Hydrogen isotopic composition, water content, and color of hydrous phenocrysts from Japanese Quaternary volcanoes.

*Isoji Miyagi and †Osamu Matsubaya

March 1, 2003

Abstract

This report provides hydrogen isotopic compositions (δD), chemical compositions, and color of separated hornblende and biotite phenocrysts from Japanese Quaternary volcanoes. Figure 1 shows location of the volcanoes studied. Table 1 shows chemical composition of the hornblende phenocrysts. Table 2 shows δDvalue, water content, and color of separated hydrous minerals (hornblende and biotite).

Samples analysed

Volcanic rock samples were collected throughout the Japanese arc (see Figure 1 and Volcanoes of Japan by GSJ, Ono et al., 1981). The samples comprise lavas, lava domes, pyroclastic flow deposits related with lava dome collapse, air-fall pumices and pumice flow deposits. A brief description of rock specimens follows (Numbers correspond with Figure 1 and Table 1-2) :

*Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology, Tsukuba Central 7, Higashi 1-1-1, Tsukuba city, Ibaraki 305-8567 JAPAN (miyagi.iso14000@aist.go.jp)

†Research Institute of Materials and Resources Faculty of Engineering and Resource Science Akita University, Tegata Gakuen-cho 1-1, Akita city, Akita 010-8502 JAPAN

1. Dacitic lava dome and lava flow of Unzen (Watanabe and Hoshizumi, 1995);

2. Dacitic lava dome of Tsurumi (Ohta et al., 1990);

3. Dacitic lava flow and intrusive rocks of Himejima (Itoh, 1989);

4. Pumice flow, pyroclastic flow, and dacitic lava dome of Sambe (Matsui and Inoue, 1971);

5. Pumice fall and pyroclastic flow associated with dacitic lava dome collapse of Daisen (Tsukui, 1984; Saji *et al.,* 1975);

6. Andesitic and dacitic lava flows of Kurohime (Hayatsu, 1972);

7. Andesitic lava flows, pumice flows, and dacitic pyroclastic flow of Myoko (Hayatsu, 1972);

8. Dacitic lava flows and lava domes of Gassan (Nakazato et al., 1996);

9. Pumice flows and pumice falls of Hijiori (Murakami and Kawaguchi, 1994);

10. Andesitic lava flows of Chokai (Hayashi, 1984; Nakano and Tsuchiya, 1992);

11. Pumice flow of Takahinata (Abe, E. 1990 Pers. Comm.);

12. Andesitic lava flows of Kanpu (Maruyama et al., 1988);

13. Pumice flow (Aoki and Fujimaki, 1982) and hornblendite xenoliths (Aoki, 1971) of Ichinome-gata;

14. Andesitic lava dome of Nanashigure (Ishikawa et al., 1985);

15. Pumice flows and dacitic lava dome of Osorezan (Togashi, 1977);

16. Pumice fall of Oshima-Ooshima (Yamamoto, 1984).

Mineral separation techniques

Hornblende and biotite phenocrysts in the volcanic rock specimens were separated by conventional ways. A rock specimen of a few kg was crushed, ground, screened (between 0.06 and 0.13 mm), and separated with magnetic and heavy liquid techniques. The final purity of the separates was almost 100 % for those from air-fall pumice fragments or pumiceous fragments from pyroclastic flows, and about 20 vol. % for lava samples. This impurity for the lava samples, however, may not give a serious error to the δD measurements because of small amount of water in contaminants, mainly pyroxenes. For example, reported hydrogen concentrations in ppm H_2O for minerals from mantle xenoliths are 100-1300 ppm H_2O for clinopyroxene, 60-650 ppm H_2O for orthopyroxene, 0-140 ppm H_2O for olivine and 1-200 ppm H_2O for garnet (Ingrin and Skogby, 2000).

D/H and H_2O analyses

Stoichiometric water in hydrous phenocrysts was extracted from about 200 mg. of separated hydrous phenocrysts by heating in vacuum (Friedman et al., 1964). The heating has three major phases. First phase is a steady heating at 300 °C for a few to several hours to remove the absorbed water. Second phase is an escalation of heating temperature up to 1000 °C in 3 to 4 hours. Final phase is a steady heating at about 1200 °C. Usually in the second heating phase, hornblende and biotite release a mixture of H_2O and H_2 gas. The H_2 gas was converted into H_2O with a CuO furnace. All the trapped water was purified and finally reduced to H_2 gas with a hot Uranium metal (or Chrome metal) and pumped into a manometer with a Töepler pump. Hydrogen isotopic analyses were carried out with a Finnigan MAT-250 mass spectrometer. Typical reproducibility of the water content and δD analysis on our hornblende working standard is better than

0.1 % and 3 $^{o}/_{oo}$, respectively.

Color measurements

Color of the minerals was measured because this provides useful information for evaluating the degree of mineral dehydrogenation (Miyagi *et al.,* 1998). We used a Minolta spectrophotometer CM-1000 and Minolta chromameter CR-300. Details about the method are reported in Nakashima *et al.,* (1992). The result of the color measurement is expressed quantitatively as L*, a* and b* units in the CIE1976 L*a*b* color space proposed by the Commission Internationale de l'Eclariage. The L* value is the psychometric lightness and ranges from 0 (black) to 100 (white). Positive and negative values of a* and b* correspond to red and green color, and yellow and blue, respectively.

Chemical composition

Chemical composition of the minerals was measured with an EPMA (JEOL JXA-733 and JXA-8800) with a 15 kV accelerating voltage and 12 nA beam current. The analytical results were reported in the formula "$A_{0-1}X_2Y_5Z_8O_{22}$", assuming that Z site is filled with Si^{4+} and a part of Al^{3+}, and that the excess Al^{3+}, Mg^{2+}, Fe^{2+}, Ca^{2+}, and Ti^{4+} occupy X and Y sites.

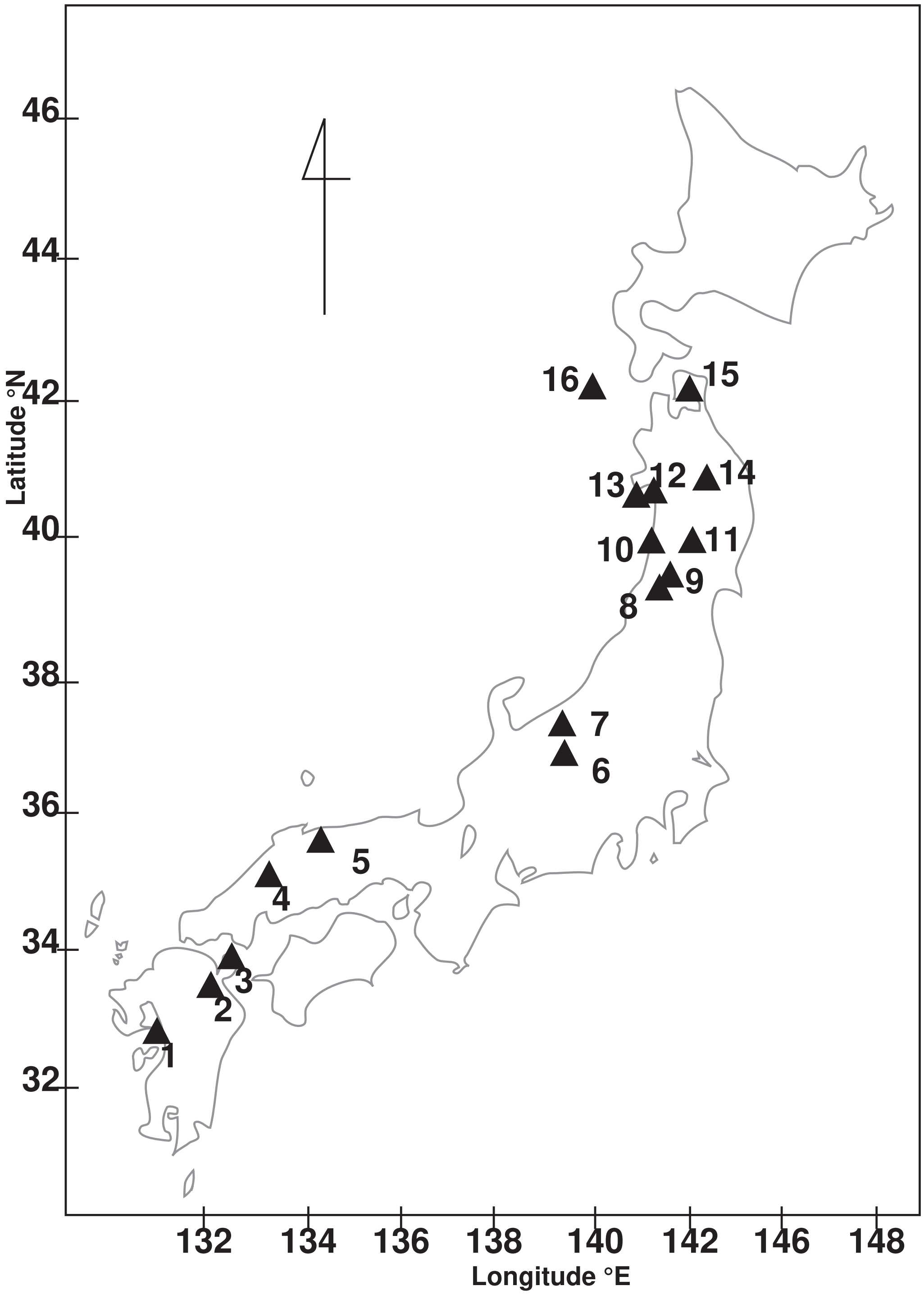

Fig. 1. Map showing the locations of the Japanese arc volcanoes studied. 1 Unzen, 2 Tsurumi, 3 Himejima, 4 Sambe, 5 Daisen, 6 Kurohime, 7 Myoko, 8 Gassan, 9 Hijiori, 10 Chokai, 11 Takahinata (Onikobe caldera), 12 Kanpu, 13 Ichinome-gata, 14 Nanashigure, 15 Osorezan, 16 Oshima-Ooshima.

Table 1

	Z=8		Y+X					A	
	Si	Al	Al	Mg	Fe	Ca	Ti	Na	K
1: Unzen									
1-1	6.96	1.04	0.31	3.10	1.67	1.78	0.19	0.23	0.03
1-3	7.08	0.92	0.33	3.18	1.67	1.73	0.14	0.17	0.04
1-4	7.05	0.95	0.41	2.91	1.76	1.76	0.16	0.20	0.04
2: Tsurumi									
2-1	6.97	1.03	0.34	3.37	1.41	1.78	0.17	0.20	0.03
2-2	7.14	0.86	0.35	3.29	1.46	1.76	0.15	0.13	0.04
3: Himejima									
3-1	6.74	1.26	0.36	3.30	1.44	1.80	0.20	0.29	0.04
3-4	6.65	1.35	0.42	3.30	1.40	1.80	0.19	0.31	0.04
3-5	6.62	1.38	0.47	3.12	1.45	1.83	0.20	0.32	0.05
3-6	6.40	1.60	0.54	2.93	1.76	1.76	0.18	0.33	0.04
4: Sambe									
4-1	6.78	1.22	0.45	3.37	1.44	1.74	0.12	0.25	0.02
4-2	6.92	1.08	0.52	3.11	1.52	1.76	0.12	0.24	0.03
5: Daisen									
5-1	6.45	1.55	0.44	3.61	1.01	1.85	0.22	0.35	0.05
5-4	6.64	1.36	0.42	3.32	1.45	1.76	0.18	0.28	0.03
5-5	6.80	1.20	0.48	3.21	1.49	1.69	0.17	0.28	0.03
5-9	7.02	0.98	0.37	3.40	1.49	1.67	0.13	0.19	0.02
5-11	6.92	1.08	0.39	3.36	1.57	1.64	0.14	0.20	0.02
5-12	6.90	1.10	0.41	3.25	1.56	1.72	0.13	0.23	0.04
5-13	7.00	1.00	0.36	3.26	1.69	1.71	0.09	0.19	0.03
5-16	6.77	1.23	0.43	3.43	1.34	1.73	0.16	0.28	0.03
6: Kurohime									
6-1	6.11	1.89	0.71	3.39	1.14	1.85	0.16	0.33	0.03
6-2	6.10	1.90	0.72	3.31	1.19	1.85	0.17	0.33	0.03
7: Myoko									
7-1	7.03	0.97	0.31	3.03	1.82	1.71	0.18	0.18	0.03
7-2	6.98	1.02	0.29	3.04	1.78	1.78	0.19	0.20	0.03
7-9	6.88	1.12	0.33	3.14	1.67	1.77	0.18	0.22	0.02
7-10	7.01	0.99	0.27	3.03	1.79	1.79	0.18	0.19	0.03
7-11	6.97	1.03	0.31	3.00	1.80	1.77	0.19	0.20	0.03

Chemical composition of hornblende phenocrysts measured with an EPMA, reported in the formula "$A_{0-1}X_2Y_5Z_8O_{22}$", assuming that the Z site is filled with Si^{4+} and partially with Al^{3+}, and that the excess Al^{3+}, Mg^{2+}, Fe^{2+}, Ca^{2+}, and Ti^{4+} occupy the X and Y sites.

Table 1 continued

	Z=8		Y+X					A	
	Si	Al	Al	Mg	Fe	Ca	Ti	Na	K
8: Gassan									
8-1	7.01	0.99	0.32	3.16	1.63	1.76	0.17	0.20	0.03
8-2	7.03	0.97	0.37	3.14	1.65	1.72	0.16	0.20	0.03
8-4	7.02	0.98	0.42	3.01	1.67	1.76	0.15	0.21	0.03
9: Hijiori									
9-1	7.24	0.76	0.33	3.36	1.62	1.60	0.12	0.16	0.01
9-3	7.24	0.76	0.30	3.34	1.60	1.65	0.13	0.17	0.02
10: Chokai									
10-8	6.52	1.48	0.43	3.01	1.59	1.84	0.24	0.30	0.05
Takahinata									
10-1	7.10	0.90	0.30	3.12	1.68	1.74	0.18	0.16	0.01
12: Kanpu									
12-1	6.07	1.93	0.68	3.17	1.24	1.90	0.21	0.32	0.08
13: Ichinome-gata									
13-1	6.39	1.61	0.58	2.87	1.82	1.69	0.19	0.32	0.02
13-6	6.13	1.87	0.68	3.05	1.28	1.84	0.27	0.36	0.04
15: Osorezan									
15-2	7.15	0.85	0.28	3.20	1.65	1.73	0.17	0.17	0.01
16: Oshima-oshima									
16-1	6.22	1.78	0.52	3.23	1.36	1.91	0.21	0.30	0.10

Table 2

δD value, water content, and color of hydrous minerals from Japanese Quaternary volcanoes.

Sample locality	Mineral	Occurrence	H_2O	δD	color L*	a*	b*
1: Unzen							
1-1	Ho	LAFL	1.6	-57	48.4	0.3	7.2
1-1	Bi	LAFL	5.8	-66	-	-	-
1-2	Bi	LAFL	1.0	-72	44.8	0.3	6.2
1-3	Ho+Px	LAFL	0.8	-39	-	-	-
1-3	Bi	LAFL	0.8	-42	50.0	0.2	7.4
1-3	Ho	LAFL	1.2	-55	-	-	-
1-4	Ho	LAFL	1.0	-49	54.7	-0.1	8.9
1-4	Bi	LAFL	2.0	-40	44.1	0.2	6.4
1-5	Ho	LADM	0.8	-60	-	-	-
2:Tsurumi							
2-1	Ho+Px+Gl	LAFL/LADM	0.8	-70	-	-	-
2-1	Ho+Px	LAFL/LADM	0.9	-61	-	-	-
2-2	Ho+Px	LAFL/LADM	0.6	-36	-	-	-
2-2	Ho+Px	LAFL/LADM	0.5	-34	53.3	0.6	8.6
3: Himejima							
3-1	Ho	LAFL	1.4	-80	50.9	-0.1	8.1
3-2	Ho	LAFL	1.2	-84	-	-	-
3-3	Ho	INTL	1.5	-75	53.6	-0.9	8.0
3-4	Ho	LAFL	1.6	-61	51.2	-0.6	7.8
3-5	Ho	LAFL	1.7	-78	53.5	-0.6	9.0
3-6	Ho	LAFL	1.5	-81	48.3	-0.9	7.4
3-7	Ho	LAFL	1.5	-83	-	-	-
4: Sambe							
4-1	Bi	PCFL	2.6	-53	45.7	0.3	7.6
4-1	Ho	PCFL	1.6	-55	50.8	-0.5	8.1
4-2	Ho	PMFL	1.7	-56	58.0	-1.8	7.0
4-3	Bi	PMFL	3.1	-67	54.3	-0.5	10.2
5: Daisen							
5-1	Ho+Px	PCFL	0.5	-59	55.4	0.7	7.9
5-1	Ho	PCFL	1.2	-61	48.4	1.1	9.6
5-1	Ho	PCFL	0.4	-51	59.1	1.0	10.8
5-2	Ho+Px	PCFL	0.1	-67	-	-	-
5-3	Ho+Px	PCFL	0.9	-76	-	-	-
5-3	Bi	PCFL	1.7	-66	-	-	-
5-4	Ho	PMFA	1.6	-53	60.2	-1.5	8.3
5-5	Ho	PMFA	1.6	-49	54.3	-1.3	7.2
5-6	Ho	PMFA	1.7	-54	54.4	-1.6	6.9
5-7	Ho	PMFA	1.8	-50	54.5	-1.7	6.9
5-7	Ho	PMFA	1.6	-49	-	-	-

Table 2. continued

Sample locality	Mineral	Occurrence	H_2O	δD	color L*	a*	b*
5-8	Ho	PMFA	2.0	-58	57.4	-1.9	7.7
5-9	Ho	PMFA	1.9	-51	54.4	-1.7	7.4
5-10	Ho	PMFA/PMFL	1.6	-53	55.8	-1.1	7.9
5-11	Ho	PMFA	1.9	-48	59.2	-2.0	6.8
5-12	Ho	PCFL	1.5	-89	47.3	-0.3	5.6
5-12	Bi	PCFL	2.7	-72	-	-	-
5-13	Ho	PCFL	1.2	-50	56.6	-0.5	8.3
5-13	Bi	PCFL	2.7	-48	-	-	-
5-14	Ho	PCFL	1.3	-42	55.2	-0.5	8.1
5-14	Bi	PCFL	2.5	-39	-	-	-
5-15	Bi	PCFL	0.8	+71	47.7	0.2	5.9
5-16	Bi	PCFL	1.5	-69	-	-	-
5-16	Ho	PCFL	0.7	-74	-	-	-
5-17	Bi	PCFL	1.5	-75	49.9	0.5	8.5
5-18	Bi	PCFL	1.8	-10	45.9	1.1	9.3
6: Kurohime							
6-1	Ho+Px	LADM	0.2	-60	-	-	-
6-2	Ho+Px	LADM	0.4	-44	-	-	-
Sadoyama							
6-3	Ho+Px	LAFL	0.3	-75			
7: Myoko							
7-1	Ho	PCFL/PMFL	1.2	-25	48.9	0.2	8.4
7-2	Ho	PCFL/PMFL	1.3	-57	47.5	-0.4	5.7
7-3	Ho	PCFL/PMFL	1.2	-39	49.5	0.1	6.8
7-4	Ho	PCFL/PMFL	1.0	-44	46.9	0.4	7.5
7-5	Ho	PCFL/PMFL	1.2	-33	51.1	0.1	7.4
7-6	Ho	PCFL/PMFL	1.1	-38	53.7	-0.4	7.1
7-7	Ho+Px	PCFL/PMFL	0.9	-41	-	-	-
7-8	Ho	LAFL	1.2	-1	47.5	0.7	7.2
7-9	Ho	LAFL	0.3	+103	51.2	3.6	12.7
7-10	Ho	LAFL	1.3	-54	51.0	-0.4	7.1
7-11	Ho	LAFL	0.6	-79	58.4	-0.7	7.8
7-12	Ho		1.4	-48	36.0	0.2	1.3
8: Gassan							
8-1	Bi	LAFL	2.1	-81	-	-	-
8-1	Ho	LAFL	1.4	-91	52.7	-0.9	7.9
8-2	Ho	LAFL	1.4	-82	-	-	-
8-3	Bi	LAFL	2.8	-74	-	-	-
8-4	Ho	LADM	1.5	-93	51.7	0.4	8.9

Table 2. continued

Sample locality	Mineral	Occurrence	H_2O	δD	color L*	a*	b*
9: Hijiori							
9-1	Ho	PMFL	1.2	-93	-	-	-
9-2	Ho	PMFL	1.5	-82	55.2	-1.3	7.4
9-3	Ho	PMFL	1.4	-86	-	-	-
9-4	Ho	PMFL	1.6	-78	57.3	-1.1	8.2
9-5	Ho	PMFL	1.2	-83	-	-	-
9-6	Ho+Px	PMFA	1.1	-58	-	-	-
9-7	Ho+Px	PMFA	1.0	-62	-	-	-
9-8	Ho+Px	PMFA	1.1	-59	-	-	-
9-9	Ho+Px	PMFA	1.0	-64	-	-	-
10: Chokai							
10-1	Ho+Px	LAFL	0.1	-80	-	-	-
10-2	Ho+Px	LAFL	(0.04)	-108	-	-	-
10-3	Ho+Px	LAFL	(0.04)	-86	-	-	-
10-4	Ho+Px	LAFL	0.1	-88	-	-	-
10-5	Ho+Px	LAFL	0.1	-95	-	-	-
10-6	Ho+Px	LAFL	0.1	-98	-	-	-
10-7	Ho+Px	LAFL	0.1	-101	-	-	-
10-8	Ho+Px	LAFL	0.1	-49	-	-	-
10-9	Ho+Px	LADM	0.1	-98	-	-	-
10-10	Ho+Px	LAFL	0.1	-93	-	-	-
10-11	Ho+Px	LAFL	0.1	-95	-	-	-
11: Takahinata							
11-1	Ho	PMFL	-	-57	54.6	-0.8	8.3
12: Kanpu							
12-1	Ho+Px	LAFL	0.2	-76	-	-	-
12-2	Ho+Px	LAFL	0.1	-67	-	-	-
13: Ichinome-gata							
13-1	Ho	IHBD 3)	1.5	-49	-	-	-
13-2	Ho	IAMP 4)	1.1	-46	48.0	-0.6	4.8
13-2	Ho	IAMP	1.6	-32	-	-	-
13-3	Ho	IAMP	1.8	-34	53.5	-1.4	7.0
13-4	Ho	IAMP	1.7	-31	37.3	0.0	2.2
13-5	Ho	IHBD	1.7	-36	37.8	0.1	2.7
13-6	Ho	IHBD	1.7	-32	-	-	-
13-7	Bi	PMFA	2.4	-57	48.0	-0.1	7.6
13-7	Bi	PMFA	2.0	-41	-	-	-
13-7	Ho+Px	PMFA	0.7	-44	52.0	-0.5	7.9
14: Nanasigure							
14-1	Ho+Px	LAFL/LADM	0.3	-79	-	-	-

Table 2. continued

Sample locality	Mineral	Occurrence	H_2O	δD	color L*	a*	b*
15: Osorezan							
15-1	Ho	PMFL	1.4	-38	51.0	0.3	9.2
15-2	Ho	LADM	0.9	-39	47.5	1.4	9.6
15-3	Ho+Px	LADM	0.8	-70	-	-	-
15-4	Ho	PMFL	1.8	-51	-	-	-
16: Oshima-Oshima							
16-1	Bi	PMFA	2.9	-56	-	-	-
16-1	Ho	PMFA	1.2	-53	53.9	-1.0	7.4

1) Ho = Hornblende; Bi = Biotite; Px = Pyroxene; Gl = Matrix glass

2) PMFA = Pumice fall deposit; PMFL = Pumice flow deposit; PCFL = Pyroclastic flow deposit; LAFL = Lava flow; LADM = Lava dome; INTL = Intrusive rock;

3) IAMP = Ichinome-gata amphibolite xenolith;

4) IHBD = Ichinome-gata hornblendite xenolith;

Acknowledgements

K. Tazaki , K. Saji and K. Ota are acknowledged for their help and support during the sample collection at the Daisen and Unzen volcanoes. K. Yamagata, K. Aoki, O. Ujike , E. Takahashi, M. Yamamoto, E. Abe, and Y. Kawaguchi kindly provided rock samples and minerals. A part of EPMA work was done at the Ocean Research Institute, Tokyo University, Department of Earth and Planetary Sciences at Tokyo Institute of Technology, and Geological Survey of Japan.

REFERENCES

Aoki, K., 1971. Petrology of mafic inclusions from Itinome-gata, Japan. Contrib. Mineral. Petrol. 30, 314-331.

Aoki, K., Fujimaki, H., 1982. Petrology and geochemistry of calc-alkaline andesite of presumed upper mantle origin from Itinome-gata, Japan. Am. Mineral., 67, 1-13.

Friedman, I., Smith, R.L., Levin, R., Moore, A., 1964. The water and deuterium content of phenocrysts from rhyolitic lavas. in Isotopic and Cosmic Chemistry (H. Craig *et al.,* ed.), North Holland Pub. Co., Amsterdam, 200-204.

Hayashi, S., 1984. Geology of Chokai volcano. J. Japan Assoc. Mineral. Petrol. Econ. Geol. 79, 249-265. (in Japanese with English abstract).

Hayatsu, K., 1972. Myoko volcano group -Geochemistry of the Kurohime and Myoko volcanoes. Tikyukagaku (Earth Science), 26, 91-103 (in Japanese with English abstract).

Ingrin J., Skogby H., 2000. Hydrogen in nominally anhydrous upper-mantle minerals: concentration levels and implications. Eur. J. Mineral., 12, 543-570.

Ishikawa, K., Yoshida, T., Kitagawa, Y., Aoki, K., Okami K., 1985. Geochemical study of Nanashigure volcano, Iwate prefecture, NE Japan. Res. Rept. Lab. Nucl. Sci. Tohoku Univ. 18, 366-378 (in Japanese with English figure captions).

Itoh, J., 1989. Geology and volcanic activity of the Hime-shima volcanic group, north Kyushu, Japan. Bull. Volcanol. Soc. Japan 34, 1-17 (in Japanese with English abstract).

Maruyama, T., Yamamoto, M., Yoshioka, S., 1988. Geology and petrology of Kampu volcano, Oga Peninsula, Japan. Report Res. Inst. Natural Resources, Mining College, Akita Univ. 53, 1-16 (in Japanese with English abstract).

Matsui, S., Inoue T., 1971. Pyroclastics and their stratigraphy from volc Sambe. Earth Sci. 25, 147-163 (in Japanese with English abstract).

Miyagi, I., Matsubaya, O., Nakashima, S., 1998. Change in D/H ratio, water content and color during dehydration of hornblende. Geochem. J. 32, 33-48.

Murakami, H., Kawaguchi, Y., 1994. Chemical variability in hornblendes related to volcanic activity of Hiziori caldera, Yamagata Prefecture. Report Res. Inst. Natural Resources, Mining College, Akita Univ. 59, 1-23 (in Japanese with English abstract).

Nakano, S., Tsuchiya, N., 1992. Geology of the Chokaisan and Fukura district. With Geological Sheet Map at 1:50,000. Geol. Surv. Japan 138p. (in

Japanese with English abstract 7p.).

Nakashima, S., Miyagi, I., Nakata, E. Sasaki, H. Nittono, S., Hirano, T. Sato, T. Hayashi, H., 1992. Color measurement of some natural and synthetic minerals - I. Report Res. Inst. Natural Resources, Mining College, Akita Univ. 57, 57-76.

Nakazato, H., Oba, T., Itaya, T., 1996. The geology and K-Ar ages of the Gassan volcano, northeast Japan. J. Mineral. Petrol. Econ. Geol. 91, 1-10 (in Japanese with English abstract).

Ohta, T., Hasenaka, T., Fujimaki, L., 1990. Geology and petrography of Yufu-Tsurumi volcano group, Oita prefecture, J. Mineral. Petrol. Econ. Geol. 85, 113-129 (in Japanese with English abstract).

Ono, K., Soya, T., Mimura, K. 1981. Volcanoes of Japan, 1:2,000,000 map series 11, Volcanoes of Japan Second Edition, Geological Survey of Japan.

Saji, K., Tazaki, K., Akagi, S., Asada, H., 1975. Atratigraphy of the Daisen tephra -Application of mineralogical and morphological studies. Tikyuka-gaku (Earth Science), 29, 199-210 (in Japanese with English abstract).

Togashi, S., 1977. Petrology of Osore-yama volcano, Japan. J. Min. Petrol. Econ. Geol. 72, 45-60 (in Japanese with English abstract).

Tsukui, M., 1984. Geology of Daisen volcano. J. Geol. Soc. Japan. 90, 643-658 (in Japanese with English abstract).

Watanabe, K., Hoshizumi, H., 1995. Geological Map of Unzen Volcano, 1:25,000, Geological Map of Volcanoes 8, Geological Survey of Japan.

Yamamoto, M., 1984. Origin of calc-alkaline andesite from Oshima-Oshima volcano, north Japan. J. Fac. Sci. Hokkaido Univ. Ser. IV 21, 77-131.