A) and a picritic variety of tholeiitic basalt (T) are rich in Cr. It is worthy of notice that Sc and V behave as iron. A marked V enrichment is found at the middle stage of fractional crystallization in the tholeiitic series (T and H) (Fig. 10). However, non-enrichment of V is traced in the calc-alkali series (C_T and C_H) (Andō, 1971 and 1972).

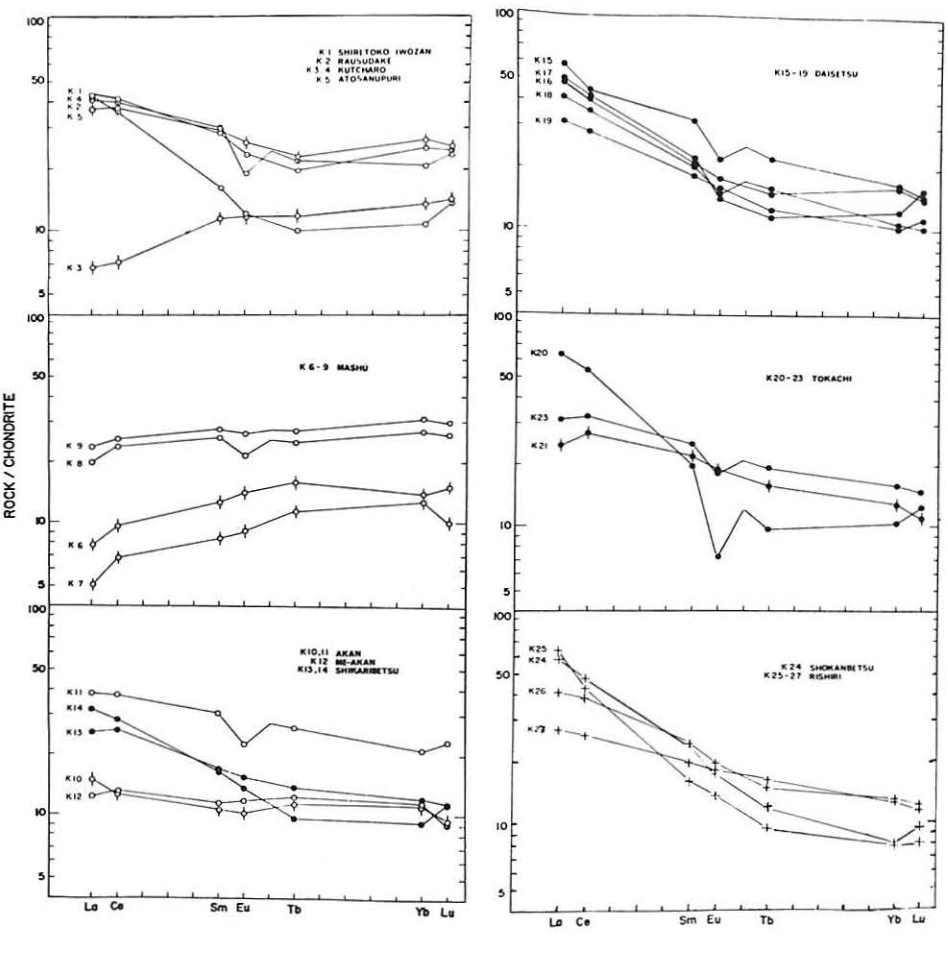

Fig. 12 Normalized rare-earth elements abundance pattern (Kurile arc). Symbols of the rock series are same as in Table 2.

Content of La and La/Sm vs. silica and chondrite-normalized patterns of REE are illustrated in Figs. 11, 12 and 13. The three rock groups, T & C_T, H & C_T, and A & C_A, are well distinguished from each other in the chondrite-normalized REE pattern. The rocks of T & C_T series have distribution patterns very similar to the ocean ridge tholeiite, showing a tendency toward depletion or equality of light REE, whereas those of the A & C_A series have a marked

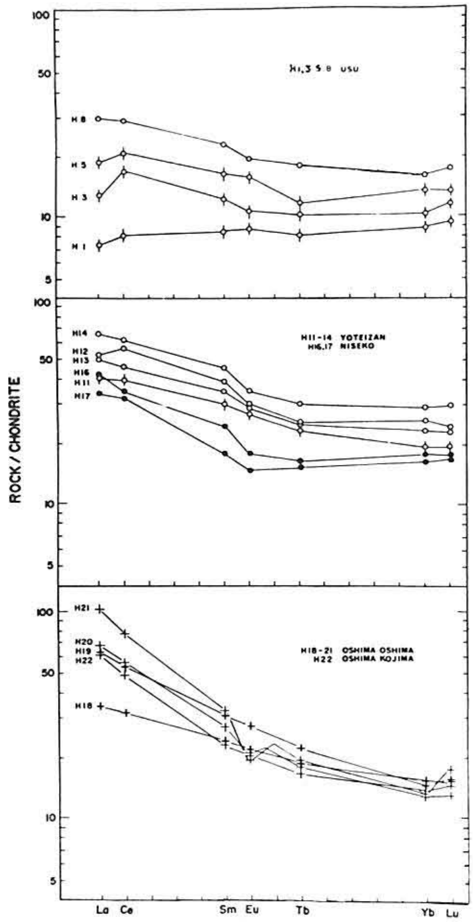

Fig. 13 Normalized rare earth elements abundance pattern (North Honshu arc). Symbols of the rock series are same as in Table 2.

enrichment of light REE over heavy REE. The rocks of H & C_H exhibit a moderate enrichment of light REE. Transitional features from T & C_T to H & C_H are also found here in the rocks of Shiretoko-iwo-zan and Yōtei. A negative Eu anomaly is a characteristic feature of the calc-alkali rocks, although this anomaly does not always appear. Because of lack of data on rock-forming minerals, detailed discussion is limited. However, the above REE patterns suggest deviation of magma from a common source material for each zonal petrographic province, as recently discussed by Masuda *et al.* (1975).

Sr-Isotopic Ratio

The Sr-isotopic ratio ($^{87}Sr/^{86}Sr$) was determined on 49 selected rocks. Aliquots of the samples for the analysis of major and trace elements were used. The $^{87}Sr/^{86}Sr$ ratio for the M.I.T. Eimer & Amend reagent $SrCO_3$ standard determined in our laboratory is 0.7079 ± 0.0001. The results are presented in Table 7 and summarized diagramatically in Fig. 14. Comparison of the Sr-isotopic ratios for the rocks of Hokkaido with those of the various regions in the world is shown in Fig. 15.

The Sr-isotopic ratios of the Quaternary volcanic rocks of Hokkaido are generally low. Especially those of the Kurile arc are all within a limited range from 0.7028 to 0.7039 which are almost comparable to those of ocean ridge basalt (0.7030 – 0.7034, Gast, 1967). The Sr-isotopic ratios of basalt to dacite (or rhyolite) in a single volvano, Mashū and Tokachi for example, are almost identical and exhibit a small range of variation without any systematic change. The isotopic ratios of a large amount of dacitic or rhyolitic pumice which erupted at caldera formation, do not, therefore, provide an interpretation in terms of an origin by anatexis of older continental crust or assimilation.

Compared with the Sr-isotopic ratios of the rocks of the Kurile arc, those of the north Honshu arc are slightly high, except those of the volcanic islands in the Japan Sea. However, the rocks of the north Honshu arc, as compared with those of southwest Japan, are substantially lower in Sr-isotopic ratio. As shown in Fig. 15, the volcanic rocks of the continental margins together with those of southwest Japan are generally higher than those of the island arcs with marginal sea. On the basis of Sr- and Pb-isotopic ratios, Kurasawa (1969a & b and 1970) showed that some felsic volcanic rocks of southwest Japan were produced from a basaltic magma possibly accompanied by contamination with older continental rocks, Similar results were obtained in New Zealand (Ewart and Stipp, 1968) and Cent. America (McBirney and Weill, 1966). Wide ranges of variation in the Sr-isotopic ratio observed in southwest Japan and other continental margins, alternatively, can be explained by isotopic and chemical heterogeneities in the upper mantle.

Table 7 Strontium isotopic compositions of the Quaternary volcanic rocks of Hokkaido

Analysts: H. Kurasawa and H. Fujimaki

Volcano	No.	Rock series	SiO_2 %	$^{87}Sr/^{86}Sr$
Shiretoko-iwo-zan	K- 1	C_T	60.69	0.7029$_5$
Rausudake	K- 2	C_T	61.76	0.7029$_8$
Kutcharo	K- 3	C_T	54.14	0.7031$_5$
	K- 4	C_T	71.25	0.7038$_6$
Atosanu-puri	K- 5	T	64.26	0.7039$_2$
Mashū	K- 6	T	55.08	0.7037$_0$
	K- 7	T	52.78	0.7039$_4$
	K- 8	C_T	65.73	0.7031$_8$
	K- 9	C_T	72.96	0.7034$_0$
Akan	K-10	T	52.43	0.7034$_1$
	K-11	C_T	65.87	–
Me-akan	K-12	C_T	57.54	0.7030$_9$
Shikari-betsu	K-13	C_H	59.16	0.7036$_4$
	K-14	C_H	61.26	0.7033$_9$
Daisetsu	K-15	C_H	56.99	–
	K-16	C_H	60.44	0.7038$_1$
	K-17	C_H	64.67	0.7035$_3$
	K-18	C_H	56.72	0.7034$_0$
	K-19	C_H	54.73	0.7030$_2$
Tokachi	K-20	C_H	71.57	0.7038$_3$
	K-21	H	46.79	0.7029$_7$
	K-22	C_H	60.67	–
	K-23	C_H	53.41	0.7033$_4$
Shokan-betsu	K-24	C_A	55.41	0.7031$_4$
Rishiri	K-25	C_A	63.48	0.7028$_2$
	K-26	A	50.69	0.7029$_6$
	K-27	A	50.78	0.7028$_5$

Volcano	No.	Rock series	SiO_2 %	$^{87}Sr/^{86}Sr$
Usu	H- 1	T	49.36	0.7040$_2$
	H- 2	T	51.80	0.7046$_6$
	H- 3	T	52.81	0.7039$_4$
	H- 4	T	53.02	0.7045$_2$
	H- 5	T	53.21	0.7039$_6$
	H- 6	T	53.36	0.7050$_7$
	H- 7	C_T	68.89	0.7039$_0$
	H- 8	C_T	68.26	0.7036$_2$
	H- 9	C_T	71.25	0.7045$_2$
	H-10	C_T	73.04	0.7032$_5$
Yōtei	H-11	T	57.84	0.7054$_8$
	H-12	C_T	57.89	0.7041$_5$
	H-13	C_T	58.23	0.7045$_7$
	H-14	C_T	63.45	0.7057$_8$
Niseko	H-15	C_H	58.20	0.7040$_0$
	H-16	C_H	59.93	0.7052$_1$
	H-17	C_H	60.35	0.7056$_8$
Oshima-ōshima	H-18	A	48.89	0.7028$_5$
	H-19	A	49.90	0.7030$_4$
	H-20	C_A	55.56	0.7030$_3$
	H-21	C_A	61.72	0.7033$_8$
Oshima-kojima	H-22	C_A	60.46	0.7026$_0$

M.I.T. Eimer and Amend reagent $SrCO_3$: $^{87}Sr/^{86}Sr = 0.7079 \pm 0.0001$

Fig. 15 Comparison of $^{87}Sr/^{86}Sr$ ratios. The $^{87}Sr/^{86}Sr$ ratios are recalculated from original data by the E & A standard = 0.7080, except for those of Cent. America. Data come from A. Ewart and J.J. Stipp, 1968; R.W. Gast, 1967; C.E. Hedge, 1966; C.E. Hedge and D.C. Noble, 1971; H. Kurasawa, 1970 and unpubl.; A.R. McBirney and D.F. Weill, 1966; Z.E. Petermann, I.S.E. Carmichael and A.L. Smith, 1970a and b; and Z.E. Petermann, G.G. Lowder and I.S.E. Carmichael, 1970.

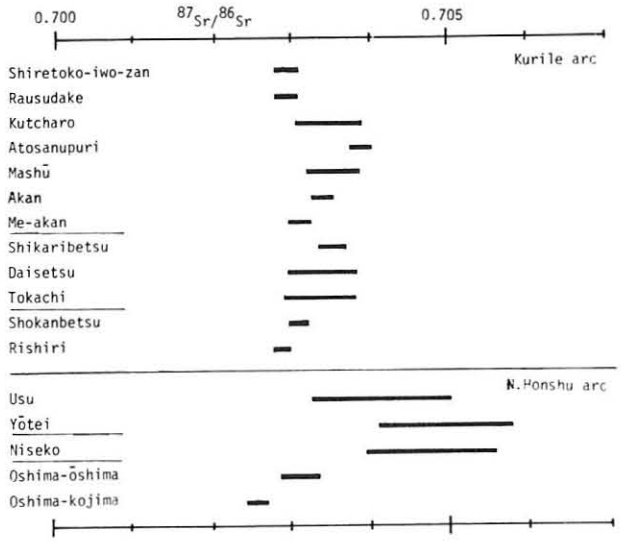

Fig. 14 $^{87}Sr/^{86}Sr$ ratios of the rocks of Hokkaido.

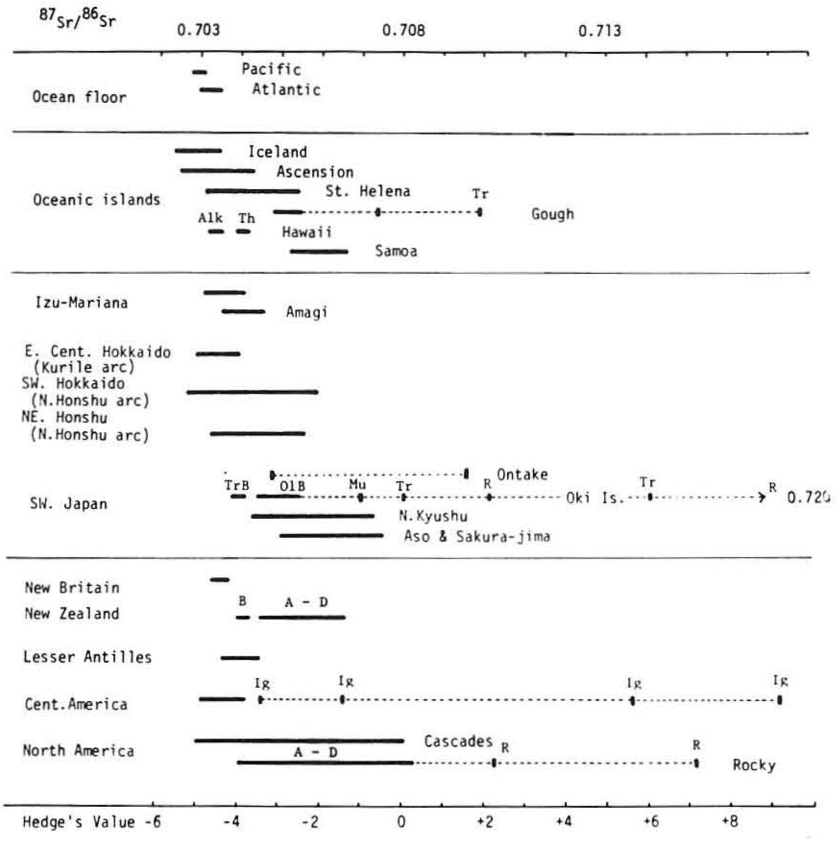

Fig. 15

Concluding Remarks

Although andesite of the calc-alkali series is abundant in the Quaternary volcanic fields of Hokkaido, substantial amounts of basaltic rocks are intimately associated with the calc-alkali andesite in many volcanoes. Petrographic provinces of the Quaternary volcanic rocks can be divided into three for each of the Kurile and the north Honshu arcs in harmony with the neotectonic feature, as follows:

Pacific side	....	*Marginal sea side*
Tholeiite series(T)	High-Al basalt ser.(H)	Alkali rock series(A)
Calc-alkali ser.(C_T)	Calc-alkali series(C_H)	Calc-alkali series(C_A)

The nature of the three calc-alkali rock series is considerably different from each other in chemistry as well as mineralogy, showing a consistent variation with that of the associated basaltic rocks from the Pacific side to the marginal sea. Alkalies, REE, Ba, U, Th and Hf are depleted in the T & C_T series, and enriched in the A & C_A series. The three groups, T & C_T, H & C_H and A & C_A are well distinguished from each other in chondrite-normalized REE pattern, i.e. T & C_T has distribution patterns similar to those of the ocean ridge tholeiite, whereas A & C_A has a marked enrichment of light REE over heavy REE. There is no essential difference in the REE pattern between the calc-alkali rocks and the associated basaltic rocks. This will require the same source material for each of the three groups. Nonenrichment of Fe together with Sc and V, and the negative Eu anomaly frequently found in REE pattern, are characteristic features of the calc-alkalic rocks. However, these features do not break the consanguinity with the respective basaltic magmas, because those can be interpreted by fractional crystallization of the same magma under certain conditions. An alternative process involving fractional melting of the same parental material as discussed by Yoder (1973) is one possible way for the generation of calc-alkali magmas.

The Sr-isotopic ratios of the various rocks of Hokkaido are as low as those of other island arcs with marginal sea, compared with those of southwest Japan and other continental margins. Especially the ratios of east-central Hokkaido are nearly comparable with those of ocean ridge basalt. This evidence would require that the magmas have been derived from a homogeneous mantle material and not modified due to contamination with older continental crust.

A number of models have been offered for the spatial zonation of magma types in island arcs and continental margins since Kuno's work (1959, 1966). A model involving anatexis in the subduction zone as recently proposed by Jakeš and White (1970), Fitton (1971), and Modreski and Boettcher (1972), may be one possible process for the generation of the Quaternary magmas in Hokkaido, if the hypothesis of downthrusting of lithospheres at island arcs is adopted (Fig. 16). This model is very interesting, but encounters a difficulty in the interpretation of the substantial difference of Sr-isotopic ratios of volcanic rocks between island arcs and continental margins, because ^{87}Sr and ^{87}Rb are originally depleted in the oceanic crust which is supposed to be a source material for magma in this model. Recently, Shuto *et al.* (1977) suggested that the rocks of the higher and lower Sr-isotopic ratios have derived from different source materials.

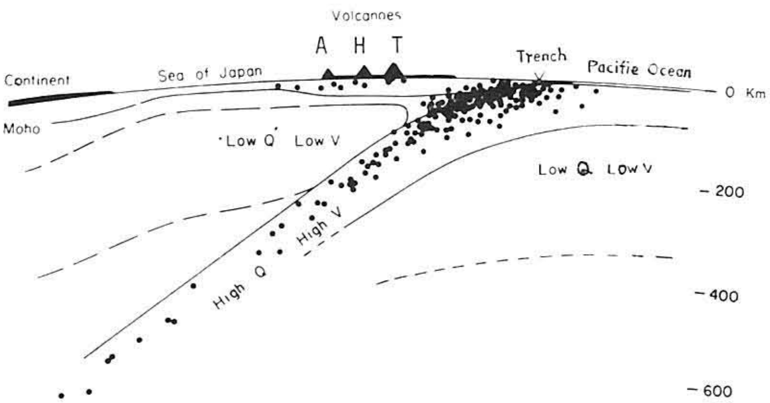

Fig. 16 Three types of magma (T, H and A) and the deep structure in the north Honshu arc. Dots represent earthquake foci. (after Utsu, 1971).

Assuming again that the magmas originate by anatexis in the subduction zone (High-Q, High-V) and ascend up to the upper zone (Low-Q, Low-V), the boundary surface between them at 100 – 200 km in depth would be obscure, as in the case of the M-discontinuity under the oceanic ridge. However, the boundary surface is interpreted to be relatively sharp, since conversion and refraction of seismic wavas have been observed at the boundary (Utsu, 1971). This suggests that partial fusion occurs in the upper zone (Low-Q, Low-V), rather than in the subduction zone. The occurrence of a relatively large amount of basaltic rocks in Hokkaido supports this alternative process. Further studies, including the structure and thermal state of the upper mantle as well as experimental petrology, are still required to provide a definite conclusion.

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