Effect of subduction components on production of basalts from Tateshina volcano, central Japan: geochemical calculation of dehydration of subducting oceanic crust and partial melting of overlying sediments, and subsequent fluid-mantle interaction

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We report the major and trace element chemistry and Sr and Nd isotopic composition of basaltic rocks from the Quaternary Tateshina volcano, central Japan, and model the composition of these rocks in terms of the partial melting and melt–solid reactions controlled by the addition of slab-derived fluid and silicate melt to the original wedge mantle beneath the Tateshina area. Tateshina basaltic rocks have a SiO₂ content ranging from 50.06 to 53.28 wt% and a MgO content ranging from 5 to 7 wt%, indicating that these rocks are less fractionated. These rocks have a narrow range of Sr and Nd isotopic compositions ($^{87}\text{Sr}/^{86}\text{Sr} = 0.703619\text{--}0.703807$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.512893\text{--}0.512945$). There is no correlation between Tateshina basaltic rocks and crustal materials in terms of $^{143}\text{Nd}/^{144}\text{Nd}\text{--}\text{Sm}/\text{Nd}$, indicating that Tateshina basaltic rocks have no crustal contamination. The wedge mantle peridotite would have experienced accumulated subduction events, including the addition of subduction components and the extraction of basalt magmas during the Tertiary period. In addition, we have accounted for the mantle motion accompanying slab subduction within the wedge mantle. Thus, we assumed that the mantle wedge before the effects of Quaternary subduction that produced the volcanic rocks of Tateshina volcano could have blended with residual mantle after the extraction of Tertiary basalt magmas with depleted MORB-source mantle (DMM).

The model includes partial melting of the blended wedge mantle peridotite metasomatized by aqueous fluid and silicate melt derived from the dehydration of altered oceanic crust (AOC) and partial melting of oceanic sediments, respectively. The trace element and Sr isotope compositions of the basaltic rocks of Tateshina volcano can be reproduced by about 10% melting of the calculated wedge mantle peridotite modified by the addition of 0.8%–1.0% silicate melt from oceanic sediments and 0.2%–0.8% aqueous fluids from the AOC, respectively.

Keywords: Ba/Th, Subduction component, Oceanic sediment, Altered oceanic crust (AOC), Trace element geochemistry, Isotope geochemistry

INTRODUCTION

Subduction zones are some of the most active volcanic regions on Earth and are important sites of continental material recycling. The melting of mantle wedge peridotite is triggered by aqueous fluid released from the subducting slab (Tatsumi, 1989).

It is generally accepted that basaltic magmas produced in subduction zones are characterized by a high

content of large-ion lithophile elements (LILEs) in comparison with the content of high-field-strength elements (HFSEs) (Gill, 1981; Pearce, 1982; Hawkesworth et al., 1993). This is because HFSEs are relatively immobile in aqueous fluids but more mobile in slab melts. The high LILE/HFSE ratio in subduction-zone basaltic magmas is mainly attributed to the modification of their mantle wedge source by the addition of LILEs through the aqueous fluids released from the down-going slab (e.g., Hawkesworth et al., 1997a and 1997b).

Some authors have argued that some of the radio-

genic isotope and trace element features of arc basaltic rocks are caused by the presence of elementally and isotopically fertile peridotite in the mantle wedge, which is unrelated to the subduction process (Kersting et al., 1996; Gust et al., 1997). However, a great number of detailed studies involving trace elements and isotopes of arc basaltic rocks have revealed the important contribution of LILEs from the subducting altered oceanic crust and overlying sedimentary cover to the mantle wedge (e.g., Morris et al., 1990; Plank and Langmuir, 1993; Reagan et al., 1994; Ryan et al., 1995; Elliott et al., 1997; Hawkesworth et al., 1997a, 1997b; Hoogewerff et al., 1997; Ishikawa and Tera, 1997; Turner et al., 1998; Tatsumi and Hanyu, 2003; Moriguti et al., 2004). The altered oceanic crust (AOC) and overlying sedimentary cover, which make up the subducting slab, have been regarded as principal sources of material flux that have modified the composition of the mantle peridotite beneath each arc. These two components have strikingly distinct isotopic signatures: the AOC has depleted $^{87}\text{Sr}/^{86}\text{Sr}$ (0.703636; Staudigel et al., 1995), while subducting sediments have enriched $^{87}\text{Sr}/^{86}\text{Sr}$ such as 0.7173 (value for global subducting sediment (GLOSS); Plank and Langmuir, 1998).

In order to understand the mechanism behind magma generation at subduction zones, several significant questions need to be resolved: (1) Is the metasomatizing component an aqueous fluid, a silicate melt, or a mixture of the two? (2) Do the aqueous fluids or silicate melts originate from the AOC, the overlying sediments, or both? And (3) what degree of wedge mantle metasomatization occurs from the subducting AOC and overlying sediments?

In this paper, we present new major and trace element chemistry data and Sr and Nd isotope data for the basaltic rocks of the Quaternary Tateshina volcano, which is part of the Yatsugatake volcanic chain found at the junction of the northeastern Japan Arc and the Izu-Mariana Arc. These basaltic rocks have the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ ratios among Quaternary volcanic rocks from the Yatsugatake volcanic chain and the surrounding areas, suggesting that these basaltic rocks could be suitable for an investigation of the magma generation at Tateshina volcano. We use these data to constrain the effect and degree of the subduction component signature for the generation of the basaltic magmas of Tateshina volcano.

GEOLOGICAL AND TECTONIC BACKGROUND OF TATESHINA VOLCANO

In the circum-Pacific region, the northeastern Japan Arc is well suited to investigations on the mechanism behind subduction-related magmatism for several reasons: First,

significant amounts of seismic tomography data have revealed the regional subducting structure in the mantle wedge (Zhao et al., 1990; Zhao et al., 1992; Wang and Zhao, 2005). Second, a large amount of geochemical data on the volcanic rocks is available (e.g., Gust et al., 1997; Shibata and Nakamura, 1997). And third, remarkable along-arc Sr and Nd isotopic variations for the volcanic rocks have been recognized; the Quaternary volcanic rocks from the northern part of the northeastern Japan Arc have depleted Sr and Nd isotopic compositions ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70311\text{--}0.70495$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.512798\text{--}0.512945$), whereas those from the southern part of the northeastern Japan Arc are isotopically enriched ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70391\text{--}0.71528$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.512224\text{--}0.512764$) (Notsu, 1983; Togashi et al., 1992; Kersting et al., 1996; Gust et al., 1997; Kimura et al., 2001; Kobayashi and Nakamura, 2001; Kimura et al., 2002).

The Yatsugatake volcanic chain, consisting of several Quaternary volcanoes, is situated in the central part of the Fossa Magna, at the junction of the northeastern Japan Arc and the Izu-Mariana Arc (Fig. 1). However, on the basis of Figure 3 in Syracuse and Abers (2006), the volcanic chain can be treated as the back-arc volcanic chain of the Izu-Mariana Arc. This suggests that the Yatsugatake volcanic chain might have been the result of the westward subduction of the Pacific Plate underneath the North American Plate. The depth of top of slab beneath the Tateshina volcano, belonging to the northernmost part of the Yatsugatake volcanic chain, is 160–170 km (Fig. 1), and this depth corresponds to Tatsumi's (1989) back-arc side dehydration depth.

The volcanic rocks from Tateshina volcano are mainly found on the eastern flank of the Itoigawa-Shizuoka tectonic line. The bending of Honshu caused by the opening of the Japan Sea resulted in development of the Fossa Magna at 15 Ma (Otofuji et al., 1994). The beginning of the uplift of the Fossa Magna was triggered by the eastward drift of Japan, resulting in the collision of the Izu Arc with central Honshu (Matsuda, 1978). Local uplift of the entire Fossa Magna started at ~ 8 Ma. The central to northern part of the Itoigawa-Shizuoka tectonic line forms an active fault system that has one of the largest slip rates (4–9 mm/y) recorded in Japan (Ikeda et al., 2002). The Tateshina area is placed under WNW-ESE horizontal compressive stress (Tsukahara and Ikeda, 1991).

Tateshina volcano is located above a continental crust composed of a thin lower crust (about 17 km in thickness) and a relatively thick upper crust (about 19 km in thickness) (Zhao et al., 1992) and is situated above a crack along with an axial-plane fold (Kawachi, 1979). This suggests that the chemical compositions of the basal-

Figure 1. Map of the central part of Japan mainland, showing the regional tectonic structure, the compilation of minimum $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for the basaltic rocks in each volcano, contours of the depth of the upper surface of the Pacific Plate (broken line), and the Philippine Sea Plate (solid line) (Ishida, 1992).

tic rocks of Tateishina volcano may not have been modified by lower crustal contamination, which may be supported by their low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. In contrast, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of volcanic rocks from central Japan and the southern part of northeastern Japan are high (Fig. 1). Thus, these basaltic rocks could be suitable for an investigation of magma generation considering the slab component contribution and not lower crustal contamination.

GEOLOGY OF TATESHINA VOLCANO AND K-Ar AGES OF VOLCANIC ROCKS

The volcanic rocks from Tateishina volcano range from basalt and andesite to dacite. Lithologically, the volcanic rocks can be divided into six groups, which are (in ascending order) Tatamiishi andesite (TA andesite), Kasuga basalt (KA basalt), Kyowa andesite (KYO andesite), Ryugamine andesite (RYU andesite), Tateishina basalt (TS basalt), and Futago dacite (FT dacite). Dykes (composed mainly of basalt) cut the KA basalt. This stratigraphic division is almost in agreement with that of Nakamura (1991) and Takahashi and Nishiki (2006).

TA andesite lava flows are 50–100 m thick with well-developed platy joints. KA basalt is composed of

several lava flows, volcanic breccias, and tuff breccias, with a total thickness of more than 200 m. The KYO and RYU andesites consist of several lava flows with well-developed platy joints every few centimeters and a total thickness of more than 70 m. TS basalt crops out as several massive lava flows with a total thickness from 50 to 70 m. FT dacite is also found as massive lava flows with a total thickness more than 80 m.

Kawachi (1998) and Terao (2001) reported K-Ar ages of 1.10 ± 0.02 Ma and 1.28 ± 0.09 Ma for TA andesite. Kaneoka et al. (1980) and Kaneoka and Kawachi (1983) reported K-Ar ages of 1.04 ± 0.02 Ma, 1.04 ± 0.09 Ma, 1.03 ± 0.02 Ma and 1.11 ± 0.06 Ma for four samples of KA basalt. Kawachi (1998) reported K-Ar ages of 1.00 ± 0.03 Ma for RYU andesite.

PETROGRAPHY OF TATESHINA BASALTIC ROCKS

Wilcox (1954) defined phenocrysts as being more than 0.03 mm in size and consisting of phenocrysts (>0.3 mm) and microphenocrysts (0.03–0.3 mm).

KA and TS basalt flows and dykes contain 18.1–29.2 vol% phenocrysts (Table 1) composed mainly of olivine

Table 1. Major and trace element compositions, Sr and Nd isotope compositions of basalts from Tateshina volcano

Sample No	031010-2	10.12-1	Dyke1	Dyke2	Dyke3	9.10-12	9.10-7	031010-16	10.18-3	10.19-1	10.19-2
SiO ₂	51.86	51.07	51.53	51.48	51.59	50.06	53.28	50.89	50.29	50.64	50.51
TiO ₂	1.11	1.28	1.25	1.26	1.26	1.18	1.16	1.21	1.19	1.14	1.11
Al ₂ O ₃	17.62	18.64	17.87	18.00	17.82	18.53	17.35	17.71	18.20	17.89	17.47
FeO*	9.84	9.70	9.84	9.73	9.85	10.25	9.01	10.17	10.16	9.88	9.96
MnO	0.17	0.17	0.17	0.18	0.18	0.18	0.17	0.19	0.18	0.20	0.17
MgO	5.48	5.12	5.13	5.01	5.10	6.14	5.17	5.44	5.86	5.81	6.60
CaO	10.24	9.85	10.64	10.69	10.57	10.14	9.78	10.80	10.45	11.24	11.05
Na ₂ O	2.69	3.05	2.71	2.75	2.74	2.69	2.94	2.67	2.65	2.49	2.44
K ₂ O	0.77	0.79	0.59	0.62	0.61	0.58	0.83	0.69	0.77	0.51	0.48
P ₂ O ₅	0.22	0.32	0.28	0.28	0.28	0.24	0.30	0.23	0.24	0.22	0.21
LOI	0.59	-0.09	1.19	1.15	1.09	0.14	0.95	0.38	-0.24	1.12	0.70
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Sr	524.886	680.246	617.393	620.528	633.237	599.573	626.373	680.298	615.194	584.102	568.019
Y	16.892	16.415	15.464	15.655	16.052	18.246	17.254	15.471	16.970	15.440	15.478
Zr	52.332	65.912	56.667	57.568	58.429	55.088	75.452	53.149	54.352	46.234	45.068
Ba	180.708	193.053	164.675	165.955	169.685	201.023	267.100	199.239	193.877	182.498	159.681
La	7.129	9.077	7.383	7.729	7.758	7.242	9.481	7.228	7.055	5.635	5.706
Ce	17.293	22.527	18.408	18.860	19.164	17.630	23.313	18.189	17.540	14.271	14.461
Nd	12.015	14.990	12.545	13.432	13.171	12.948	15.237	12.387	12.273	10.364	10.256
Sm	2.893	3.588	3.221	3.354	3.330	3.323	3.829	3.031	3.078	2.792	2.694
Eu	1.013	1.224	1.060	1.081	1.103	1.109	1.107	1.038	1.067	0.995	0.990
Gd	3.083	3.533	3.132	3.327	3.208	3.340	3.384	3.060	3.175	2.827	2.930
Tb	0.474	0.500	0.464	0.478	0.489	0.535	0.528	0.479	0.501	0.439	0.438
Dy	2.800	2.834	2.678	2.725	2.715	2.949	2.899	2.557	2.915	2.538	2.608
Ho	0.594	0.576	0.542	0.550	0.542	0.597	0.604	0.534	0.617	0.543	0.539
Er	1.563	1.555	1.511	1.588	1.540	1.647	1.672	1.537	1.627	1.528	1.508
Yb	1.474	1.340	1.304	1.365	1.378	1.527	1.521	1.330	1.498	1.381	1.363
Lu	0.215	0.202	0.196	0.202	0.204	0.230	0.223	0.199	0.224	0.206	0.203
Pb	2.959	3.782	3.470	3.389	3.564	4.261	5.077	4.185	4.192	3.459	3.451
Th	1.006	0.990	0.810	0.822	0.861	0.778	1.132	0.756	0.802	0.584	0.558
U	0.270	0.261	0.242	0.247	0.251	0.232	0.376	0.241	0.244	0.202	0.191
⁸⁷ Sr/ ⁸⁶ Sr	0.703619	0.703701	0.703679	0.703651	0.703740	0.703672	0.703754	0.703657	0.703714	0.703807	0.703697
2σ	0.000009	0.000011	0.000009	0.000010	0.000010	0.000006	0.000011	0.000013	0.000009	0.000014	0.000010
¹⁴³ Nd/ ¹⁴⁴ Nd	0.512901	0.512914	0.512927	0.512927	0.512925	0.512915	0.512910	0.512945	0.512893	0.512918	0.512926
2σ	0.000011	0.000010	0.000007	0.000008	0.000008	0.000012	0.000008	0.000009	0.000012	0.000014	0.000014
Mode (vol%)	47.0	29.6	27.2	32.4	29.1	24.2	18.1	38.6	48.9	32.6	31.6
Ol	3.0	0.5	3.6	3.6	3.1	3.0	2.8	3.2	5.8	7.0	5.4
Cpx	6.6	5.3	2.2	1.8	1.8	0.8	1.6	4.4	6.2	1.0	3.4
Opx	-	-	-	-	-	0.1	-	-	-	-	-
Pl	36.1	23.0	21.4	27.0	24.2	20.3	13.7	30.2	35.7	24.5	22.8
Fe-Ti oxide	1.3	0.8	-	-	-	-	-	0.8	1.2	0.1	-

Major element compositions are shown on an anhydrous basis.

FeO* = FeO + 0.9 × Fe₂O₃.

LOI., loss on ignition; Ol, olivine; Cpx, clinopyroxene; Opx, orthopyroxene; Pl, plagioclase.

(<7.0 vol%), clinopyroxene (<6.6 vol%), and plagioclase (12.5–24.2 vol%). Orthopyroxene (<0.1 vol%) and Fe–Ti oxides (<0.1 vol%) are also present as microphenocryst phases in most samples.

Olivine phenocrysts (~ 0.5 mm long) are usually euhedral and normally zoned, with some containing tiny euhedral spinel inclusions. Both clinopyroxene (0.5–1.0

mm long) and plagioclase (~ 1.0 mm long) phenocrysts are euhedral-to-subhedral tabular crystals that are normally zoned. Orthopyroxene phenocrysts (0.5–1.0 mm long) are mostly euhedral-to-subhedral crystals, and most are in granular or tabular form and commonly show normal zoning. Fe–Ti oxides (less than 0.3 mm long) are sporadically found. The groundmass is intergranular, interser-

Table 2. Abundances of trace elements in W-2 and BIR-1

	W-2			BIR-1		
	AV	RV	RD(%)	AV	RV	RD(%)
Sr	191.542	191.800	0.135	104.643	106.400	1.679
Y	22.634	22.800	0.732	16.617	16.200	2.507
Zr	91.070	92.000	1.022	14.400	14.470	0.486
Ba	176.232	171.000	2.969	6.720	6.520	2.978
Ce	23.219	23.080	0.599	1.900	1.897	0.158
Nd	12.793	12.950	1.226	2.400	2.380	0.833
Sm	3.289	3.310	0.643	1.082	1.117	3.247
Eu	1.098	1.093	0.447	0.519	0.524	0.979
Gd	3.651	3.690	1.068	1.810	1.850	2.228
Dy	3.840	3.790	1.314	2.517	2.530	0.516
Ho	0.792	0.798	0.728	0.585	0.585	0.007
Er	2.344	2.260	3.604	1.805	1.734	3.948
Yb	2.051	2.030	1.029	1.578	1.649	4.510
Lu	0.302	0.299	0.930	0.243	0.247	1.727
Pb	8.067	7.810	3.188	2.908	2.970	2.130
Th	2.296	2.210	3.760	0.029	0.030	4.138
U	0.498	0.497	0.207	0.010	0.010	1.411

AV, analysed value (ppm) in this study.

RV, recommended value (ppm) by Eggins et al. (1997).

RD (%), $|AV - RV| / RV \times 100$.

tal, or seriate in texture, and consists of plagioclase, pyroxene, Fe-Ti oxides, and glass.

GEOCHEMISTRY OF BASALTIC ROCKS OF TATESHINA VOLCANO

Analytical methods

Major and trace element analyses on 79 basalts from the KA and TS basalt flows and dykes were performed by X-ray fluorescence (XRF) spectrometry using the Rigaku RIX 3000 system at the Faculty of Science, Niigata University. Glass disks were prepared by fusing rock powder samples (0.5 g) with lithium tetraborate ($\text{Li}_2\text{B}_4\text{O}_7$, 5.0 g) for major element analysis, and rock powder samples (1.8 g) with lithium tetraborate (2.88 g) and lithium metaborate (LiBO_2 , 0.72 g) for Ni and Cr analysis. The analytical procedures have been described in detail by Takahashi and Shuto (1997).

Trace element abundances were determined for 11 representative basalts using an inductively coupled plasma-mass spectrometer (ICP-MS; Agilent 7500a) at the Faculty of Science, Niigata University. Whole rock powders (0.05 g) were dissolved in an HF-HNO₃ mixture on a hotplate and diluted by a factor of 10000 with 5% HNO₃. A single solution of USGS reference material, BHVO-1, was used as an external calibration standard with reference values from Eggins et al. (1997). Sensitivity variation during the analytical runs was corrected for using four internal standards (In, Tm, Re, and Bi). External

standardization was performed for individual elements in unknown samples by interpolating results for replicate analyses of BHVO-1 after 5–6 unknown samples. Analytical quality was examined by comparing the results for USGS reference materials W-2 and BIR-1 with literature values (Table 2).

Mass spectrometric analysis for Sr and Nd isotopes in the 11 basalt samples was performed on a MAT262 mass spectrometer at the Faculty of Science, Niigata University, following the procedures of Miyazaki and Shuto (1998). The extraction of Rb, Sr, Sm, and Nd from rock powder has been described by Kagami et al. (1987). The measured $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$, respectively. Blank tests yielded errors of 1.0 ng for Sr, 0.1 ng for Rb, 0.06 ng for Sm, and 0.6 ng for Nd.

The Sr isotopic ratios for NBS987 were measured ten times during this study, and averaged 0.710251 ± 0.000003 (2σ , $N = 51$). The mean $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of the JB-1a igneous rock standard provided by the Geological Survey of Japan (GSJ; $N = 9$) was 0.512782 ± 0.000007 (2σ). During the course of this study, the $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of the La Jolla and JNdi-1 standards was measured. The latter is a new standard provided by GSJ. The La Jolla standard had a mean $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of 0.511851 ± 0.000006 (2σ , $N = 17$) and JNdi-1 a mean $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of 0.512106 ± 0.000003 (2σ , $N = 44$).

Major element abundances

Whole rock major and trace element concentrations were measured for 79 basaltic samples of KA basalt, TS basalt, and dykes, and the results for 11 representative basalt samples are listed in Table 1. In the following discussion, the major element compositions are stated on an anhydrous basis, and all analyses results are plotted in Figure 2.

The SiO_2 content in the analyzed rocks range from 50.06% to 53.28%. All these basaltic rocks, including basalt and basaltic andesite, are classified as being tholeiitic by Miyashiro (1974) in terms of $\text{FeO}^*/\text{MgO}-\text{SiO}_2$, and as high-alkali tholeiite by Kuno (1966) in term of the $\text{SiO}_2-(\text{Na}_2\text{O} + \text{K}_2\text{O})$ diagram (Fig. 2). With increasing SiO_2 content, the concentrations of TiO_2 , FeO^* , MgO , MnO , and CaO slightly decrease, whereas the concentrations of K_2O and Na_2O slightly increase. This figure obviously illustrates that the 11 basalts listed in Table 1 with MgO content higher than 5 wt% and FeO^*/MgO ratios lower than about 2.0 are relatively unfractionated samples of the basaltic rocks of Tateshina volcano.

Figure 2. SiO_2 versus FeO^*/MgO , and SiO_2 versus major elements for basaltic rocks of Tateshina volcano. The boundary between the fields of calc-alkaline series (CA) and tholeiitic series (TH) for SiO_2 versus FeO^*/MgO is from Miyashiro (1974). The boundary of low-alkaline tholeiite (LT), high-alkaline tholeiite (HT), and alkali basalt (AB) for $\text{SiO}_2 - (\text{K}_2\text{O} + \text{Na}_2\text{O})$ is from Kuno (1966). And the boundary of low-K (LK), medium-K (MK), and high-K (HK) for $\text{SiO}_2 - \text{K}_2\text{O}$ is from Gill (1981). Black squares indicate the 11 representative basalt samples listed in Table 2, and white squares indicate other analyzed Tateshina basalts.

Trace element abundances

Trace element data for 11 representative basalts of Tateshina volcano are plotted on an N-MORB-normalized spider diagram (normalizing factor and order of ele-

ments after Pearce and Parkinson, 1993) (Fig. 3). One of the most conspicuous geochemical characteristics of arc basalts is their positive LILE anomalies (such as Rb, Ba, U, and Pb), and their negative HFSE anomalies (such as Nb and Zr) on such diagrams (Gill, 1981; Pearce, 1982;

Figure 3. N-MORB normalized patterns of trace elements for basaltic rocks of Tateshina volcano and the calculated primary melt shown by the point A' (open star) in Figure 8. Normalizing factor and order of elements are after Pearce and Parkinson (1993). Black and gray lines indicate patterns of 11 primitive basalts of Tateshina volcano and the calculated primary melt shown by point A' (open star) in Figure 8.

Hawkesworth et al., 1993).

Sr and Nd isotopic composition

The Sr isotope compositions ($^{87}\text{Sr}/^{86}\text{Sr}$) and Nd isotope compositions ($^{143}\text{Nd}/^{144}\text{Nd}$) of the basaltic rocks of Tateshina volcano vary from 0.703619 to 0.703807 and from 0.512893 to 0.512945, respectively. These ratios are depleted compared with those of basaltic rocks from other Quaternary volcanoes around Tateshina volcano (Fig. 1), which range from 0.704420 to 0.707000 and 0.51267 to 0.51289.

DISCUSSION

Evaluation of crustal contamination during production of basaltic rocks at Tateshina volcano

It is estimated that the magma chamber of Tateshina basaltic magmas was situated at a depth of 30 km beneath the Tateshina region (Nakamura, 1991). Figure 1-A shows that 30 km is greater than the depth of the Conrad discontinuity and just short of the depth of the Moho discontinuity; therefore, the depth of 30 km corresponds to the lower crust. Therefore, we assess the contamination of the crustal materials at the lower crust during the production of Tateshina basalts.

Kobayashi and Nakamura (2001) suggested lower crustal contamination rather than upper crustal contamination during the generation of Quaternary volcanic rocks from the northeastern Japan Arc, on the basis of multi-isotope and trace element systematics, which require interactions between the water-rich magma and the lower crust along with amphibole fractionation. We do not ob-

Figure 4. $^{143}\text{Nd}/^{144}\text{Nd}$ vs. Nd/Sm diagram for Quaternary Tateshina basaltic rocks. Data for pre-Tertiary granitic rock as silicate melt derived from partial melting of the lower crust are also shown. The broken lines represent calculated simple mixing curves for mixing between calculated mantle and pre-Tertiary granitic rocks (silicate melt derived from partial melting of the lower crust) with different Nd isotope ratios and Nd/Sm ratios, which were drawn using equation of Langmuir et al. (1978). End member parameters: a), average pre-Tertiary granitic rock, $^{143}\text{Nd}/^{144}\text{Nd}$, 0.512354; Sm, 4.63 ppm; Nd, 22.00 ppm. Data source: pre-Tertiary granitic rocks, Rezanov et al. (1999); average lower continental crust, Weaver and Tarney (1984) and McLennan (2001). Black squares, gray squares, the black star, and the black triangle indicate basalt samples from Tateshina volcano, pre-Tertiary granitic rock, average pre-Tertiary granitic rock, and calculated mantle, respectively.

tain the appropriate trace elemental and isotopic information for lower crustal materials under Tateshina volcano. However, pre-Tertiary granitic rocks could be regarded as silicate melts derived from partial melting of the lower crust (Shibata and Ishihara, 1979; Kagami et al., 1993); therefore, the chemical composition of pre-Tertiary granitic rocks reflects the chemical composition of the silicate melt derived from lower crust materials. And the average composition of the lower crustal continental crust (according to Weaver and Tarney (1984) and McLennan (2001)) is similar to that of pre-Tertiary granitic rocks (Fig. 4), suggesting that pre-Tertiary granitic rocks are made of lower continental crustal material. We examine the lower crustal contamination in terms of $^{143}\text{Nd}/^{144}\text{Nd}$ -Nd/Sm (Fig. 4). In order to evaluate the role of lower crustal contamination in the generation of Tateshina basalts, we calculated simple mixing trajectories between basaltic and average pre-Tertiary granitic compositions as partial melt derived from lower crust material; the results of the mixing calculation are shown in Figure 4. The Tateshina basalt data are not plotted along the mixing line in Figure 4, but across the line, which indicates that lower crustal contamination is an unlikely explanation for the chemistry of Quaternary Tateshina basalts.

Figure 5. Flow chart for geochemical modeling in adopted this study. Methods and parameters employed in this model are shown in Tables 3, 4, and 5.

Therefore, crustal contamination may not play an important role in the generation of Tateshina basaltic rocks, suggesting that the relatively unfractionated basalts of Tateshina volcano can be used to investigate basaltic magma generation in terms of slab component contributions without the need to consider crustal contamination.

Assessment for fractional crystallization

It is desirable to use a primitive basalt sample in this model, because the composition of basaltic rocks during partial melting and melt–solid reactions is controlled by the addition of slab-derived fluids and silicate melt to the original wedge mantle.

The Tateshina basalts having a MgO content between 5 and 7 wt% are relatively unfractionated, but are not very primitive. The partition coefficients of Ba and Th between fractionated minerals such as olivine, clinopyroxene, and plagioclase and basaltic melt (Rollinson, 1993; Green, 1994) are very low (olivine/basaltic melt for Ba, 0.0003–0.0099; clinopyroxene/basaltic melt for Ba, 0.0017–0.026; plagioclase/basaltic melt for Ba, 0.23; olivine/basaltic melt for Th, 0.0001; clinopyroxene/basaltic melt for Th, 0.0035–0.03; plagioclase/basaltic melt for Th, 0.01). This indicates that the fractional crystallization of olivine, clinopyroxene, and plagioclase may have negligible effect on the abundances of Ba and Th in basaltic rocks. In addition, the Ba/Th ratio is uniform and is not changed by the fractional crystallization of these minerals because the partition coefficients of olivine, clinopyroxene, and plagioclase for Ba and Th in basaltic melt are similar (Rollinson, 1993 and Green, 1994).

Subduction components and wedge mantle compositions

As upper and lower continental crustal contamination may be negligible for the production of basaltic rocks at Tateshina volcano, the method for trace element and isotopic modeling of the subduction components involved in the generation of Tateshina basaltic rocks is illustrated in Figure 5.

The following components contribute to the chemistry of arc volcanics: the wedge mantle peridotite, AOC, and overlying oceanic sediments (e.g., Hoogewerff et al., 1997). Various geochemical features of arc basalts reflect the extent of elemental flux derived from the AOC and overlying oceanic sediments, which form a major part of the subducting slab.

Therefore, it is important to clarify whether the flux was an aqueous fluid, a silicate melt, or a mixture of both, and whether these aqueous fluids or silicate melts were derived from the AOC, oceanic sediments, or both. The following sections discuss the characteristics of the AOC, oceanic sediments, and original wedge mantle, and outline parameters used for the present geochemical model of the dehydration and partial melting processes in the slab.

AOC. The AOC, which makes up the majority of the subducting slab, has been regarded as the principal source of aqueous fluid (e.g., Tatsumi, 1989). As pointed out by Nichols et al. (1994, 1996) and Kincaid and Sacks (1997), some authors suggest that adakite in some island arcs provides evidence for partial melting of the subducting oceanic crust. However, adakite is unlikely to be found in the Izu–Mariana Arc, as adakite production requires the subduction of a young, hot lithosphere at a slow rate (e.g.,

Figure 6. Chondrite normalized REE patterns for the Tateshina basalt (this study) and adakites (Drummond et al., 1996). Normalizing values are after Taylor and McLennan, (1985). Black and gray lines indicate patterns of 11 primitive basalts of Tateshina volcano and the adakites, respectively.

Morris, 1995; Ujike et al., 1999; Kimura et al., 2005). The rare earth element compositions of Tateshina basalts (black line) are compared with those of adakite (gray line) in Figure 6. In this figure, these rare earth element compositions are normalized to those of CI chondrite (Taylor and McLennan, 1985). The rare earth element patterns of Tateshina basalts are distinctly different from those of adakite, suggesting that the subducting oceanic crust may not melt. Therefore, it is likely that the AOC is the major

source of aqueous fluid (rather than of silicate melt), and the aqueous fluid compositions of Brennan et al. (1995) and Staudigel et al. (1995) were selected for the present geochemical model (Table 3).

Oceanic sediments. It is generally accepted that sediment overlying the AOC is a likely source for material flux that would metasomatize the overlying mantle peridotite (e.g., Elliot et al., 1997; Turner et al., 1997; Class et al., 2000; Plank, 2005). We examined the dominant metasomatizing components, such as aqueous fluid, silicate melt, or a mixture of both, derived from the subducting oceanic sediments from the view point of the Th content of Tateshina basalts. Tateshina basalts are characterized by a higher Th content than that of MORB. These island-arc-type Th concentrations would be the result of contributions from silicate melt that originated from the oceanic sediments (Hawkesworth et al., 1997a, 1997b). In addition, Th enrichment in arc basalts and fluid immobility (Staudigel et al., 1996) suggest that the oceanic sediments on the top of the slab must melt (Elliott et al., 1997; Hoogewerff et al., 1997; Plank and Langmuir, 1993; Ryan et al., 1995; Turner et al., 1996). We used the silicate melt composition (Table 3) of Johnson and Plank (1999) and Plank and Langmuir (1998) for the present geochemical model of dehydration and partial melting

Table 3. Compositions of fluid and silicate melt fluxes, and original mantle components

	Sr	Y	Zr	Ba	Ce	Nd	Sm	Eu
Distribution coefficient ^a								
Olivine	0.0015	0.005	0.0006	0.0003	0.000075	0.00046	0.00077	0.0017
Orthopyroxene	0.019	0.11	0.039	0.00017	0.012	0.028	0.06	0.022
Clinopyroxene	0.09	0.45	0.09	0.0017	0.056	0.15	0.25	0.29
Source mantle modal composition ^b								
Olivine	50%							
Orthopyroxene	30%							
Clinopyroxene	20%							
Bulk distribution coefficient	0.02445	0.1255	0.03	0.000541	0.014838	0.03863	0.068385	0.06545
Calculated Tertiary mantle from SW-01S								
SW-01S ^c	345.00	17.00	40.00	59.00	10.50	7.22	2.07	0.74
Degree of melting	20%	20%	20%	20%	20%	20%	20%	20%
Calculated Tertiary mantle	69.01	4.09	8.00	11.80	2.10	1.45	0.43	0.15
Original pre-subduction wedge mantle								
Degree of melting	20%	20%	20%	20%	20%	20%	20%	20%
Residue after extraction of SW-01S	55.51	3.37	6.45	9.44	1.69	1.17	0.35	0.12
DMM ^d	7.66	3.33	5.08	0.56	0.55	0.58	0.24	0.10
Original wedge mantle:DMM=1:1								
Original blended wedge mantle	31.59	3.35	5.76	5.00	1.12	0.87	0.29	0.11
Oceanic sediment								
Silicate melt ^e	184.10	40.26	68.23	394.87	111.79	70.00	16.43	1.95
Altered oceanic crust								
Aqueous fluid ^{f, g}	550	0	1.88	2542	2.78	0.148	0	0

^a Green, (1994) and Kennedy et al., (1993). ^b Tatsumi, (2000). ^c Shuto et al., (2006). ^d Workman and Hart, (2005) (trace element); Su and Langmuir, (2003) (isotope). ^e Johnson and Plank, (1999) (except for isotope); Plank and Langmuir, (1998) (isotope value of GLOSS).

^f Ishizuka et al., (2003) (Nd, Ce, Zr); Brennan et al., (1995) (except for isotope); Staudigel et al., (1995) (isotope). ^g REE and HFSE are assumed to be immobile (Ishikawa et al., 2005).

Element concentrations are in ppm.

processes.

Original wedge mantle. Tatsumi and Hanyu (2003) argued that the chemical composition of the original wedge mantle peridotite prior to modification by subduction components would be identical to that of an N-MORB source (e.g., Sakuyama and Nesbitt, 1986), because MORB has a relatively uniform chemical character, and both MORB and arc basalts have similar abundance ratios for HFSE. As pointed out by Tatsumi and Hanyu (2003), this assumption may be valid for immature island arcs such as the Izu–Mariana Arc, but variably metasomatized subcontinental mantle material may be an important component in the original wedge mantle beneath mature island arcs such as the northeastern Japan Arc. The wedge mantle peridotite, from which the Tateshina basalt magmas were derived, would have experienced accumulated subduction events, including the addition of subduction components and the extraction of basalt magmas during the Tertiary. It is impossible to determine the amount of added and extracted material. In this paper, a simplified method is adopted to overcome this problem: we assume that the Quaternary pre-subduction wedge mantle peridotite beneath the Tateshina area is the residual rock left after extraction of Tertiary basalt magma. For this approach, we selected a sample (SW-01S) of middle Mio-

cene Maze basalt that erupted on the back-arc side of the northeastern Japan Arc (Shuto et al., 2006) as having a suitable extracted Tertiary basalt magma composition. This is because this sample was relatively unfractionated, being characterized by a relatively high MgO content (9.3 wt.%) and a low FeO*/MgO content (0.95). The presumed composition of the pre-subduction wedge mantle peridotite that produced the basalt magmas of Tateshina basalt was estimated by the extraction of a 20% fractional melt from the mantle composition calculated from the same Tertiary volcanic component (SW-01S) by the inversion of the process of 20% fractional modal melting of a peridotite composed of 55% olivine, 30% orthopyroxene, and 15% clinopyroxene (Table 3). In addition, in order to account for the mantle motion accompanying slab subduction within the wedge mantle, we blended the mantle predicted from SW-01S (the original pre-subduction wedge mantle peridotite prior to the production of Tateshina basalts) with a depleted MORB-source mantle (DMM). The compositions of this original blended wedge mantle peridotite are shown in Table 3.

Table 3. (Continued)

Gd	Dy	Ho	Er	Yb	Lu	Pb	Th	U	⁸⁷ Sr/ ⁸⁶ Sr
0.0027	0.0035	0.006	0.01	0.02	0.04	0.0003	0.0001	0.000035	
0.07	0.06	0.09	0.1	0.08	0.06	0.015	0.00011	0.00023	
0.35	0.4	0.4	0.4	0.38	0.35	0.08	0.0035	0.0065	
0.09235	0.09975	0.11	0.115	0.11	0.108	0.02065	0.000783	0.0013865	
2.39	2.47	0.54	1.58	1.42	0.22	0.96	0.41	0.19	
20%	20%	20%	20%	20%	20%	20%	20%	20%	
0.53	0.55	0.12	0.37	0.33	0.05	0.19	0.08	0.04	0.703589
20%	20%	20%	20%	20%	20%	20%	20%	20%	
0.43	0.45	0.10	0.30	0.27	0.04	0.15	0.07	0.03	0.703589
0.36	0.51	0.12	0.35	0.37	0.06	0.02	0.01	0.00	0.702630
0.39	0.48	0.11	0.33	0.32	0.05	0.09	0.04	0.02	0.703110
8.77	6.68	1.28	3.42	3.07	0.49	66.67	5.02	1.59	0.717300
0	0	0	0	0	0	15	0.63	0.27	0.703636

^a Green, (1994) and Kennedy et al., (1993). ^b Tatsumi, (2000). ^c Shuto et al., (2006). ^d Workman and Hart, (2005) (trace element); Su and Langmuir, (2003) (isotope). ^e Johnson and Plank, (1999) (except for isotope); Plank and Langmuir, (1998) (isotope value of GLOSS).

^f Ishizuka et al., (2003) (Nd, Ce, Zr); Brenan et al., (1995) (except for isotope); Staudigel et al., (1995) (isotope). ^g REE and HFSE are assumed to be immobile (Ishikawa et al., 2005).

Element concentrations are in ppm.

Table 4. Results of trace element and isotope modeling for calculated mantle composition

	Sr	Y	Zr	Ba	Ce	Nd	Sm	Eu	Gd	Dy	Ho	Er	Yb	Lu	Pb	Th	U	$^{87}\text{Sr}/^{86}\text{Sr}$
*	33.84	3.63	6.25	13.19	2.00	1.42	0.42	0.12	0.46	0.53	0.12	0.35	0.34	0.05	0.64	0.08	0.03	0.703743
**																		

* Calculated mantle.

** Original blended peridotite: silicate melt: aqueous fluid = 99 : 0.8 : 0.2.

Figure 7. Ba/Th versus $^{87}\text{Sr}/^{86}\text{Sr}$ diagram for metasomatized peridotite, showing the results of mixing calculations using Ba/Th and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of three end-members (original blended wedge mantle peridotite, silicate melt, and aqueous fluid) listed in Table 3. For example, point A shows compositions of metasomatized wedge mantle peridotite derived by hybridization and calculated from mass balance equations (Langmuir et al., 1978) assuming 3% silicate melt (white triangle) and 2% fluid (white square) mix with 95% of the original blended wedge mantle peridotite. Solid lines and dotted lines indicate rate of silicate melt flux derived from oceanic sediments and rate of aqueous fluid flux derived from the AOC, respectively. Labeled numbers on mixing curves give the proportion of end-members (fluid and silicate melt) in the mixture. The enclosure by three mixing curves indicates the possible compositional field of the calculated metasomatized mantle composition (Table 4).

Trace element and isotopic modeling of slab metasomatization

In order to assess the compositional change in the wedge mantle peridotite due to addition of aqueous fluid derived from the AOC and silicate melt derived from oceanic sediments, we performed a mixing calculation using the trace element abundances and Sr isotope ratios of three end-members, the original (blended) wedge mantle peridotite, silicate melt, and aqueous fluid (Table 3). The results of these mixing calculations are shown in Table 4, and the compositions of the calculated metasomatized mantle peridotite (in terms of Ba/Th - $^{87}\text{Sr}/^{86}\text{Sr}$) are shown in Fig. 7.

Moreover, it is remarkable that the Ba/Th ratio is largely controlled by the aqueous fluid derived from the AOC, while the amount of silicate melt derived from oceanic sediments dominates changes in $^{87}\text{Sr}/^{86}\text{Sr}$ (Fig. 7).

Modeling for primary magma from the calculated metasomatized peridotite

For arc basalts, it is generally accepted that partial melting of mantle peridotite is 15%–30% (Pearce and Parkinson, 1993) or 10%–25% (Plank and Langmuir, 1988). In our present model, we adopted an 11% fractional modal melt of the original blended wedge mantle peridotite

Table 5. Results of trace element and isotope modeling for calculated primary magma composition

	Sr	Y	Zr	Ba	Ce	Nd	Sm	Eu	
Distribution coefficient ^a									
Olivine	0.0015	0.005	0.0006	0.0003	0.000075	0.00046	0.00077	0.0017	
Orthopyroxene	0.019	0.11	0.039	0.00017	0.012	0.028	0.06	0.022	
Clinopyroxene	0.09	0.45	0.09	0.0017	0.056	0.15	0.25	0.29	
Garnet	0.012	4.6	0.6	0.0011	0.032	0.05	0.5	0.56	
Source mantle modal composition ^b									
Olivine	50%								
Orthopyroxene	30%								
Clinopyroxene	20%								
Garnet	1%								
Bulk distribution coefficient									
	0.02456	0.17145	0.035994	0.000549	0.015157	0.039125	0.073377	0.071033	
Degree of melting									
	11%	11%	11%	11%	11%	11%	11%	11%	
Calculated primary magma									
Silicate melt									
Aqueous fluid									
0.8	0.2	315.61	16.45	56.31	124.29	18.83	12.66	3.12	0.93

^a Green, (1994) and Kennedy et al., (1993).

^b Values are slightly modified from modal composition of mantle peridotite used by Tatsumi (2000).

Element concentrations are in ppm.

(composed of 49% olivine, 30% orthopyroxene, 20% clinopyroxene, and 1% garnet), which has a slightly different composition from that of the modal mantle peridotite used by Tatsumi (2000). The possible primary magma composition was computed using the crystal-melt partition coefficients for trace elements, which were determined on the basis of the compilation of experimental data by Green (1994). The results are shown in Table 5 and Figure 8. The figure shows part of the possible compositional field of the calculated primary magmas derived by 10% fractional modal melting of the original metasomatized peridotite illustrated in Figure 7 and Table 4. For example, point A' (open star in Fig. 8) represents the composition of the calculated primary magma derived from the metasomatized peridotite (original blended peridotite : silicate melt : aqueous fluid = 99 : 0.8 : 0.2). The actual compositions of 11 Tateshina basalts are plotted in the limited region in Figure 8 and indicate that these basalts can be generated from blended wedge mantle peridotite modified by the addition of 0.8%–1.0% silicate melt from oceanic sediments and 0.2%–0.8% aqueous fluids from the AOC.

In order to confirm adequacy this model, the calculated trace element compositions of a melt obtained by 10% fractional modal melting of the metasomatized peridotite (original blended peridotite : silicate melt : aqueous fluid = 99 : 0.8 : 0.2) are compared with the actual trace element compositions of Tateshina basalts (Fig. 3). In this figure, these trace element compositions are normalized to MORB. The calculated primary magma possesses trace element patterns (gray line) identical to those of actual

Tateshina basalts (black line). It can therefore be concluded that the geochemical model reasonably explains the compositions of Tateshina basalts.

CONCLUSIONS

Tateshina volcano, a part of the Yatsugatake volcanic chain, is found at the junction of the northeastern Japan Arc and the Izu–Mariana Arc. To clarify the mechanism behind the generation of basalts at Tateshina volcano, we used geochemistry to model partial melting and melt–solid reactions.

Tateshina basaltic rocks, with a less fractionated nature, have a SiO₂ content ranging from 50.06 to 53.28 wt% and a MgO content ranging from 5 to 7 wt% and a narrow range of Sr and Nd isotopic compositions (⁸⁷Sr/⁸⁶Sr = 0.703619–0.703807, ¹⁴³Nd/¹⁴⁴Nd = 0.512893–0.512945). There is no correlation between Tateshina basaltic rocks and crustal materials in terms of ¹⁴³Nd/¹⁴⁴Nd–Sm/Nd. Thus, Tateshina basaltic rocks show no evidence of crustal contamination.

The wedge mantle peridotite, from which basaltic magmas in the Tateshina area were derived, would have experienced accumulated subduction events, including the addition of subduction components and the extraction of basalt magmas during the Tertiary, as well as the mantle motion accompanying slab subduction within the wedge mantle. We assumed that the composition of the original Quaternary subduction wedge mantle peridotite prior to Quaternary magmatism could be represented by a 1 : 1 blending of the residual mantle after the extraction of Ter-

Table 5. (Continued)

Gd	Dy	Ho	Er	Yb	Lu	Pb	Th	U	$^{87}\text{Sr}/^{86}\text{Sr}$
0.0027	0.0035	0.006	0.01	0.02	0.04	0.0003	0.0001	0.000035	
0.07	0.06	0.09	0.1	0.08	0.06	0.015	0.00011	0.00023	
0.35	0.4	0.4	0.4	0.38	0.35	0.08	0.0035	0.0065	
4.00	5.00	6.00	7.00	8.00	9.00	0.025	0.0014	0.005	
0.13232	0.14972	0.16994	0.1849	0.1898	0.1976	0.020897	0.000796	0.00143615	
11%	11%	11%	11%	11%	11%	11%	11%	11%	
2.48	2.62	0.54	1.50	1.42	0.22	5.98	0.73	0.29	0.703743

^a Green, (1994) and Kennedy et al., (1993).

^b Values are slightly modified from modal composition of mantle peridotite used by Tatsumi (2000).

Element concentrations are in ppm.

Figure 8. Ba/Th versus $^{87}\text{Sr}/^{86}\text{Sr}$ diagram for primary magmas derived from the metasomatized wedge mantle peridotite. Actual compositions of 11 primitive basalts of Tateshina volcano (black squares) and a part of the compositional field of calculated primary magmas (Table 5) are shown in this figure. These primary magma compositions were calculated by assuming 10% fractional modal melting of the metasomatized peridotite (Table 4), as described in the text. For example, point A' (white star) is the primary magma composition calculated from metasomatized wedge mantle peridotite derived by hybridization of 99% original blended wedge mantle peridotite, 0.8% silicate melt, and 0.2% fluid. Solid and dotted lines and labeled numbers are the same as in Figure 7.

tiary basalt magmas with DMM. The present model includes the partial melting of this blended wedge mantle peridotite following metasomatism by aqueous fluid and silicate melt produced by the dehydration of AOC and the partial melting of oceanic sediments, respectively.

The modeling results demonstrate that the trace element compositions and Sr and Nd isotope compositions of the basalts of Tateshina volcano can be accounted for by about 10% melting of the blended wedge mantle peridotite modified by the addition of 0.8%–1.0% silicate melt from oceanic sediments and 0.2%–0.8% aqueous fluid from the AOC, respectively.

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