Lateral Variation of Trace Element Contents in Quaternary Volcanic Rocks Across Northeast Japan

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Lateral Variation of Trace Element Contents in Quaternary Volcanic Rocks Across Northeast Japan

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Trace element abundances in sixty-two volcanic rocks from Northeast Japan are determined mainly by instrumental neutron activation analysis. On the basis of these date, lateral increase of K_2O, Ba, Th, U, rare-earth elements and other LIL (large-ion-lithophile) element contents towards the Japan Sea side is demonstrated for the rocks of the tholeiitic series, calc-alkaline series and alkaline series. The compositional variation between the tholeiitic rocks and alkaline rocks could be interpreted by the difference in degrees of partial melting of the upper mantle. On the other hand, the lateral variation of trace element contents observed in the calc-alkaline rocks cannot be explained by partial melting processes. It may be related to the difference in fractional crystallization processes of the calc-alkaline magmas at the Nasu zone and the Chokai zone.

1. Introduction

In Japan, there are four active island arcs, namely the Kurile, Northeast Japan, Izu-Bonin and Ryukyu arcs, and the former three arcs are joined together in the eastern part of Japan facing to the Pacific Ocean. Trace element abundances in the Quaternary volcanic rocks were reported by several workers for the Kurile and Izu-Bonin arcs, but for the Northeast Japan arc are absent until now.

The purpose of this paper is, first, to determine the trace element abundances in the Quaternary volcanic rocks of the Northeast Japan arc using the instrumental neutron activation analysis, and then to demonstrate the lateral variation in trace element composition of the volcanic rocks across the arc.

Lateral variation in chemical composition of volcanic rocks across island arcs is an interesting phenomenon of island arc volcanism, and is one of the most important problems of petrology. Kuno[1,2], Sugimura[3] and Katsui[4] showed that the alkali content ($Na_2O + K_2O$) of volcanic rocks increases across the island arcs of Japan toward the Asiatic continent, and Kuno's[5] scheme of parental basalt variation from tholeiitic magma, through high alumina basalt, to alkali olivine basalt and its relation to depth of earthquake foci have been widely accepted.

Trace element data for such lateral variation in island arcs have been presented by Jakes and White[6] and Gill[7] for the Fiji and New Britain-New Guinea areas, and by Masuda[8], Masuda et al.[9] and Philpotts et al.[10] for the Japanese islands. According

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to their data, LIL (large-ion-lithophile) element content shows a regular increase toward the continent as well as alkali contents.

2. Samples and Analytical Method

Trace elements were analyzed for 62 volcanic rocks from Northeast Japan. Fig. 1 shows the locations of the volcanoes from which the samples were collected. The Quaternary volcanoes in the Northeast Japan are divided into two longitudinal volcanic zones of an outer volcanic zone on the trench-side and an inner volcanic zone on the

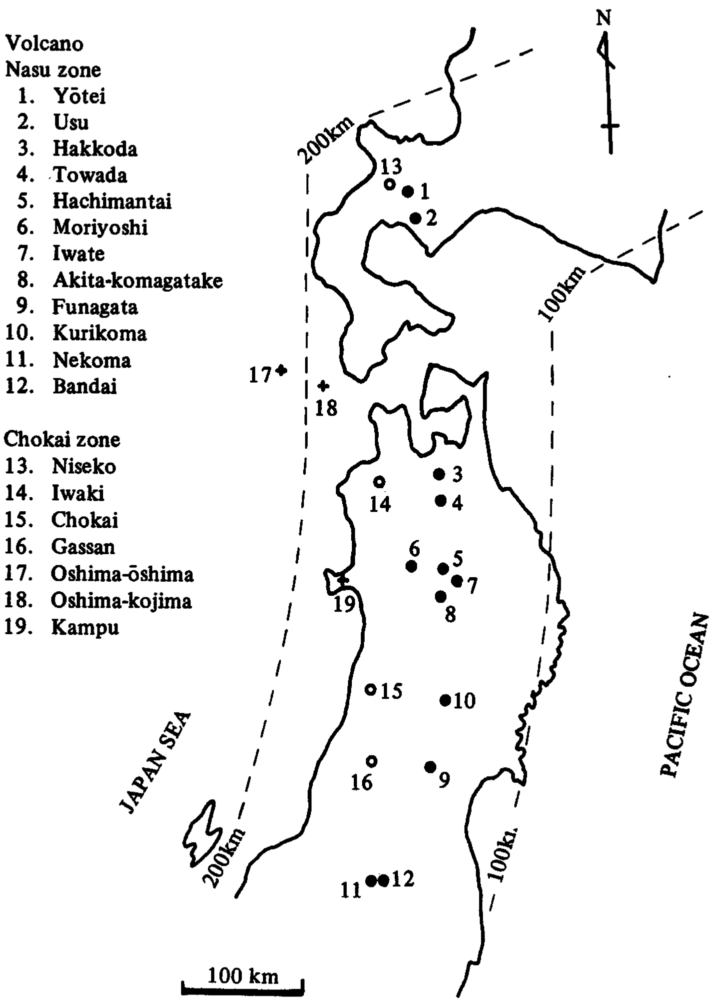

Fig. 1. Location of the Quaternary volcanoes, from which the samples were collected, in Northeast Japan. Solid circles are the volcanoes of the Nasu zone, open circles are those of the main part of the Chokai zone, and crosses are the volcanoes located in the most Japan Sea side of the Chokai zone. The broken lines are the isobaths of the depth to the seismic zone.

continental-side. According to Kawano et al.[11], the volcanic rocks of the outer volcanic zone, called the Nasu zone, are basalt – dacite of the tholeiitic series and andesite – rhyolite of the calc-alkaline series, while those of the inner volcanic zone, called the Chokai zone, are mainly andesites of the calc-alkaline series and some basalts of the high-alumina basalt series. In Oshima-ōshima volcano, which is located in the most Japan Sea side, occur basalts of the alkaline series and andesites of the calc-alkaline series. The rocks of the Nasu zone tend to less alkalic than those of the Chokai zone. Among the samples analyzed, fourty seven samples were collected from 12 volcanoes of the Nasu zone, and fifteen samples were from 7 volcanoes of the Chokai zone. The samples belonging to the high alumina basalt series were not collected. Description and major element data of the samples analyzed are given in the appendix.

Instrumental neutron activation technique[9,12] was utilized for the determination of Co, Cr, Sc, Ba, Hf, Th, La, Ce, Sm, Eu, Tb, Yb and Lu. Uranium was determined by fission track registration method, and nickel was by atomic absorption spectrometry. The probable error of these analyses is about 10% for almost all elements, and about 15% for Tb.

3. Results

Results of individual analyses are given in the appendix along with the major element data. Average trace element compositions of basalts (about 50% SiO_2), basaltic andesites (about 55% SiO_2) and andesites (about 60% SiO_2) were calculated as shown in Table 1 to 5 for the tholeiitic series, the calc-alkaline series and the alkaline series.

3.1 Rare earth element abundance pattern

The chondrite-normalized patterns of rare-earth elements (REE patterns) for the basalts of the tholeiitic series and alkaline series are shwon in Fig. 2. The tholeiitic basalts, which are in the Pacific Ocean side, have unfractionated flat REE patterns, and their chondrite normalized values (about 7 to 11) of La are comparatively low, while the alkaline basalts, which are in the Japan Sea side, have fractionated REE patterns, their normalized La values ranging from 40 to 60.

The REE patterns for the calc-alkaline andesites from Northeast Japan are shown in Fig. 3. Calc-alkaline rocks were divided by Masuda et al.[9] for the rocks of Hokkaido, northern Japan, into three groups denoted by C_T, C_H and C_A, which are intimately associated with the rocks of tholeiitic series, high-alumina basalt series and alkaline series, respectively, and the slopes of their REE patterns increase in the order of C_T, C_H and C_A. The calc-alkaline rocks of Northeast Japan are also tentatively classified into three types on the basis of the slope of REE patterns and the geographical locations of the volcanoes, i.e., C_T type calc-alkaline rocks which occur in the Nasu zone, C_H type calc-alkaline rocks which occur in the main part of the Chokai zone (Niseko, Iwaki,

Table 1. Average contents of SiO_2, K_2O and trace elements in the tholeiitic rocks from Usu, Towada, Hachimantai, Akita-komagatake, Funagata and Nekoma volcanoes of the Nasu zone, Northeast Japan (SiO_2 and K_2O in wt.%; trace elements in ppm).

	Tholeiitic rocks		
Range of SiO_2	49.06 – 52.85	53.21 – 55.85	60.26 – 62.63
Number of samples	11	5	3
SiO_2	50.76 (1.35)	54.97 (1.07)	61.70 (1.27)
K_2O	0.27 (0.12)	0.49 (0.10)	0.69 (0.12)
Co	35.4 (5.7)	24.0 (3.7)	12.5 (1.0)
Cr	89 (49)	25 (20)	5 (2)
Sc	37.9 (4.9)	32.3 (3.5)	24.6 (2.9)
Ba	125 (35)	183 (23)	200 (–)
Hf	1.1 (0.2)	1.7 (0.2)	2.8 (–)
Th	0.49 (0.25)	1.14 (0.20)	2.13 (0.86)
U	0.15 (0.05)	0.34 (0.03)	0.49 (0.03)
La	3.2 (0.9)	5.7 (0.5)	9.3 (1.2)
Ce	10.8 (3.2)	19.1 (1.3)	27.9 (1.7)
Sm	2.0 (0.3)	3.0 (0.2)	4.4 (0.5)
Eu	0.80 (0.11)	1.03 (0.14)	2.01 (–)
Tb	0.48 (0.08)	0.64 (0.09)	0.88 (0.38)
Yb	1.8 (0.3)	2.5 (0.3)	3.6 (0.8)
Lu	0.28 (0.04)	0.39 (0.03)	0.53 (0.07)
Ni	49 (14)	18 (5)	13 (0.4)
La/Yb	1.7 (0.4)	2.3 (0.4)	2.7 (0.8)
Th/U	2.8 (0.4)	3.4 (0.4)	5.3 (0.6)

The numbers in parenthesis are the standard deviations.

Table 2. Average contents of SiO_2, K_2O and trace elements in the calc-alkaline rocks (C_T type*) from Usu, Hakkoda, Hachimantai, Moriyoshi, Kurikoma and Bandai volcanoes of the Nasu zone, Northeast Japan (SiO_2 and K_2O in wt.%; trace elements in ppm).

	C_T type calc-alkaline rocks		
Range of SiO_2	54.38 – 57.85	58.06 – 60.21	60.51 – 62.24
Number of samples	4	10	4
SiO_2	56.01 (1.49)	59.02 (0.72)	61.36 (0.71)
K_2O	0.84 (0.18)	1.08 (0.19)	1.34 (0.17)
Co	28.2 (3.9)	24.8 (4.9)	15.9 (5.6)
Cr	96 (54)	51 (41)	22 (14)
Sc	28.6 (2.8)	27.8 (3.6)	21.2 (3.2)
Ba	365 (177)	293 (48)	356 (75)
Hf	2.2 (0.5)	3.0 (0.6)	3.9 (0.3)
Th	2.73 (0.68)	3.12 (0.48)	4.15 (0.83)
U	0.80 (0.14)	0.82 (0.14)	1.14 (0.36)
La	8.3 (2.9)	8.3 (1.7)	13.2 (3.1)
Ce	22.8 (6.8)	25.7 (6.1)	34.6 (10.9)
Sm	3.2 (0.4)	3.4 (0.6)	5.1 (0.9)
Eu	1.00 (0.28)	1.19 (0.31)	1.55 (0.35)
Tb	0.64 (0.03)	0.80 (0.14)	1.08 (0.13)
Yb	2.3 (0.35)	2.8 (0.6)	3.8 (0.6)
Lu	0.40 (0.04)	0.44 (0.08)	0.61 (0.08)
Ni	45 (13)	34 (21)	23 (9)
La/Yb	3.6 (1.3)	3.2 (0.9)	3.5 (0.7)
Th/U	3.4 (0.6)	3.9 (0.9)	3.8 (0.7)

The numbers in parenthesis are the standard deviations. * See the text for C_T type.

Table 3. Average contents of SiO_2, K_2O and trace elements in the calc-alkaline rocks (C_H type*) from Niseko, Iwaki, Chokai and Gassan volcanoes of the Chokai zone, Northeast Japan (SiO_2 and K_2O in wt.%; trace elements in ppm).

	C_H type calc-alkaline rocks			
Range of SiO_2	54.56 – 56.58		59.23 – 60.35	
Number of samples	3		4	
SiO_2	55.69	(1.03)	59.91	(0.48)
K_2O	1.89	(0.10)	1.55	(0.21)
Co	21.3	(0.4)	16.5	(1.4)
Cr	11	(7)	6	(2)
Sc	17.9	(2.1)	17.5	(2.9)
Ba	483	(40)	593	(130)
Hf	4.3	(0.9)	3.0	(0.3)
Th	5.60	(0.36)	4.93	(1.88)
U	1.5	(0.2)	1.7	(0.6)
La	15.8	(0.9)	11.0	(1.6)
Ce	33.1	(4.7)	30.4	(3.6)
Sm	4.1	(0.1)	3.8	(0.7)
Eu	1.47	(0.12)	1.13	(0.17)
Tb	0.68	(0.11)	0.65	(0.16)
Yb	2.9	(0.6)	2.8	(0.6)
Lu	0.46	(0.04)	0.41	(0.07)
La/Yb	5.6	(1.0)	4.1	(0.9)
Th/U	3.7	(0.5)	2.9	(0.6)

The numbers in parenthesis are the standard deviations.
* See the text for C_H type.

Table 4. Average contents of SiO_2, K_2O and trace elements in the calc-alkaline rocks (C_A type*) from Oshima-ōshima, Oshima-kojima and Kampu volcanoes of the Chokai zone, Northeast Japan (SiO_2 and K_2O in wt.%; trace elements in ppm).

	C_A type calc-alkaline rocks			
Range of SiO_2	54.78 – 55.56		60.46 – 61.72	
Number of samples	4		2	
SiO_2	55.34	(0.38)	61.09	(0.89)
K_2O	1.46	(0.36)	2.56	(1.02)
Co	19.4	(5.5)	11.2	(4.2)
Cr	33	(29)	7	(1)
Sc	16.6	(5.8)	10.5	(6.7)
Ba	715	(111)	1115	(375)
Hf	2.6	(0.6)	3.5	(0.4)
Th	6.1	(1.0)	13.7	(4.2)
U	1.6	(0.4)	2.9	(0.4)
La	22.2	(2.0)	26.2	(9.2)
Ce	50.1	(8.0)	59.8	(19.2)
Sm	5.1	(0.8)	5.5	(1.6)
Eu	1.56	(0.22)	1.41	(0.04)
Tb	0.74	(0.18)	0.88	(0.08)
Yb	2.5	(0.6)	2.5	(0.0)
Lu	0.41	(0.06)	0.49	(0.06)
La/Yb	9.4	(2.1)	10.5	(3.7)
Th/U	4.0	(0.4)	4.8	(0.9)

The numbers in parenthesis are the standard deviations.
* See the text for C_A type.

Table 5. Average contents of SiO_2, K_2O and trace elements in the alkaline rocks from Oshima-ōshima volcano of the Chokai zone, Northeast Japan (SiO_2 and K_2O in wt.%; trace elements in ppm).

	Alkaline rocks	
Range of SiO_2	48.89 – 49.90	
Number of samples	2	
SiO_2	49.40	(0.71)
K_2O	1.53	(0.56)
Co	39.1	(9.3)
Cr	435	(361)
Sc	39.4	(5.8)
Ba	485	(120)
Hf	1.7	(1.1)
Th	4.1	(2.7)
U	1.1	(0.8)
La	15.5	(6.2)
Ce	40.6	(14.4)
Sm	5.4	(1.1)
Eu	1.77	(0.36)
Tb	1.00	(0.13)
Yb	2.8	(0.0)
Lu	0.47	(0.0)
La/Yb	5.5	(2.2)
Th/U	3.9	(0.5)

The numbers in parenthesis are the standard deviations.

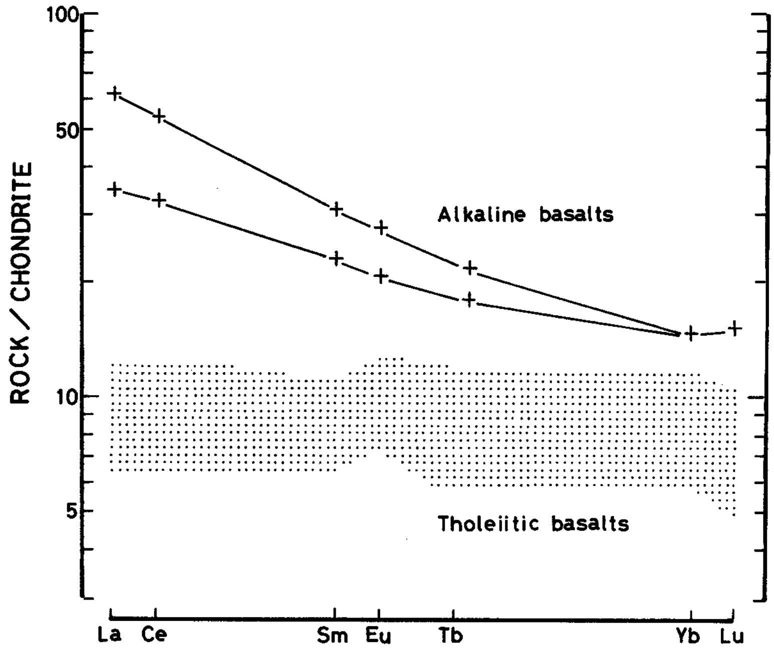

Fig. 2. Rare earth element (REE) patterns of the tholeiitic basalts and the alkaline basalts from Northeast Japan. The REE patterns of the tholeiitic basalts are shown by dotted area. See Masuda and Aoki[15] for their individual patterns.

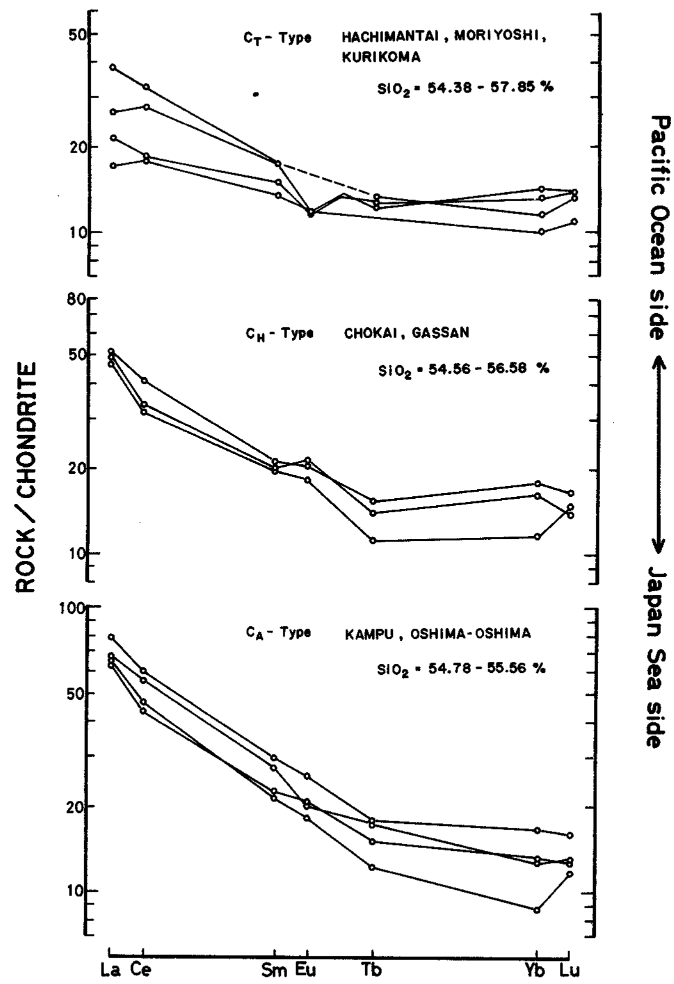

Fig. 3. Rare earth element patterns of the basaltic andesites of the calc-alkaline series from Northeast Japan. See the text for C_T, C_H and C_A types.

Chokai and Gassan volcanoes), and C_A type calc-alkaline rocks which occur in the nearest Japan Sea side of the Chokai zone (Oshima-ōshima, Oshima-kojima and Kampū volcanoes). An increase tendency in the enrichment of light REE, relative to heavy REE, from the Pacific Ocean side toward the Japan Sea side is also found in the calc-alkaline rocks (Fig. 3).

3.2 Silica variation diagram

Silica variation diagram for some trace elements are shown in Fig. 4 for all samples of Northeast Japan including the tholeiitic rocks, calc-alkaline rocks and alkaline rocks. The figure confirms that at a given silica content the contents of K_2O, Ba, Th, U and La

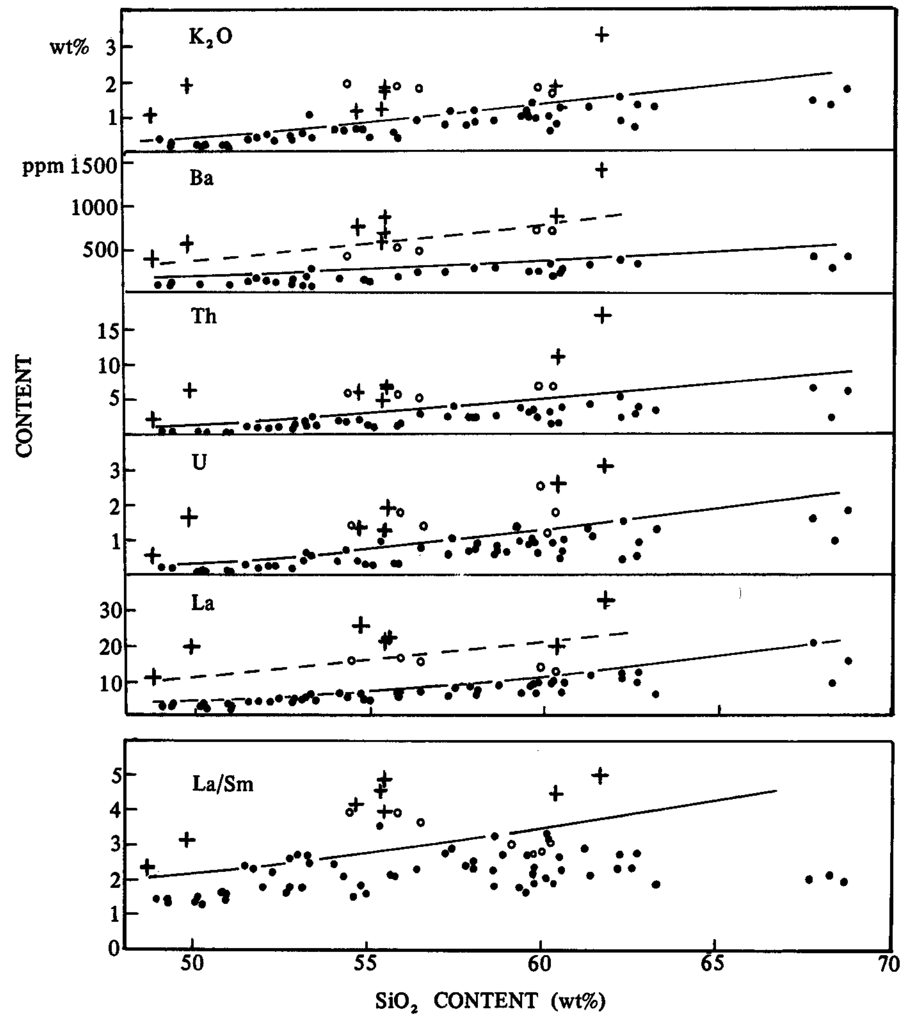

Fig. 4. Silica variation diagrams vs. trace elements for the volcanic rocks of Northeast Japan. Solid circles are the rocks of Nasu zone, open circles are those of Niseko, Iwaki, Chokai and Gassan volcanoes of Chokai zone, and crosses are those of Oshima-ōshima, Oshima-kojima and Kampu volcanoes of Chokai zone.

(LIL, large-ion-lighophile, elements) are higher in the rocks of the Chokai zone than the Nasu zone. This increase tendency of LIL element contents toward the Japan Sea side is particular in the case for Ba and La, whose contents increase in the order of the rocks from the Nasu zone, the main part of the Chokai zone and the nearest Japan Sea side of the Chokai zone. Masuda et al.[9] demonstrated the lateral increase of La/Sm ratio toward the continent side for the rocks of Hokkaido. Such lateral increase of La/Sm ratio is found also in Northeast Japan as shown in the bottom figure of Fig. 4.

3.3 Relations to seismi zone

Dickinson and others[13,14] demonstrated that at a given SiO_2 content (55% and 60%)

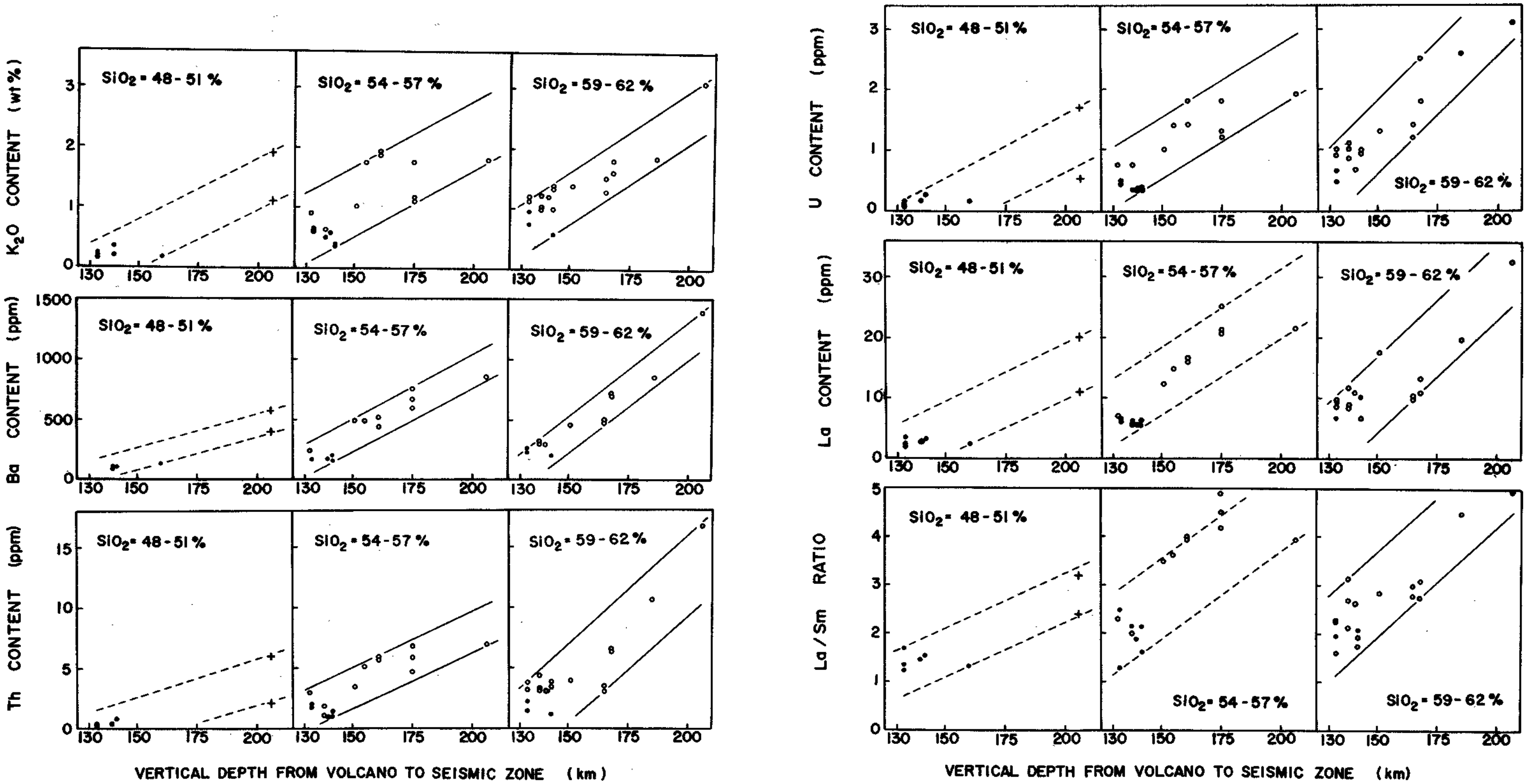

Fig. 5. Relationship between the trace element contents in the volcanic roks of North-east Japan and the depths to the seismic zone. Solid circles are the tholeiitic rocks, open circles are thecalc-alkaline rocks, and crosses are the alkaline rocks.

K_2O content in recent volcanics of island arcs increases with depth from volcanoes to the dipping seismic zone in individual island arcs. Fig. 5 shows the relationship between the trace element contents and the depth to the seismic zone beneath the Northeast Japan arc for the basalts (SiO_2 = 49 – 51%), basaltic andesites (54 – 57%) and andesites (59 – 62%). Volcanoes of the Nasu zone are about 130 km to 160 km above the seismic zone, and those of the Chokai zone are about 160 to 200 km. Since the seismic zone beneath the Northeast Japan arc is dipping toward the Japan Sea side, the lateral increase of K_2O and LIL element contents in the volcanic rocks can be more visually seen in Fig. 5 than Fig. 4.

4. Discussion

4.1 Geochemical relation between the tholeiitic rocks and alkaline rocks

Fig. 6 shows the correlation between Cr and Th contents in the rocks of the tholeiitic series and alkaline series of Northeast Japan. Masuda and Aoki[15] proved for the rocks

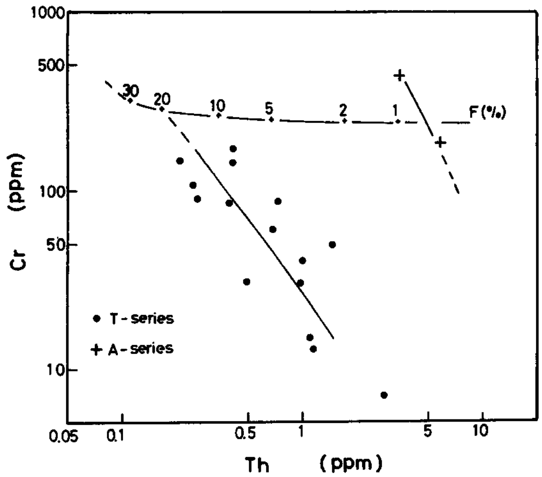

Fig. 6. Log-log diagram of Cr and Th contents in the tholeiitic rocks (solid circles) and in the alkaline rocks (crosses) from Northeast Japan. The curve attached the numbers of F(%), which are degrees of partial melting, represents the correlation between Cr and Th contents in the possible primary magmas generated in the upper mantle (See Masuda and Aoki[15]).

from the Nasu zone that the Cr-Th diagram as shown in Fig. 6 is very useful to examine the genetic relations between the tholeiitic magma and the associated calc-alkaline magma. The two elements of Cr and Th chosen here have contrast geochemical properties in the generation and the fractional crystallization of magmas, that is, Cr tends to enter preferentially into solid phase (crystals), while Th enters into liquid phase (magmas). In Fig. 6, the line drawn along the plots of the tholeiitic rocks (solid circles) represents the possible fractionation trend of the tholeiitic magma. It is seen from the fractionation trend that the Cr content in magmas decreases rapidly with proceeding of fractional crystallization, while the Th content increases. On the other hand, possible contents of Cr and Th in primary magmas produced by partial melting of the upper mantle were estimated as shown by the curve attached the numbers of F(%), which are degrees of partial melting[15]. Masuda and Aoki[15] estimated the primary magma of the tholeiitic rocks from the Nasu zone to have been formed by about 20% degree of partial melting, extrapolating the possible fractionation trend for the tholeiitic rocks upwards as shown by broken line.

Alkaline basalts from Oshima-ōshima volcano have relatively high Cr content ranging from 180 to 690 ppm (435 ppm in average, Table 5). The chemical composition of these alkaline basalts is considered to be close to that of the primary alkaline basalt magma, because about 300 ppm is expected to be the Cr content in primary magmas, when the partial melting models mentioned above is applied. Accordingly, the alkaline basalt magma is infered to have been formed by very low degrees of partial melting (about 1%). Chemical composition of the primary magma is intimately related, of course, to the pressure, temperature and other conditions at which the magma was generated in the upper mantle[27]. However, the present result suggests still that the difference in the LIL element contents between the tholeiitic rocks and the alkaline rocks (Fig. 2) might be ascribed to the difference in the degrees of partial melting of the upper mantle. This result is consistent with the hypothesis of Gast[28].

4.2 Geochemical relation between the three types of calc-alkaline rocks

In the section 3.1, three type classification of calc-alkaline rocks was proposed. The geochemical relations between these rocks are examined based on their Cr and Th contents in this section.

Masuda and Aoki[15] examined already the C_T type calc-alkaline rocks from the Nasu zone to suggest that the primary magma of the C_T type rocks might be generated

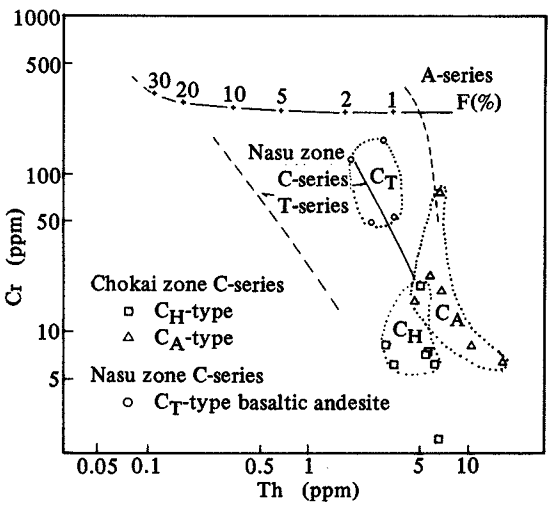

Fig. 7. Log-log diagram of Cr and Th contents in the C_T, C_H and C_A type calc-alkaline rocks from Northeast Japan.

by about 3% degree of partial melting of the upper mantle. Possible fractionation trend of the C_T type calc-alkaline rocks is shown in the Cr-Th diagram of Fig. 7. In the figure, the C_H and C_A type calc-alkaline rocks from the Chokai zone are also plotted, but it may be difficult to construct reasonable fixt fractionation trends for these rocks, because of scattering of the plots. To examine the geochemical relations between the three types of calc-alkaline rocks, the more detailed investigations with the more precise analyses of trace elements will be necessary. However, almost all the plotts of C_H and C_A type rocks seem to be distributed on or around the extending line of the fractionation trend for C_T type calc-alkaline rocks. It is conceived from this fact that the primary magmas of the C_T, C_H and C_A type calc-alkaline rocks were generated by the same degrees of partial melting. If it is so, the lateral variation of LIL element contents in the calc-alkaline rocks (Figs. 3, 4, 5) is unable to be ascribed to the difference in the degree of partial melting of the upper mantle.

Average Cr content of the C_T type calc-alkaline basaltic andesites is about 96 ppm (Table 2), while that of C_H and C_A type basaltic andesites is about 11 ppm and 33 ppm, respectively (Table 3 and 4). This low Cr contents in C_H and C_A type rocks suggests that these rocks have undergone a more extensive fractional crystallization than the C_T type rocks, although they have all similar SiO_2 contents. On the other hand, recently, Sakuyama[29] showed the lateral variation of mafic phenocryst assemblages of Quaternary volcanic rocks from eastern Japan, and suggested that the temperature and H_2O content of the parental magmas generated beneath the island arc decrease and increase, respectively, towards the Japan Sea side. This supports strongly that the fractional crystallization process for the magmas of the Chokai zone is significantly different from that for the magmas of the Nasu zone. Thus, the lateral variation of trace element contents in the calc-alkaline rocks from Northeast Japan seems to be related to the difference in the fractional crystallization processes rather than the difference in the partial melting processes. In this respect, it may be necessary to investigate the fractional crystallization processes of the calc-alkaline magmas at the Nasu zone and the Chokai zone in order to explain the lateral variation in chemical composition of the calc-alkaline rocks across Northeast Japan.

5. Conclusion

K_2O, Ba, Th, U and REE contents and La/Sm ratio (Fig. 4) in the volcanic rocks increase laterally from the Pacific Ocean side (in the Nasu zone) toward the Japan Sea side (in the Chokai zone) across Northeast Japan. The tholeiitic basalts which occur in the Nasu zone have flat REE patterns, while the alkaline basalts which occur in the Chokai zone have flactionated (light REE enriched) REE patterns (Fig. 2). Increase tendency in the enrichment of light REE, relative to heavy REE, toward the Japan Sea side is observed for the calc-alkaline rocks (Fig. 3). The lateral variation of trace element contents in the volcanic rocks is intimately related to the depth from the volcanoes to the seismic zone beneath the Northeast Japan arc (Fig. 5). Differences in trace element contents between the tholeiitic rocks and the alkaline rocks could be interpreted by the difference in the degrees of partial melting of the upper mantle in the generation of magmas, on the basis of the geochemical relations between Cr and Th contents. However, in order to explain the lateral variation in the trace element contents of the calc-alkaline rocks, it may be necessary to take into account the difference in the fractional crystallization processes of magmas in the Nasu zone and the Chokai zone.

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Appendix

Major and trace elment composition of the Quaternary volcanic rocks from Northeast Japan.

Volcano	1. Yōtei				2. Usu			
Sample	H-11	H-12	H-13	H-14	H-1	H-3	H-6	H-8
Rock series+	T	C	C	C	T	T	T	C
Major oxide (wt.%)								
SiO_2	57.84	57.89	58.23	63.45	49.36	52.81	53.21	68.26
Al_2O_3	17.48	18.33	15.98	15.97	16.07	16.47	19.22	15.77
FeO*	8.19	7.23	9.00	6.60	11.09	10.10	8.44	3.87
MgO	3.14	2.65	3.32	1.95	8.92	6.23	4.21	0.99
CaO	7.77	7.97	7.65	5.08	10.75	9.95	10.43	4.37
Na_2O	3.13	3.30	2.89	3.75	2.03	2.46	2.76	3.83
K_2O	0.99	1.07	1.01	1.34	0.18	0.43	0.53	1.29
Trace elements (ppm)								
Co	12.5	13.3	16.8	5.8	40.8	33.1	25.7	5.2
Cr	4	6	8	6	31	31	13	9
Sc	21.7	23.5	27.4	20.5	33.4	35.5	30.1	10.3
Ba	640	730	870	1050	140	170	200	280
Hf	2.7	3.4	3.6	4.8	0.9	1.1	1.5	2.8
Th	3.2	4.4	5.2	6.3	–	0.99	1.14	2.43
U	1.5	1.5	2.0	2.2	–	–	–	0.94
La	13.0	16.8	16.0	21.4	2.3	4.1	5.8	9.5
Ce	37.5	53.1	43.4	58.6	7.6	15.3	18.8	27.5
Sm	6.1	7.8	7.1	9.4	1.7	2.4	3.2	4.4
Eu	2.02	2.20	2.16	2.57	0.64	0.84	1.12	1.35
Tb	1.1	1.2	1.2	1.5	0.40	0.50	0.57	0.87
Yb	3.5	4.8	4.3	5.5	1.6	1.9	2.5	3.0
Lu	0.58	0.73	0.70	0.92	0.28	0.35	0.41	0.52
Ni	–	–	–	–	–	–	–	–
Ref #	17	17	17	17	18	18	18	19

\+ Volcanic rock series : T = tholeiitic series; C = calc-alkaline series; A = alkaline series.

* FeO* is total iron as FeO.

\# References for the sample description and major element data.

1. Yōtei

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

H-12 Augite hypersthen andesite, the 1st stage lava of the Yōtei volcano. Loc., western foot of Yōtei.

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.

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.

2. Usu

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

H-3 Olivine-bearing augite hypersthene basalt, IV type somma lava of the Usu volcano. Loc., south of Nishiyama.

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

H-8 Hypersthene dacite, dome lava of O-Usu, a lava dome of the Usu volcano.

Major and trace elment composition of the Quaternary volcanic rocks from Northeast Japan.

Volcano	3. Hakkoda				4. Towada			5. Hachimantai		
Sample	1	2	3	4	TH-35	TH-36	TH-37	3	4	5
Rock series+	C	C	C	C	T	T	T	T	C	T
Major oxides (wt.%)										
SiO_2	58.67	59.39	59.76	63.22	55.85	55.09	50.27	52.85	54.38	55.79
Al_2O_3	16.06	15.86	15.33	14.71	–	–	–	19.34	17.02	15.33
FeO*	7.79	7.44	7.62	7.21	9.4	9.8	10.5	8.93	9.59	10.63
MgO	4.26	3.71	3.69	3.06	3.2	3.2	5.4	4.54	5.82	3.92
CaO	7.53	7.14	7.01	6.11	–	–	–	8.74	8.57	8.40
Na_2O	2.44	2.52	2.58	2.77	2.8	3.3	2.5	2.40	2.08	2.48
K_2O	0.87	0.99	1.38	1.23	0.39	0.39	0.14	0.32	0.63	0.53
Trace elements (ppm)										
Co	25.6	33.7	27.7	31.5	25.3	18.1	29.6	32.5	32.9	27.7
Cr	58	29	28	–	50	4	31	61	120	15
Sc	25.2	26.1	24.8	21.2	30.5	29.0	37.6	35.1	30.0	37.3
Ba	280	–	–	–	200	160	110	–	–	–
Hf	2.2	–	–	–	1.7	1.8	1.3	1.1	1.7	1.6
Th	2.6	3.9	3.5	3.3	1.48	0.99	0.50	0.69	1.9	1.1
U	0.86	0.98	0.94	1.3	0.37	0.31	0.14	0.22	0.75	0.33
La	7.0	6.7	6.7	6.6	6.0	5.2	3.2	4.8	5.5	6.3
Ce	16.8	21.5	23.8	22.1	19.0	17.2	8.9	16.5	16.8	19.9
Sm	3.1	3.8	3.5	3.6	2.8	3.2	2.1	2.7	2.7	2.9
Eu	0.80	–	–	1.58	0.89	1.23	0.94	0.99	0.87	0.97
Tb	0.77	–	–	–	0.69	0.77	0.48	–	–	0.61
Yb	2.7	3.5	–	3.0	2.2	2.9	2.2	2.2	1.9	2.4
Lu	0.37	0.46	0.34	0.39	0.34	0.42	0.30	0.31	0.34	0.43
Ni	46	32	29	25	21	13	–	42	55	19
Ref#	11	11	11	11	–	–	–	20	20	20

3. Hakkoda	1	Olivine augite hypersthene andesite, summit of Odake.
	2	Olivine augite hypersthene andesite, summit of Idodake.
	3	Quartz-bearing olivine hypersthene augite andesite, crater wall of Idodake.
	4	Quartz-bearing hypersthene augite andesite, summit of Kita-akakuradake.
4. Towada	TH-35	Hypersthene augite andesite, Goshiki-iwa, central cone of Towada volcano (collected by Masuda)
	TH-36	Hypersthene augite andesite, Caldera wall of Towada volcano, northeast of Towada lake (collected by Masuda)
	TH-37	Augite hypersthene basalt, Caldera wall of Towada volcano, northeast of Towada lake (collected by Masuda)
5. Hachimantai	3	Olivine augite hypersthene basalt, summit of Maemoriyama volcano
	4	Augite olivine hypersthene andesite, summit of Chausudake volcano
	5	Hypersthene augite andesite, summit of Mokkodake volcano

Major and trace elment composition of the Quaternary volcanic rocks from Northeast Japan.

Volcano	5. Hachimantai (contd.)								6. Moriyoshi	
Sample	6	7	8	9	10	11	12	13	18	19
Rock series+	C	T	C	C	C	C	T	T	C	C
Major oxides (wt.%)										
SiO_2	57.85	58.09	59.68	60.21	61.39	62.24	67.68	68.61	55.36	61.28
Al_2O_3	16.38	14.73	16.11	15.41	14.72	15.09	14.38	14.33	18.01	17.64
FeO*	8.46	9.48	8.07	8.01	7.24	6.87	4.87	3.93	7.76	5.39
MgO	4.62	4.68	3.90	3.53	2.87	2.90	1.12	0.52	4.54	1.52
CaO	7.29	8.00	7.37	7.30	5.65	5.43	3.59	3.08	7.27	6.42
Na_2O	2.24	2.42	2.63	2.64	2.58	2.79	3.08	3.15	2.76	3.67
K_2O	0.77	0.85	0.99	1.00	1.22	1.56	1.45	1.78	1.05	1.38
Trace elements (ppm)										
Co	29.1	25.9	26.5	24.4	21.4	17.6	14.4	7.9	23.5	8.1
Cr	48	87	47	40	24	34	8	–	53	–
Sc	29.6	30.4	31.1	31.7	25.0	21.2	19.3	17.0	24.4	17.2
Ba	–	–	–	310	310	360	420	430	490	460
Hf	2.5	2.7	–	2.7	3.7	4.1	5.1	4.7	2.7	4.1
Th	2.5	2.5	3.3	3.2	4.4	5.1	6.6	6.2	3.5	4.0
U	0.69	0.89	1.0	0.87	1.1	1.5	1.6	1.8	1.0	1.3
La	8.4	7.2	8.9	9.5	11.7	12.2	20.9	15.9	12.3	17.8
Ce	26.0	26.8	29.2	25.5	37.2	–	69.6	46.6	30.7	49.7
Sm	3.5	3.1	3.3	3.0	5.5	4.5	10.0	7.9	3.5	6.2
Eu	0.86	0.90	0.97	0.97	1.29	1.32	1.87	1.58	–	2.05
Tb	0.61	–	0.75	0.65	1.2	1.0	1.8	1.9	0.67	1.2
Yb	2.7	2.9	3.3	3.0	4.4	3.7	8.3	7.1	2.2	4.2
Lu	0.43	0.40	0.51	0.47	0.68	0.54	1.2	1.1	0.41	0.67
Ni	33	45	31	21	26	34	15	7	57	14
Ref #	20	20	20	20	20	20	20	20	20	20

+ Volcanic rock series : T = tholeiitic series; C = calc-alkaline series; A = alkaline series.
* FeO* is total iron as FeO.
# References for the sample description and major element data.

5. Hachimantai	6	Olivine augite hypersthene andesite, crater wall of Obukadake volcano
	7	Olivine augite hypersthene andesite, a valley north of Hachimantai volcano
	8	Olivine augite hypersthene andesite, 0.8 kms north of Tohichi hot spring
	9	Hypersthene augite andesite, summit of 1470m Peak
	10	Olivine augite hypersthene andesite, 0.3 kms north of Tohichi hot spring
	11	Olivine bearing augite hypersthene andesite, summit of Kamotayama volcano
	12	Augite hyperthene dacite, summit of Gentamori volcano
	13	Hypersthene augite dacite, summit of Appidake volcano
6. Moriyoshi	18	Augite hypersthene olivine andesite, summit of central cone, Moriyoshiyama volcano
	19	Augite hypersthene andesite, a valley north-west of Moriyoshiyama volcano

Major and trace elment composition of the Quaternary volcanic rocks from Northeast Japan.

Volcano	7. Iwate		8. Akita-komagatake				9. Funagata			
Sample	35	40	1	2	3	4	17	18	19	20
Rock series+	T	T	T	T	T	T	T	T	T	T
Major oxides (wt.%)										
SiO_2	51.09	50.19	49.06	49.37	52.13	54.90	50.12	50.37	50.94	51.07
Al_2O_3	18.23	19.33	20.48	20.15	16.71	17.87	17.06	16.24	18.00	16.52
FeO*	9.55	9.47	8.51	8.54	10.15	9.24	10.06	11.05	9.92	10.39
MgO	6.91	6.17	5.17	5.07	5.21	3.79	6.61	7.13	6.32	6.42
CaO	10.68	10.57	11.66	12.46	10.43	8.19	10.63	11.17	10.55	10.81
Na_2O	1.96	2.14	2.17	2.30	2.76	3.16	1.61	1.46	2.14	1.65
K_2O	0.15	0.19	0.35	0.22	0.50	0.60	0.18	0.21	0.22	0.20
Trace elements (ppm)										
Co	32.1	33.5	29.7	29.1	30.6	23.3	39.0	45.5	39.0	40.6
Cr	117	72	144	170	86	41	103	144	84	88
Sc	28.7	27.3	33.0	32.8	38.6	34.5	41.8	47.4	36.5	44.7
Ba	98	–	81	96	154	170	–	–	–	–
Hf	0.19	–	0.94	0.99	1.5	1.9	–	–	–	–
Th	0.32	–	0.42	0.42	0.74	1.01	0.25	0.21	0.40	0.26
U	0.07	–	0.16	0.16	0.24	0.34	0.09	0.10	0.13	0.10
La	2.0	2.0	2.6	2.6	4.0	5.3	2.6	2.1	3.7	2.9
Ce	–	6.1	–	11.7	11.4	20.7	7.6	7.1	11.8	10.0
Sm	1.3	1.3	1.8	1.8	2.2	2.8	1.9	1.7	2.2	2.0
Eu	0.53	0.51	0.71	0.67	0.79	0.95	0.85	0.76	0.89	0.72
Tb	0.29	–	0.36	0.40	0.57	0.54	0.59	0.46	0.56	0.49
Yb	1.1	1.2	1.4	1.4	2.0	2.5	1.9	1.8	1.8	2.0
Lu	0.15	0.20	0.22	0.23	0.29	0.37	0.27	0.25	0.29	0.32
Ni	–	–	–	68	32	–	–	45	60	–
Ref #	21	21	22	22	22	22	11	11	11	11

\+ Volcanic rock series : T = tholeiitic series; C = calc-alkaline series; A = alkaline series.
* FeO* is total iron as FeO.
\# References for the sample description and major element data.

7. Iwate	35	Olivine basalt, lava of Yakushidake cone (the younger Iwate volcano) 1450 m
	40	Hypersthene olivine basalt, lava of Myokodake cone (the younger Iwate volcano) 1950 m
8. Akita-komagatake	1	Older lava or Scoria, Me-dake
	2	Bomb, Me-dake
	3	Older bomb, northern slope of Yoko-dake
	4	Lava or dyke, summit of O-dake
9. Funagata	17	Pigeonite bearing bronzite augite olivine basalt, 0.5 km north of Kurohanayama
	18	Olivine bronzite pigeonite basalt, summit of Kurohanayama
	19	Bronzite bearing augite olivine basalt, summit of Funagatayama
	20	Bronzite olivine pigeonite basalt, southern foot of Izumidake

Major and trace elment composition of the Quaternary volcanic rocks from Northeast Japan.

Volcano	10. Kurikoma		11. Nekoma			12. Bandai			
Sample	TH-7	TH-6	43	44	45	B-01	B-02	B-03	B-04
Rock series+	C	C	T	T	T	C	C	C	C
Major oxides (wt.%)									
SiO_2	56.46	58.06	60.26	62.22	62.63	58.67	58.70	58.97	60.51
Al_2O_3	–	–	17.63	16.57	16.47	15.42	16.08	16.38	17.51
FeO*	6.7	7.3	6.73	6.61	6.35	8.26	8.16	7.94	5.97
MgO	4.8	4.4	2.13	1.67	2.04	1.86	3.93	3.22	2.56
CaO	8.6	8.3	5.88	6.01	6.23	8.15	7.90	6.86	6.58
Na_2O	2.5	–	3.63	3.85	3.86	3.86	3.06	2.98	3.95
K_2O	0.90	1.18	0.58	0.82	0.67	1.38	1.00	1.11	1.20
Trace elements (ppm)									
Co	27.4	26.8	12.1	11.8	13.7	17.3	23.7	16.7	16.3
Cr	160	70	3	5	7	6	140	4	7
Sc	30.2	29.9	28.0	23.1	22.8	31.9	24.2	22.5	21.2
Ba	240	290	200	–	–	370	220	290	300
Hf	1.9	–	2.8	–	–	3.7	2.8	3.7	3.5
Th	3.0	2.5	1.2	2.3	2.9	3.6	3.0	3.1	3.1
U	0.75	0.75	–	0.45	0.51	0.60	0.69	0.66	0.66
La	6.9	6.0	8.1	10.4	9.4	10.2	9.7	10.8	10.9
Ce	17.5	17.2	26.3	29.7	27.6	36.5	30.6	29.2	27.9
Sm	3.0	2.4	4.9	4.4	3.9	4.5	3.0	4.0	4.2
Eu	0.86	0.72	2.01	–	–	1.70	1.13	1.31	1.55
Tb	0.64	–	1.3	0.63	0.69	1.0	0.70	0.89	0.92
Yb	2.5	1.7	4.5	3.3	3.0	2.9	2.0	2.9	3.0
Lu	0.43	0.34	0.60	0.54	0.46	0.55	0.37	0.55	0.53
Ni	35	28	13	13	12	14	84	13	18
Ref #	–	–	11	11	23	23	23	23	23

\+ Volcanic rock series : T = tholeiitic series; C = calc-alkaline series; A = alkaline series.
* FeO* is total iron as FeO.
\# References for the sample description and major element data.

10. Kurikoma	TH-7	Hypersthene augite andesite, western ridge of Kurikomayama (collected by Masuda)
	TH-6	Hypersthene augite andesite, 1 km south of Sukawa hot spring (ibid.)
11. Nekoma	43	Augite hypersthene andesite, western caldera wall of Nekoma
	44	Augite hypersthene andesite, 1 km west of Kanazawa-toge
	45	Augite hypersthene andesite, 1 km west of Kanazawa-toge
12. Bandai	B-01	Augite hypersthene andesite
	B-02	Olivine bearing augite hypersthene andesite
	B-03	Augite hypersthene andesite
	B-04	Augite hypersthene andesite

Major and trace elment composition of the Quaternary volcanic rocks from Northeast Japan.

Volcano	13. Niseko		14. Iwaki		15. Chokai		16. Gassan
Sample	H-16	H-17	TH-43	TH-45	TH-207	TH-206	TH-213
Rock series+	C	C	C	C	C	C	C
Major oxides (wt.%)							
SiO_2	59.93	60.35	59.23	60.11	54.56	55.93	56.58
Al_2O_3	18.50	15.77	–	–	–	–	–
FeO*	5.62	7.29	–	–	–	–	–
MgO	3.21	3.39	–	–	–	–	–
CaO	6.13	5.68	–	–	–	–	–
Na_2O	3.90	2.85	3.25	–	3.55	3.58	2.86
K_2O	1.80	1.61	1.51	1.29	1.95	1.88	1.76
Trace elements (ppm)							
Co	16.8	18.4	15.3	15.5	21.0	21.7	21.1
Cr	6	2	6	8	7	7	19
Sc	19.6	20.4	15.4	14.6	17.3	16.2	20.3
Ba	710	700	490	470	440	520	490
Hf	2.6	3.0	3.0	3.3	4.5	5.0	3.3
Th	6.5	6.6	3.5	3.1	5.9	5.7	5.2
U	2.5	1.8	1.4	1.2	1.4	1.8	1.4
La	13.3	10.8	9.6	10.1	15.9	16.6	14.9
Ce	33.8	32.6	25.7	29.3	31.8	38.3	29.2
Sm	4.8	3.5	3.2	3.6	4.0	4.2	4.1
Eu	1.37	1.07	1.09	0.99	1.56	1.51	1.34
Tb	0.82	0.75	0.53	0.50	0.70	0.78	0.56
Yb	3.3	2.0	2.7	3.0	3.1	3.4	2.2
Lu	0.52	0.38	0.36	0.38	0.43	0.51	0.45
Ref #	24	24	–	–	–	–	–

\+ Volcanic rock series : T = tholeiitic series; C = calc-alkaline series; A = alkaline series.

* FeO* is total iron as FeO.

\# References for the sample description and major element data.

13. Niseko	H-16	Hypersthene augite andesite, lava of Niseko-annupuri, a lava cone of the Niseko volcano
	H-17	Quartz-bearing hypersthene augite andesite, dome lava of Ō-iwaonupuri, one of the lava domes of the Niseko volcano
14. Iwaki	TH-43	Hypersthene augite andesite, summit of Iwaki volcano (Mikura-ishi)
	TH-45	Hyperthene augite andesite, 0.5 km southeast of summit of Iwaki (Torinoumi)
15. Chokai	TH-207	Olivine hypersthene augite andesite, northeastern foot of Chokai volcano (Kuromori)
	TH-206	Hypersthene augite andesite, northeastern foot of Chokai volcano (Kuromori)
16. Gassan	TH-213	Olivine hypersthene augite andesite, Ubagadake

Major and trace elment composition of the Quaternary volcanic rocks from Northeast Japan.

Volcano	17. Oshima-ōshima				18. Oshima-kojima	19. Kampu		
Sample	H-18	H-19	H-20	H-21	H-22	75	76	TH-29
Rock series+	A	A	C	C	C	C	C	C
Major oxides (wt.%)								
SiO_2	48.89	49.90	55.56	61.72	60.46	54.78	55.47	55.56
Al_2O_3	15.00	16.05	18.28	17.71	16.30	20.37	19.98	–
FeO*	9.04	10.08	7.32	5.34	5.67	6.46	6.71	–
MgO	10.60	7.03	4.05	1.83	3.31	3.73	3.61	–
CaO	10.91	10.51	8.57	5.19	7.11	8.69	8.31	–
Na_2O	1.95	2.15	2.62	3.21	3.04	2.74	2.89	2.78
K_2O	1.13	1.92	1.80	3.28	1.84	1.12	1.18	1.74
Trace elements (ppm)								
Co	45.7	32.5	18.0	8.2	14.1	20.5	13.0	26.2
Cr	690	180	17.6	6.3	8	22	15	76
Sc	43.5	35.3	14.2	5.7	15.2	17.1	10.7	24.3
Ba	400	570	850	1380	850	750	590	670
Hf	0.9	2.4	2.9	3.7	3.2	3.2	2.5	–
Th	2.2	6.0	7.0	16.7	10.7	5.9	4.7	6.8
U	0.52	1.7	1.9	3.1	2.6	1.3	1.2	1.8
La	11.1	19.8	21.7	32.7	19.7	25.1	20.9	21.0
Ce	30.4	50.8	52.4	73.3	46.2	60.3	43.5	44.0
Sm	4.6	6.2	5.5	6.6	4.4	6.0	4.6	4.3
Eu	11.51	2.02	1.48	1.38	1.43	1.87	1.54	1.35
Tb	0.90	1.09	0.88	0.93	0.82	0.90	0.56	0.61
Yb	2.8	2.8	2.4	2.5	2.5	3.2	2.5	1.7
Lu	0.47	0.47	0.40	0.53	0.45	0.50	0.40	0.35
Ref #	25	25	25	25	26	11	11	–

\+ Volcanic rock series : T = tholeiitic series; C = calc-alkaline series; A = alkaline series.
* FeO* is total iron as FeO.
\# References for the sample description and major element data.

17. Oshima-ōshima
- H-18 Augite olivine basalt, a lava of the younger somma (Nishi-yama)
- H-19 Olivine augite basalt, a central cone lava
- H-20 Olivine and hornblende-bearing augite hypersthene andesite, lava of the younger somma (Nishi-yama)
- H-21 Hornblende augite hypersthene andesite, a lava of the older somma (Higashiyama)

18. Oshima-kojima
- H-22 Biotite quartz-bearing hornblende hypersthene augite andesite, a lava of the Oshima-kojima volcano

19. Kampu
- 75 Augite hypersthene andesite, a quarry of Somuzawa
- 76 Augite hypersthene andesite, a quarry of Ohira
- TH-29 Augite hypersthene andesite, summit of Kampu-san volcano

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