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Oxygen isotopic constraints on the geneses of the Cretaceous granitoids in the Kitakami and Abukuma terrains, Northeast Japan

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Abstract: Oxygen isotopic ratios ($^{18}O/^{16}O$) were measured on 48 whole rock samples for the Early Cretaceous granitoids of the Kitakami Mountains and the Abukuma Highland. Together with 10 published data, origins of these granitoids are considered.

In the Kitakami Mountains, the granitoids generally belong to magnetite series and their initial Sr isotopic ratios are low (0.70363 - 0.70463). The Zone I granitoids are lowest in $\delta^{18}O$ value, indicating they were originated in ^{18}O-depleted mafic rocks, such as underplated tholeiite. The $\delta^{18}O$ values of the Zone II plutons where slab-melting has been proposed for the high-^{87}Sr granitoids and those of the Zone Va Tono-Kesengawa plutons are not particularly high but close to the average plots for the Kitakami granitoids. The $\delta^{18}O$ values are relatively high in the K-alkalic Hinomiko and calc-alkaline Hitokabe plutons. Oxidized and K-rich metasomatized upper mantle may be needed to produce such a potassic magma at the Hinomiko body, but mafic igneous source rocks with intercalated terrestrial sediments may be enough to generate the calc-alkaline magma of the Hitokabe pluton.

The Abukuma granitoids generally belong to ilmenite series and their initial Sr isotopic ratios are around 0.70518. Their $\delta^{18}O$ values are higher than those of the Kitakami granitoids. The Abukuma granitoids of the western zone where metamorphic grade of the intruded rocks are higher than in the eastern zone, have slightly higher $\delta^{18}O$ values than in the eastern zone. The two-mica granites of the western zone have the highest $\delta^{18}O$ values and are least in magnetic susceptibility. These granites have the largest amount of sedimentary components of terrestrial origin in their protolith, while the other quartz diorite - granodiorite has had predominantly mafic igneous rocks in their source region.

Keywords: Northeast Japan, granitoids, Cretaceous, $\delta^{18}O$ values, magnetite series, ilmenite series, K-alkalic, Na-alkalic

1. Introduction

Oxygen isotopic compositions of the largest batholith unit in the Inner Zone of Southwest Japan were reported in Ishihara and Matsuhisa (2002). This paper describes $\delta^{18}O$ values of plutonic rocks of the second largest batholith unit in Northeast Japan, which includes those of the Kitakami Mountains and Abukuma Highland, to complete the genetic consideration on the Cretaceous granitoids of Japan. The studied rocks are the freshest samples available on surface. The analytical methods are the same as those described in Ishihara and Matsuhisa (2002). Some samples from the Abukuma Highland were analyzed by both the Geological Survey of Japan and the Chinese Academy of Geological Sciences. The results of the latter laboratory were slightly higher than those of the former institute (see Table 2).

2. Granitoids of the Kitakami Mountains

The Kitakami Mountains are underlain by Carboniferous to Jurassic sedimentary rocks with fragments of old granitic and metamorphic basement in the southern part, and by Jurassic to Cretaceous accretionary complexes in the northern part, bounded by the Hayachine Tectonic Zone, which are named as Southern Kitakami Belt, and Northern Kitakami and Iwaizumi Belts. Early Cretaceous plutonic rocks intrude into these sedimentary rocks. Coeval volcanic rocks and porphyries occur locally. The above rocks are intruded by Paleogene felsic dikes and plugs (Kanisawa *et al*., 1989).

The plutonic rocks are mostly quartz diorite, tonalite and granodiorite in composition. Granite (sensu stricto) and gabbroids are small in amount. The region is the only place in Japan where the quartz diorite line of Moore (1959) can be drawn. The plutonic rocks belong to essentially magnetite series but converted to

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ilmenite series at their margins where the granitic magmas interacted with sedimentary wall rocks (Ishihara *et al.*, 1985). The plutonic rocks are divided into calc-alkaline suite and local K-alkaline suite. The former is subdivided into high-^{87}Sr, low-^{87}Sr and intermediate series. The high-^{87}Sr rocks are characterized by SiO_2 more than 61 wt.%, high Na_2O but low K_2O, slightly high Al_2O_3, and rich in Sr and Ga but poor in Rb, Pb and Y (Tsuchiya and Kanisawa, 1994; Tsuchiya *et al.*, 2000). Thus, the high-^{87}Sr series are similar to high-Al TTG (tonalite-trondhjemite and granodiorite).

The plutonic rocks of the Kitakami Mountains are divided into 6 zones from Zones I to VI and the Zone VI further subdivided into VIa and VIb (Katada, 1974), as shown in Fig. 1. We further subdivide the Zone V into highly magnetic Va (Tono-Kurihashi, Goyozan) in the east and low to intermediate magnetic Vb in the west (Hitokabe and Senmaya). Those of the Zones I, II and V belong to calc-alkaline suite, in which the high-^{87}Sr and intermediate-series rocks occur largely in the Zone II plutons, such as Hashigami, Tanohata and Miyako and locally in the Zone Va plutons of Tono, Kurihashi and Goyozan (Tsuchiya and Kanisawa, 1994; Tsuchiya *et al.*, 2000). Similar high-^{87}Sr granitoids are also found in the Ganidake stock related to intense magnetite and copper mineralizations (Ishihara and Murakami, 2004).

The plutonic rocks of the Zones III, IV and VI are composed of gabbroids and granitoids, and are K-rich alkalic locally in the Zones III and VIb, which can be called as shoshonite (Tsuchiya *et al.*, 2000). These rocks are not modally quartz deficient but shown by K-feldspar > quartz characteristic (Ishihara and Suzuki, 1974). In the largest Orikabe pluton of the Zone VIb, the major K-feldspar > quartz Orikabe type was intruded successively by the central quartz > K-feldspar Sasamori type (Ujiie, 1989).

The initial Sr isotopic ratios of the above plutonic rocks are low, being 0.7043 and 0.7045 for the gabbroids and 0.7042 - 0.7049 for the granitoids (Shibata and Ishihara, 1979). Recent studies indicate 0.70355 for the Hashigami pluton (Fujimaki *et al.*, 1992), 0.70416 and 0.70451 for the Tono pluton, 0.70431 for the Kesengawa pluton, 0.70445 for the Senmaya pluton, and 0.70435 for the Tabashine pluton (Maruyama *et al.*, 1993). The initial Sr isotopic ratios were found to be as low as 0.70392 ± 0.00007 at 119 Ma, on the Orikabe-type of the Orikabe pluton but the Sasamori type had somewhat higher values as 0.70419 - 0.70428 (Ujiie-Mikoshiba *et al.*, 2004).

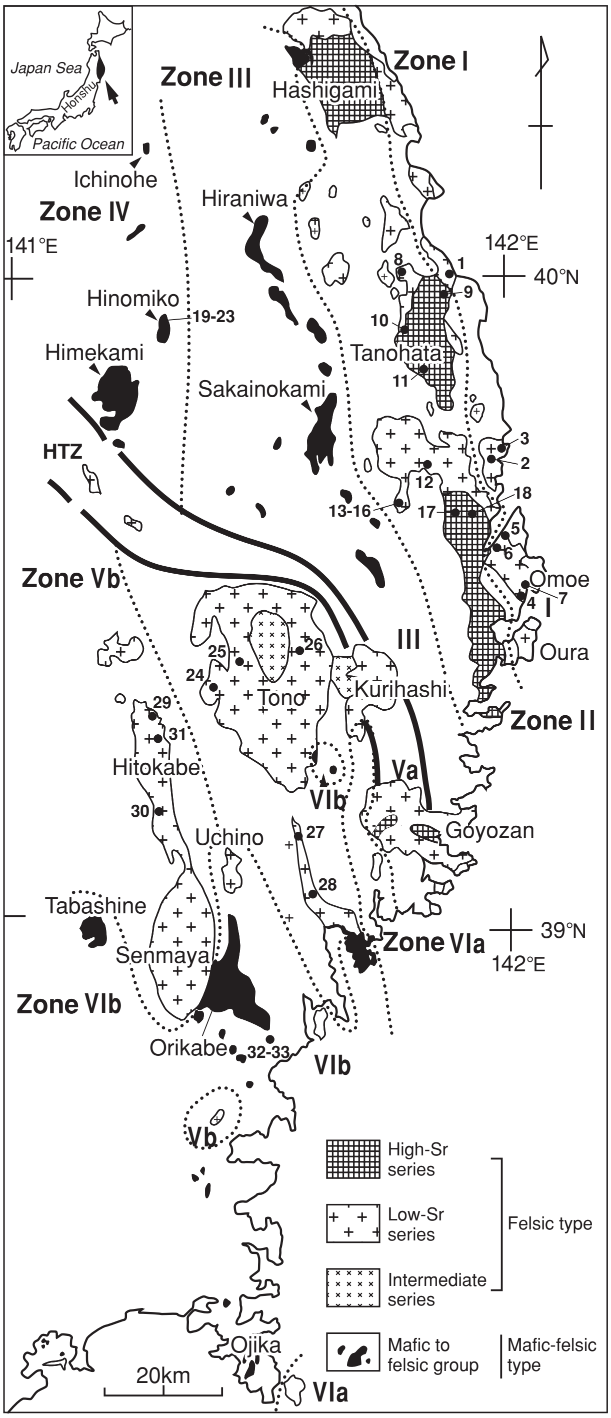

Fig. 1 Distribution of the Early Cretaceous plutonic rocks and the analyzed sample localities in the Kitakami Mountains. Zone division and rock types of the granitoids after Katada (1974) and Tsuchiya and Kanisawa (1994). The sample numbers 1 to 33 correspond to those of Table 1.

3. O Isotopes of the Kitakami Granitoids

Oxygen isotopic values, $\delta^{18}O$ (‰) relative to SMOW, of the Kitakami granitoids are listed in Table 1. Among the Zone I granitoids, those of the Taro and Omoe plutons were analyzed on the samples studied previously by Kanisawa (1974) and Ishihara (1973), respectively. They vary from 5.1‰ (68.0% SiO_2) to 8.5‰ (76.3% SiO_2), placed on the lowest level in the Kitakami Mountains, and are plotted around the Hachijo-jima tholeiite trend (Fig. 2), which may be the most juvenile magma trend (Matsuhisa, 1979). The next

Table 1 Locality, rock types and analytical results of the Early Cretaceous granitoids in the Kitakami Mountains.

Nos.	Pluton & locality	Rock type	SiO_2 (%)	$\delta^{18}O$(‰)	MS
Zone I					
1, 79K127	Otanabe, Mitsune mine, Fudai, Shimohei	vf bt aplitic granite	76.3	8.5 (YM)	122
2, SK0405	Taro, Lower Taro river, Taro, Shimohei	f hb-bt granodiorite	67.7	6.8 (CA)	n.d.
3, SK0403	ditto, Koshida, Taro, Shimohei	f hb-bt granodiorite	68.0	5.1 (CA)	n.d
4, 70K99	Omoe, Hei Peninsula S, Kawashiro, Miyako	f bt-bearing actinolite quartz gabbro	54.0	5.4 (YM)	683
5, 70K104	ditto, ditto, Shirahama, Miyako	m bt-hb granodiorite	65.8	7.4 (YM)	1033
6, 70K103A	ditto, Hokuto mine, 500m W, Miyako	f hb-bearing bt granodiorite	72.2	6.8 (YM)	379
7, 70K100	ditto, Hei Pen. S, Kanpu-toge, Miyako	m bt monzogranite (porphyritic)	74.4	6.7 (YM)	321
Zone II					
8, Moi-4	Tanohata, Shigei, Tanohata	m bt-hb quartz diorite, foliated, “Kawaguchi”	55.5	7.7 (YM)	n.d.
9, Ochi-3	ditto, Ochiai, Tanohata,	m hb-bt granodiorite, “Moichi”	63.4	7.8(YM)	n.d.
10, Hoso	ditto, Hosozawa, Tanohata,	c hb-bt leucogranodiorite, “Hagyu”	66.8	8.1(YM)	n.d.
11, Sawa	ditto, Sawanaka, Iwaizumi, Shimohei	c bt leucogranoiorite, “Otomo”	70.3	8.1 (YM)	n.d.
12, 70K114	ditto, Kamegasawa, 1 km E ,Yamaguchi mine	f hb-bt granodiorite	67.6	8.2 (YM)	217
13, KT627C	Miyako, Kitayamazawa, 0.8 km from the mouth	m bt-hb tonalite	56.6	11.0 (YM)	22
14, KT628B	ditto, Kitayamazawa, 0.5 km from KT627	m bt-hb tonalite	62.8	9.2 (YM)	46
15, KT629	ditto, ditto, 0.7 km NNE of KT628	m hb-bt tonalite	63.2	8.5 (YM)	280
16, KT630	ditto, Kitayama, 0.5 km NNE of KT628	c hb-bt tonalite	61.7	8.5(YM)	840
17, KT639	ditto, 1 km west of Iwafune, Miyako	c hb-bt tonalite	63.4	7.7 (YM)	1280
18, KT640	ditto, Ota, Miyako	c hb-bt tonalite	64.4	8.3 (YM)	1100
Zone IV					
19, K339	Hinomiko, Shirakaba, Iwate-cho, Iwate	m bt-cpx gabbro	51.2	8.6 (CA)	1160
20, K806	ditto, Shirakaba, Iwate-cho, Iwate	m hb-bt-cpx gabbro	51.8	8.8 (CA)	n.d.
21, K338	ditto, Shirakaba, Iwate-cho, Iwate	m ol-bt-cpx gabbro	53.0	8.8 (CA)	1084
22, K807	ditto, Hinomiko, Iwate-cho, Iwate	m tremolite-bt-hb quartz monzodiorite	64.3	9.1 (CA)	n.d.
23, K343	ditto, Hinomiko, Iwate-cho, Iwate	m bt-hb quartz monzodiorite	64.4	9.5 (CA)	654
Zone V					
24, 70K47	Ohgami, Miyamori, Kamihei	m hb-bt quartz diorite	54.1	6.6 (YM)	1117
25, 70K49	ditto, Ohbora, Tono	m bt-hb tonalite	63.2	7.3 (YM)	812
26, 70K79	ditto, Arakawa, Tono	f-m bt monzogranite	72.4	8.2 (YM)	186
27, SK2201A	Kesengawa, Setamai, Sumida, Kesen	m hb-bt granodiorite	57.1	8.8 (CA)	n.d.
28, SK2401	ditto, Motojuku E, Rikuzen-Takata	m cpx-hb-bt granodiorite	65.0	8.2 (CA)	n.d.
29, SK1703	Hitokabe, Yanai-toge, Towa, Waga	m bt-hb quartz diorite	60.7	8.8 (CA)	108
30, SK1512	ditto, Masuwa, Esashi	m hb-bt granodiorite	66.2	9.8 (CA)	53
31, SK1405	ditto, Kanenari-san, Towa, Waga	m hb-bt granodiorite	68.0	10.4 (CA)	178
Zone VIb					
32, S001	Dike, Oya mine area	granodiorite porphyry	53.2	10.8	n.d.
33, H022	Oya mine stock	quartz monzodiorite	56.4	8.4	n.d.

$\delta^{18}O$ and SiO_2 data of nos.8-10 are taken from Kato (1979) and those of nos.32-33 from MITI(2000). Abbreviations: vf, very fine; f, fine; m, medium; c, coarse-grained; ol, olivine; cpx, clino-pyroxene; hb, hornblende; bt, biotite; MS, magnetic susceptibility, x 10^{-6} emu/g (measured H. Kanaya). Analysts for $\delta^{18}O$, YM, Yukihiro Matsuhisa; CA, Chinese Academy of Geological Sciences.

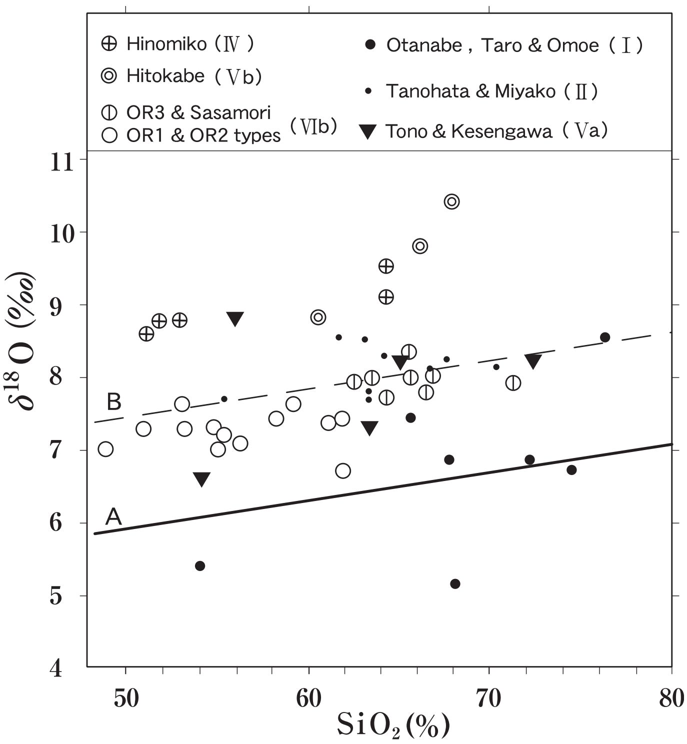

Fig. 2 $\delta^{18}O$ vs. SiO_2 diagram of the plutonic rocks of the Kitakami Mountains. Line A, tholeiitic trend of volcanic rocks in the Hachijo-jima (Matsuhisa, 1979). Line B, boundary line between the magnetite-series and ilmenite-series granitoids of Southwest Japan (see Ishihara and Matsuhisa, 2002). The original data are given in Table 1. Those of OR1, OR2, OR3 and Sasamori types from Ujiie-Mikoshiba *et al.* (2004).

low- $\delta^{18}O$ group is granitoids of the Tono pluton, which range from 6.6 ‰ $\delta^{18}O$ (54.1% SiO_2) to 8.2 ‰ $\delta^{18}O$ (72.4% SiO_2). Sodic granitoids of the four subtypes (Kawaguchi, Moichi, Hagyu and Otomo, Kato 1977) of the Tanohata pluton are slightly higher as 7.7 ‰ $\delta^{18}O$ (55.5% SiO_2) to 8.1 ‰ $\delta^{18}O$ (70.3% SiO_2, Kato, 1979), and are plotted on the boundary line between the magnetite- and ilmenite-series granitoids of Southwest Japan (Fig. 2). The main phases of Miyako pluton (Zone II) and the Kesengawa pluton (Zone Va) are slightly higher as 8.2 to 8.8 ‰ $\delta^{18}O$. The marginal contaminated, ilmenite-series phase of the Miyako pluton (Ishihara *et al.*, 1985) is much higher as 9.2 ‰ $\delta^{18}O$ (KT628B) and 11.0 ‰ $\delta^{18}O$ (KT627C).

Among the calc-alkaline granitoids of the Kitakami Mountains, those of the Hitokabe pluton (Kanisawa, 1969) of the Zone Vb are the highest, ranging between 8.8 ‰ $\delta^{18}O$ (57.1% SiO_2) and 10.4 ‰ $\delta^{18}O$ (68.0% SiO_2), which are least in magnetic susceptibility. K-alkaline rocks of the Hinomiko pluton of the Zone IV (Abe, 1973), which are intruded by high-K andesite dikes (Kanisawa *et al.*, 1994), are similarly high in $\delta^{18}O$ value, varying from 8.6 ‰ $\delta^{18}O$ (51.2% SiO_2) to 9.5 ‰ $\delta^{18}O$ (64.4% SiO_2), and also very high in the magnetic susceptibility.

Ujiie-Mikoshiba *et al.* (2004) reported 19 whole rock analyses from the Orikabe- and Sasamori-type granitoids of the Orikabe pluton, which is also K-alkalic series in the Zone VIb. They pointed out the results changing in the $\delta^{18}O$ values with SiO_2 (see Fig. 2) are almost parallel to the trend of island arc volcanic rocks (line A, Fig. 2).They interpreted that the rocks of OR1 and OR2 were derived through fractional crystallization from a mafic parental magma, while the Sasamori type rocks were derived from a distinct parental magma, suggesting the involvement of a small amount of crustal components in the source. There is a little gap, however, between the OR1-OR2 types and OR3-Sasamori types in details. The average of the OR1 and OR2 types is 7.24 ‰ $\delta^{18}O$ (n=10) at 57.8% SiO_2, while that of the OR3 and Sasamori types is 7.93 ‰ $\delta^{18}O$ (n=9) at 65.5% SiO_2. By modal analyses, Orikabe granitoids have similar plagioclase/K-feldspar ratio but the OR3 and Sasamori types are characterized by higher content of quartz. Thus, the slightly higher $\delta^{18}O$ values are due to the higher contents of modal quartz, implying that the parental magma may be different from that of the OR1 and OR2 types.

4. Abukuma Granitoids and their $\delta^{18}O$ Values

The Abukuma Highland is underlain by regional metamorphic rocks and late Cretaceous granitoids. The granitoids often contain ultra-mafic to mafic blocks and small gabbroic masses. The granitoids are traditionally divided into older and younger (Watanabe *et al.*, 1955). The older granitoids are generally granodiorite in composition, but the younger ones are composed of grey granodiorite, pink granodiorite and granites, grey biotite granite and grey muscovite-biotite granites. Absolute age differences among these granitoids are still unknown. The Abukuma granitoids have generally low magnetic susceptibility equivalent to ilmenite series, but intermediate values are seen to the east beyond the Hatakawa Sheared Zone and locally in the south (see Ishihara, 1990, Fig. 6). Kamei and Takagi (2003) studied the granitoids of the western zone around the Funehiki-Miharu area in detail, and found that the gabbroids are strongly magnetic but the granitoids yielded ilmenite-series values in general, except for the Ishimori-type medium-grained biotite-hornblende tonalite, which has largely magnetic susceptibility values of magnetite- and intermediate-series.

Metamorphic grades of the metamorphic rocks in the studied area (Fig. 3), which is located between N37° 00' and N37° 20' at E140° 30' and E141° 00', are high

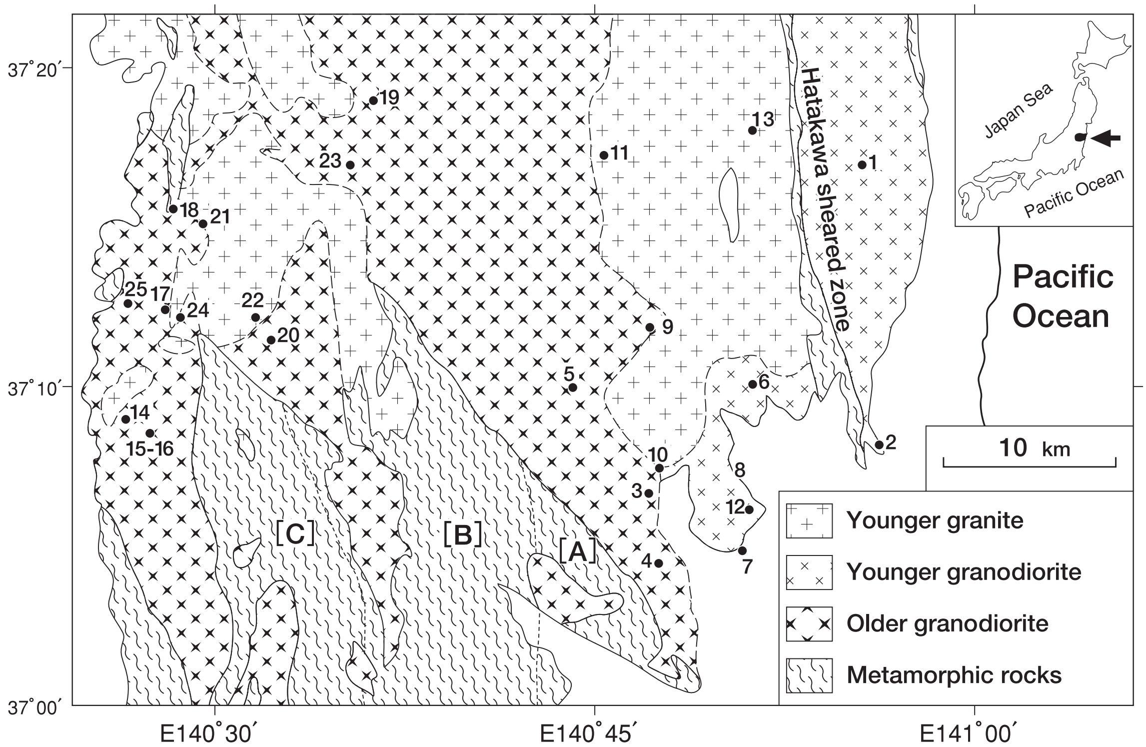

Fig. 3 Distribution of the Late Cretaceous plutonic rocks and the analyzed sample localities in the Abukuma Highland. Simplified from Ishihara *et al.* (1973). The sample numbers from 1 to 25 correspond to those of Table 2. Metamorphic grades of A and B, green schist facies, and C, amphibolite facies of Miyashiro (1958).

in the west (Miyashiro 1958's C zone) and decrease toward east (Miyashiro 1958's A zone). The older granitoids occur in the west-central part but the younger granitoids tend to be distributed in the western and eastern zones (Ishihara *et al.*, 1973). The younger one of the muscovite-biotite granite occurs only in the western zone. These granitoids have low magnetic susceptibility of the ilmenite series, lower than 100 x 10^{-6} emu/g, except for three sample localities (nos. 2, 19, 23, Table 2). The initial Sr isotopic ratios of both the gabbroids and granitoids vary from 0.7052 - 0.7053 (Shibata and Ishihara, 1979). Typical older granitoids of the Ishikawa pluton has the ratio of 0.70518 ± 15 (Shibata and Tanaka, 1987).

The granitoids in the eastern zone vary from 9.0 to 11. 4‰ in δ^{18}O value, except unusually low value (4.1 ‰) of no.2, which may have been interacted with meteoric water during alteration that the rock received. The δ^{18}O values of the granitoids with hornblende and biotite assemblages from the western zone vary from 8.9 to 11.5‰. Thus there are no clear differences in δ^{18}O value, depending upon so-called "older granites" or "younger granites" , which is very clear on the δ^{18}O - SiO_2 diagram (Fig. 4). High δ^{18}O values are only seen on muscovite-biotite or muscovite-bearing granites in

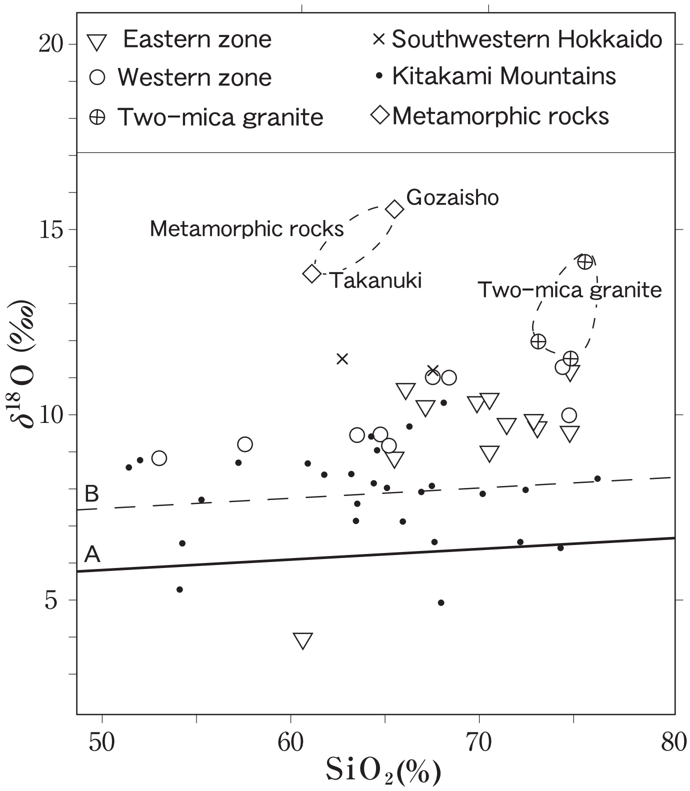

Fig. 4 δ^{18}O vs. SiO_2 diagram of the plutonic rocks in the Abukuma Highland. Lines A and B are the same as in Fig. 2.

Table 2 Locality, rock types and analytical results of the Early Cretaceous granitoids in the Abukuma Highland

Sample no.	Locality	Rock type	SiO_2 (%)	$\delta^{18}O$(‰)	MS
Eastern Zone					
1, 68A51	Otojiro 2.5 km E, Naraha, Futaba	m hb-bt granodiorite	65.9	9.0 (CA)	25
2, TS2610	Tamagawa spring 1 km N, Yotsukura, Iwaki	m bt-hb quartz diorite, altered	60.5	4.1 (CA)	430
3, TS0712	Miwa Interchg. 1.8 km NE, Miwa, Iwaki	m hb-bt granodiorite	65.9	10.8 (CA)	24
4, TS2264	Yabuiri 1 km S, Miwa, Iwaki	m bt-hb granodiorite	67.0	10.4 (CA)	25
5, 68A29	Saiso south, Miwa, Iwaki	m bt-hb granodiorite	68.3	11.0(YM), 11.4(CA)	16
				Average 11.2	
6, TS3052	Yokokawa, Ogawa, Iwaki	f bt-hb granodiorite	70.4	9.2 (CA)	34
7, TS2272	Tsunezumi, Iwaki	m bt-hb granodiorite	69.8	10.5 (CA)	27
8, TS3072	Takahagi 2 km W, Ogawa, Iwaki	m bt-hb granodiorite	70.3	10.6 (CA)	24
9, TS3068	Natsuigawa Gulch, Miwa, Iwaki	f bt-hb granodiorite	71.3	9.9 (CA)	32
10, TS0711	Nakayama 1 km E, Iwaki	m bt monzogranite	73.0	9.9 (CA)	57
11, 68A22	600m W, Yoshimada, Kawamae, Iwaki	m bt monzogranite	73.3	10.0 (CA)	79
12, TS2712	Tagashira, Ogawa, Iwaki	m bt monzogranite	74.6	11.4 (CA)	63
13, 68A48	Kotashiro, Kawauchi, Futaba	vf porphyritic bt monzogranite	75.1	9.8 (CA)	84
Western zone					
14, 68A12	Ishizuka south, Ishikawa	m bt-hb diorite-gabbro “Kuromikage”	52.5	8.9 (CA)	30
15, 68A01	Town office site, Ishikawa	f hb-bt granodiorite, foliated	57.7	9.3 (CA)	25
16, 68A04	ditto,	f hb-ms-bearing bt granodiorite dikelet	74.3	10.2 (CA)	21
17, 68A36	Kitanoyado, Hirata, Ishikawa	m hb-bt granodiorite, foliated	63.2	9.6 (CA)	36
18, 68A41	Yamagoya SE 500m, Sukagawa	f hb-bt granodiorite, foliated	64.4	9.3 (YM), 9.8(CA)	24
				Average 9.6	
19, 68A25	Yukusada, Ono, Tamura	f titanite-bearing hb-bt granodiorite	65.4	9.3 (CA)	364
20, 68A37	Kusaba, Hirata, Ishikawa	m hb-bt granodiorite foliated	66.9	11.2 (CA)	20
21, 68A40	Yamagoya 2 km SE, Daito	m hb-bt granodiorite	68.1	11.2 (CA)	22
22, 68A38	Aoi-zawa, Hirata, Ishikawa	f ms-bearing bt monzogranite, foliated	73.1	11.8 (YM), 12.4(CA)	20
				Average 12.1	
23, 68A18	Nishida, Ono, Tamura	vf bt monzogranite, foliated	74.8	11.5 (CA)	144
24, 68A34	Ohki quarry, Rokutannda, Tamagawa, Ishikawa	f ms-bt monzogranite	75.2	11.7 (CA)	16
25, 68A35	Kanisawa, Tamagawa, Ishikawa	m ms-bt monzogranite	75.3	14.2 (YM), 14.4 (CA)	14
				Average 14.3	
Southwestern Hokkaido					
26, 74HK99	Raruishi, Kitahiyama, Hokkaido	f-m hb-bt granodiorite	62.5	11.6 (CA)	15
27, 74HK110	Nicchube, Kitahiyama, Hokkaido	f-m hb-bt granodiorite, porphyritic	67.3	11.3 (CA)	12
Metamorphic rocks of the Abukuma Highland					
28, ABTM	Takanuki metamorphic rocks, average		60.8	13.9 (YM)	n.d.
29, ABGM	Gozaisho metamorphic rocks, average		65.0	15.7 (YM)	n.d.

Abbreviations: vf, very fine; f, fine; m medium; c, coarse-grained; hb, hornblende; bt, biotite; ms, muscovite; MS, magnetic susceptibility, x 10^{-6} emu/g (measured H. Kanaya). Analysts for $\delta^{18}O$, YM, Yukihiro Matsuhisa; CA, Chinese Academy of Geological Sciences.

the western zone, which vary between 11.7 and 14.3 ‰. Muscovite-hornblende-bearing granodiorite (no. 16) of a dikelet (15 cm wide) with irregular form, whose muscovite may be subsolidus product, has a $\delta^{18}O$ value 0.9‰ higher than the host diorite-gabbro with 9.3 ‰ $\delta^{18}O$ (no. 15).

Ilmenite-series granitoids with hornblende-biotite assemblages are exposed in the southwestern Hokkaido, and are considered as the northern extension of the Abukuma granitoids for the magnetite-free character (Ishihara, 1979). Two samples from this area (nos. 26 and 27, Table 2) give an average $\delta^{18}O$ value of 11.5‰ at SiO_2 64.9%, while the average of 4 granodiorites from the western zone (nos. 17-20, Table 2) is calculated to be 9.9‰ at SiO_2 65.0%.Thus, a regional heterogeneity is clearly seen.

The powdered metamorphic rock samples used in the studies of Ishihara *et al*. (1973) were mixed and aver-

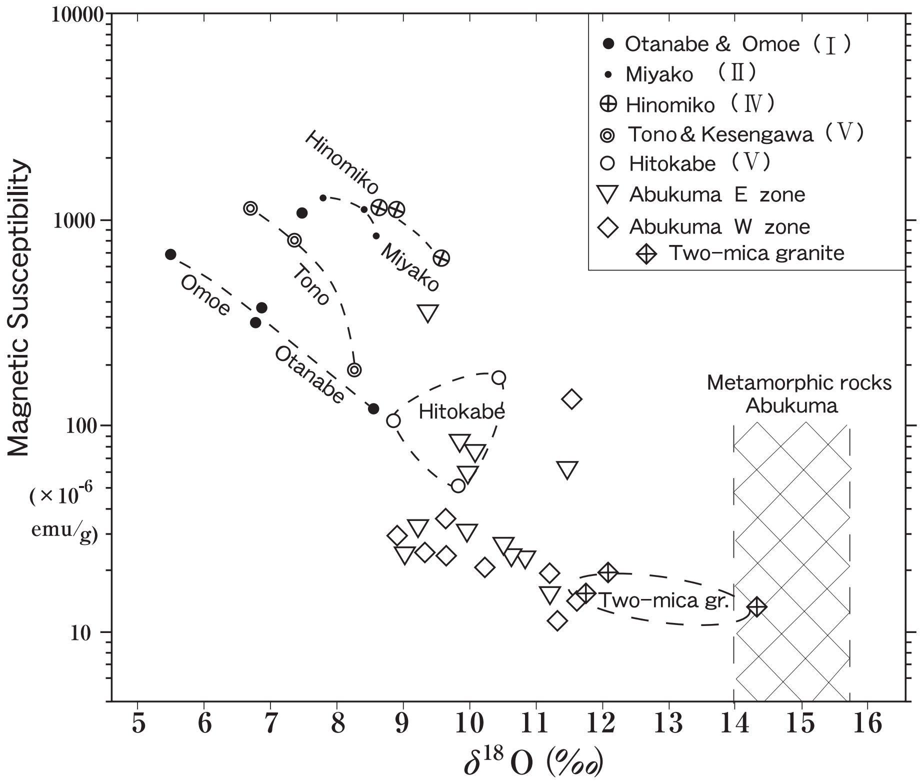

Fig. 5 δ^{18}O vs. magnetic susceptibility diagram of the granitoids in the Kitakami Mountains and Abukuma Highland. For the Miyako pluton, the main phase of KT630, 639 and 640 is plotted.

aged for the Gozaisho and Takanuki Groups, which have been known to be generally mafic igneous and pelitic in composition, respectively. They have δ^{18}O values of 15.7‰ and 13.9 ‰ δ^{18}O, respectively (Table 2), the former of which is somewhat lower than the δ^{18}O value of 18.5‰ of the pelitic gneiss in the Ryoke Belt of the Chubu District (Ishihara and Matsuhisa, 2002), and 15.9 ‰ δ^{18}O of the late Paleozoic to Cretaceous shales of the accretionary complex in the Outer Zone of Southwest Japan (Ishihara and Matsuhisa, 1999).

5. Oxygen Isotopic Constraints on the Magma Geneses

As shown in Fig. 4, the Abukuma granitoids are higher in δ^{18}O values than the Kitakami granitoids. Clear difference between the two terrains is whether magnetite is absent or present in these granitoids, which is very well shown by their magnetic susceptibility (Kanaya and Ishihara, 1973; Ishihara, 1979). The granitoids are generally magnetite-bearing with sporadic magnetite-free values in the Kitakami Mountains, while in the Abukuma Highland, they are ilmenite series in most places with intermediate values in the eastern block bounded by two fault zones of the Hatakawa and the Futaba (Ishihara, 1990), and drill cores from further east at the Matsukawa-ura are composed of oxidized tonalites (Abe and Ishihara, 1985).

Figure 5 shows a clear inverse correlation of the δ^{18}O values against the magnetic susceptibility. It is evident that most of the Abukuma granitoids are high in δ^{18}O value, but low in magnetic susceptibility, while the Kitakami granitoids are low in δ^{18}O value but high in magnetic susceptibility; the relationship commonly observed in the Inner Zone of Southwest Japan (Ishihara and Matsuhisa, 2002). The most probable source for the ^{18}O-enrichment may be sedimentary rocks and their metamorphic equivalents in the granitoid geneses (Matsuhisa *et al.*, 1972). Contribution of these materials can be considered to the Abukuma granitoids.

In the Kitakami Mountains, Tsuchiya and Kanisawa (1994) proposed a genetic model that the high-^{87}Sr granitic magmas were formed by partial melting of hot MORB (Mid-Oceanic Ridge Basalt), plus 5% altered MORB, plus 5% sediments, leaving garnet, clinopyroxene, quartz, rutile and apatite as restite at depth of 2.0 - 2.2 GPa (70-80 km). The low-^{87}Sr series rocks with some mafic rocks are considered derived from partial melting of lower crust. K-alkalic rocks of Hinomiko and Ichinohe plutons of the Zone IV are considered as partial melting products in the upper mantle for Mg-rich cumulates associated.

In the magnetic susceptibility vs. $\delta^{18}O$ values diagram (Fig. 5), plutonic rocks of the Hinomiko pluton are very high in magnetic susceptibility, hence magnetite content, and also high in the $\delta^{18}O$ values. Both K-feldspar and biotite are always present in these rocks and the K_2O contents range from 2.6 to 4.1 wt. % with SiO_2 51.2 to 64.4% (Abe, 1973). To produce an oxidized and potassic magma, oxidized and K-rich protolith are required. Such metasomatized upper mantle may have existed during the Cretaceous time underneath the Hinomiko body.

The low-^{87}Sr rocks are distributed widely in the magnetic susceptibility vs. $\delta^{18}O$ values diagram, implying that these rocks were originated in a variety of the source rocks. The granitoids of the Zone I are least in $\delta^{18}O$ values. Tholeiitic rocks are generally low to this level (Matsuhisa *et al.*, 1973), so that these magmas may have been originated in tholeiitic basalts once underplated in the lower continental crust, and generated by partial melting with aid of volatiles squeezed out from the subducting MORB. On the other hand, granitoids of the Hitokabe pluton have relatively high $\delta^{18}O$ values and low magnetic susceptibility. They are meta-aluminous rocks containing no sedimentary but mafic enclaves (Kanisawa, 1969). These granitic magmas are considered generated in meta-igneous rocks intercalating some sedimentary layers within the middle-lower continental crust.

In the Abukuma Highland, the majority of the granitoids is ilmenite-series granodiorite and monzogranite, among which muscovite-biotite variety has the highest $\delta^{18}O$ values and are least in magnetic susceptibility (Fig. 5). This rock contains per-aluminous minerals such as muscovite and garnet. This rock may therefore have originated in the continental crust containing pelitic components. In the Inner Zone of Southwest Japan, such a rock was identified to have sedimentary components up to 57 wt.% in their protolith (Ishihara and Matsuhisa, 2002).

Using trace elements data, Kamei and Takagi (2003) postulated in the Funehiki-Miharu area of the western zone that relatively mafic quartz diorite to granodiorite were generated by partial melting of basaltic lower crust under 1 GPa pressure, leaving amphibole or garnet/plagioclase containing restite. Similar rocks in our studied area are high in $\delta^{18}O$ value but contain no sedimentary but mafic granular enclaves. Thus we propose a mixed protolith of mafic igneous and sedimentary rocks, in which the igneous-dominant part formed tonalite-granodioritic magmas, while the sediment-dominant portion produced the muscovite-biotite and/or biotite granitic magmas.

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* J, in Japanese; JwE, in Japanese with English abstract.

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東北日本の白亜紀花崗岩類の成因に対する酸素同位体組成からの束縛条件

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要　旨

北上山地と阿武隈高地に産出する白亜紀花崗岩類の酸素同位体比（$\delta^{18}O_{SMOW}$）を48個の全岩試料について新たに報告するとともに，既存値10個とあわせて花崗岩類の起源に関する考察を行った．

北上山地の白亜紀前期の花崗岩類は主に磁鉄鉱系に属し，低いSr同位体比初生値（0.70363-0.70463）を持つ．$\delta^{18}O$値はI 帯の花崗岩類で最も低く，この花崗岩類が^{18}O に枯渇したソレアイト系苦鉄質岩類の部分溶融によって発生した可能性を暗示する．II 帯や Va 帯の花崗岩類には高^{87}Sr岩類が認められており，その起源に沈み込む海洋地殻の部分溶融が示唆されている．変質海洋地殻が溶融すれば高い$\delta^{18}O$ も期待できるが，II 帯の値は北上山地で平均的なもので特に高くはない．カリウム質の日神子岩体とカルクアルカリ岩系の人首岩体からはやや高い値が得られた．日神子岩体の諸岩石は酸化的でKに富むから，そのような起源物質が上部マントル レベルで必要であり，人首岩体は主にやや還元的なカルクアルカリ岩であるから，その起源物質には大陸地殻下部の若干の堆積岩を含む苦鉄質岩類が考えられる．

阿武隈高地の花崗岩類は主にチタン鉄鉱系に属し，そのSr同位体比初生値は北上山地よりやや高く0.70518前後である．$\delta^{18}O$値は北上山地に於ける値よりも全般的に高く，花崗岩系列の相違と一致し，その起源に大陸地殻の堆積性物質の混在が推察される．被貫入岩類の広域変成度が高い西列の花崗岩類は東列のものよりもやや高い$\delta^{18}O$値を持つ．西列の両雲母花崗岩は最も高い$\delta^{18}O$値を持ち，この花崗岩類の起源に^{18}Oに富む大陸地殻起源の堆積岩類の比率が最も高く，他の石英閃緑岩-花崗閃緑岩類は主に苦鉄質火成岩起源であったことを示している．