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## Setouchi high-Mg andesites revisited: geochemical evidence for melting of subducting sediments

G. Shimoda<sup>a,b</sup>, Y. Tatsumi<sup>c,\*</sup>, S. Nohda<sup>d</sup>, K. Ishizaka<sup>a</sup>, B.M. Jahn<sup>e</sup>

<sup>a</sup> Graduate School of Human and Environmental Sciences, Kyoto University, Kyoto 606-01, Japan

<sup>b</sup> Kyoto Fission Track Co. Ltd., Kyoto 606, Japan

<sup>c</sup> Geothermal Research Institute, Kyoto University, Beppu 874-0903, Japan

<sup>d</sup> Kyoto Sangyo University, Kamigamo, Kyoto 603, Japan

<sup>e</sup> Géosciences Rennes, Université de Rennes 1, 35042 Rennes, France

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### Abstract

In order to evaluate the mechanism of production of unusual high-Mg andesite (HMA) magmas, Pb–Nd–Sr isotopic compositions were determined for HMAs and basalts from the Miocene Setouchi volcanic belt in the SW Japan arc. The isotopic compositions of Setouchi rocks form mixing lines between local oceanic sediments and Japan Sea backarc basin basalts, suggesting a significant contribution of the subducting sediment component to the HMA magma generation. Mixing calculations using compositions of an inferred original mantle and local oceanic sediments suggest that a sediment-derived melt, neither an H<sub>2</sub>O-rich fluid nor an amphibolite/eclogite-derived melt, could have been produced first and served as a plausible metasomatic agent for the HMA magma source. The unusual tectonic setting, including subduction of a newly-borne hence hot plate, may be responsible for melting of subducting sediments. © 1998 Elsevier Science B.V. All rights reserved.

*Keywords:* andesites; lead; isotopes; subduction; sediments; Japan

### 1. Introduction

Melting of a foundering oceanic crust as it sank into hot mantle is a likely consequence of subduction in Archean times. This likelihood is due to the steep geothermal gradient, and such melting could have contributed to the formation of the continental crust [1,2]. In most modern subduction zones, in contrast, melting of the oceanic crust does not occur [3]. Instead, aqueous fluids are released which trigger melting of the overlying mantle wedge to form a variety of arc magmas [4]. High-Mg an-

desites (HMAs), characterized by their high MgO contents and/or high Mg/Fe ratios, are uncommon arc magmas whose compositions are in equilibrium with upper mantle peridotites [5]. HMAs are not limited to Cenozoic volcanic arcs, but also occur in the Archean as monzodioritic and trachyandesitic rocks, otherwise known as sanukitoids [6,7]. Although volumetrically small, they form a recognizable part of the continental crust. Thus, the petrogenesis of HMA and its tectonic setting are important for understanding the mechanisms of continental formation.

Since the pioneering work by Kushiro [8], several experimental studies have demonstrated that andesitic melts can be produced by partial melting of hydrous mantle [9–11]. On the other hand, Baker

\* Corresponding author. Tel.: +81 (977) 220-713;  
Fax: +81 (977) 220-965; E-mail: tatsumi@bep.vgs.kyoto-u.ac.jp

et al. [12] have yielded HMA melt compositions by small degrees of partial melting of an anhydrous peridotite even at mantle pressures, suggesting that the presence of H<sub>2</sub>O may not be essential for the formation of HMA magmas. However, the minimum H<sub>2</sub>O content of certain SW Japanese HMA magmas, necessary for equilibration with mantle minerals at depths greater than Moho, would be ~5 wt% [13,14]. Further, Hirose [15] demonstrated, based on results of direct partial melting experiments on hydrous peridotites, that HMA melts can be produced only at temperatures below 1100°C under hydrous conditions. Using a generalized model for arc magmatism [16], Tatsumi and Maruyama [17] proposed that hydrous melting of the mantle wedge beneath the near-trench region where HMAs are typically distributed, could occur only at unusually high mantle temperatures in association with backarc spreading and hot plate subduction.

Alternatively, partial melting of a subducting lithosphere and interaction of such melts with overlying mantle peridotites [2,18] has been increasingly considered as a possible mechanism of generation of HMA magmas. Yogodzinski et al. [19] demonstrated that HMAs from western Aleutian possess trace element and isotope signatures broadly transitional between MORBs and basalts on normal arcs such as central and eastern Aleutians, and proposed that mixtures of amphibolitic slab-derived melts and depleted sub-arc mantle produce an HMA magma source. Pearce et al. [20] indicated that the subduction component contributing to formation of the magma source for boninites, typical HMAs from the Bonin Islands, is characterized by high concentrations of Zr and Hf and low concentrations of Nb and Ta, and proposed adakitic melts produced by partial fusion of the subducting slab of amphibolite facies as the source of such a subduction component. More generally, a slab melt would play an important role in governing not only unusual HMA but also normal arc magma source in other subduction zones [21–23]. Further, slab melting could also take place in the present SW Japan arc, as Morris [24] documented adakite-type andesites/dacites with typical slab melt compositions [25–27] from volcanoes of this arc. If this is the case, then HMA magmatism during the Miocene in this arc might have been also triggered by slab melting, because a warmer slab than the

present should have been subducted during Miocene time.

Isotope geochemistry of Setouchi volcanic rocks documented a rather radiogenic signature for HMAs, suggesting a major role of an enriched subduction component in producing Setouchi HMA magmas [28,29]. However, the mechanism of transportation of such a subduction component, via aqueous fluids or slab melts, has not been well constrained. We here present new Pb–Sr–Nd isotope data of Setouchi HMAs and show that a melt from subducting sediments is the major component governing isotope compositions of such HMAs.

## 2. Tectonic setting and samples

A rather young (<26 Ma; Okino et al. [30]) lithosphere of the Philippine Sea plate is subducting beneath the Eurasian plate to form the SW Japan arc (Fig. 1). Although seismicity in the downgoing slab is limited to depths <40 km beneath the central part of this arc, Nakanishi [31] and Hirahara [32] suggested that an aseismic slab is located beneath Quaternary volcanoes in that region. The presence of such an aseismic slab together with the occurrence of adakite-type andesites/dacites from those volcanoes led Morris [24] to the speculation that slab melting takes place beneath this arc.

The Setouchi volcanic belt is located ~80 km south of the Quaternary volcanic front, and extends for about 600 km along the SW Japan arc (Fig. 1). The volcanic belt can be divided into five sub-provinces, the central three being characterized by the occurrence of HMAs. The volcanic belt is parallel to the Nankai Trough (Fig. 1) and the occurrence of typical calc-alkaline andesites in the region [33] indicates the contribution of the subducting slab to the genesis of Setouchi magmas. Radiometric dating shows that Setouchi volcanism took place in a short time span at  $13 \pm 1$  Ma [34,35]. Additional K–Ar age determination has confirmed that the volcanism was limited to 12.4–14.8 Ma [36].

The Shikoku Basin, located south of the SW Japan arc, and the Japan Sea behind the Japanese Islands are backarc basins formed at 26–15 Ma [30] and in Early to Middle Miocene [37,38], respectively. Paleomagnetic studies have demonstrated that

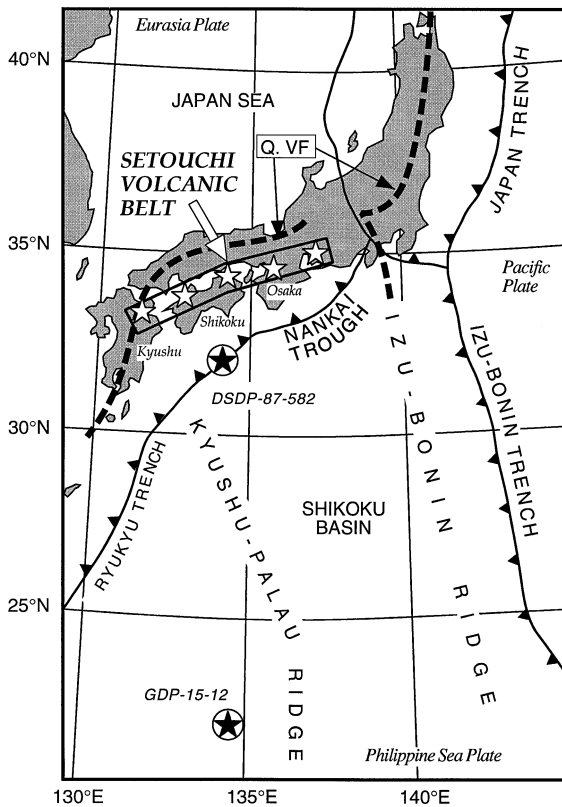


Fig. 1. A simplified tectonic map of the SW Japan arc. The Setouchi volcanic belt is located in the forearc region of the SW Japan arc, that is, the trenchward region of the Quaternary volcanic front (Q. VF). The volcanic belt is divided into five subprovinces (open stars), and the central three in Shikoku and Osaka are characterized by the occurrence of HMAs. Sediment samples are from the Nankai Trough and east of the Kyushu–Palau Ridge (filled stars).

the SW Japan arc sliver underwent clockwise rotation of  $40^{\circ}$ – $50^{\circ}$  during 14–16 Ma, which corresponds to the major mode of the Japan Sea opening [39–41]. Recent paleomagnetic measurements on Setouchi samples from localities identical to those for K–Ar dating revealed that the rotation of the SW Japan arc sliver was contemporaneous with the magmatism in the Setouchi volcanic belt [36]; the magmatism took place during  $\sim 60^{\circ}$  drifting of the SW Japan arc sliver. It is thus suggested that the clockwise rotation of the arc sliver led to southward drift of the SW Japan arc relative to the Shikoku Basin, which resulted in subduction of a very young oceanic crust of the Shikoku Basin beneath the arc lithosphere. When

the opening of the Japan Sea was arrested, the SW Japan arc sliver ceased to drift, thereby terminating subduction of the Shikoku Basin plate. The Setouchi magmatism was then switched off.

Fourteen samples from the Setouchi volcanic belt were selected for Pb–Sr–Nd isotopic analyses. These samples are from two volcanic fields, NE Shikoku and Osaka areas (Fig. 1). In order to examine the role of the subducting sediments in the Setouchi magma genesis, two types of oceanic sediments, terrigenous and pelagic, were selected for analysis; the terrigenous sediments were recovered from the floor of the Nankai Trough at Site 582 of DSDP Leg 87 (Fig. 1), and pelagic sediments from the central Philippine Sea (GDP 15-12). Furthermore, basement rocks of the Setouchi region including a granite and two granitic gneisses were analyzed. These rocks are considered as the subarc crustal component.

### 3. Analytical procedures

Pb, Nd and Sr isotopic compositions were measured with a Finnigan' MAT 261 mass spectrometer at Kyoto Sangyo University. The averages and standard deviations of seventeen separated analyses for NBS SRM 981 lead were  $^{206}\text{Pb}/^{204}\text{Pb} = 16.900 \pm 0.005$ ,  $^{207}\text{Pb}/^{204}\text{Pb} = 15.463 \pm 0.007$  and  $^{208}\text{Pb}/^{204}\text{Pb} = 36.529 \pm 0.020$ . The correction factors per amu for  $^{206}\text{Pb}/^{204}\text{Pb}$ ,  $^{207}\text{Pb}/^{204}\text{Pb}$  and  $^{208}\text{Pb}/^{204}\text{Pb}$  are 0.11%, 0.11% and 0.13%, respectively. The values of BCR-1 by duplicated analyses are  $^{206}\text{Pb}/^{204}\text{Pb} = 18.813$  and  $18.812$ ,  $^{207}\text{Pb}/^{204}\text{Pb} = 15.626$  and  $15.627$ , and  $^{208}\text{Pb}/^{204}\text{Pb} = 38.717$  and  $38.727$ . Details of the analytical procedures are given in Shimoda and Nohda [42]. Nd isotopic compositions were normalized to  $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ . The La Jolla standard value and error ( $2\sigma$ ) of single analysis in this study was  $0.511833 \pm 26$ . Sr isotopic compositions were normalized to  $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ . The average and standard deviation of duplicated analyses of NBS SRM 987 were  $0.710198 \pm 27$ . The value and error ( $2\sigma$ ) of the Eimer & Amend standard of single analysis were  $0.708009 \pm 24$ . Total analytical blanks of Pb, Nd, and Sr are lower than 100 pg, 200 pg, and 300 pg, respectively. Major and trace elements were analyzed with RIGAKU Symalitics 3550 and 3070 X-ray fluorescence (XRF)

spectrometers at Kyoto University on fused glass beads and pressed powder pallets, respectively, following the methods by Goto and Tatsumi [43,44].

**4. Results**

Major and trace element data and Sr–Nd–Pb isotopic compositions are given in Table 1.

FeO\*/MgO ratios of the selected basalts and the HMAs are less than unity except NJSB (Table 1), suggesting that they have equilibrated with mantle olivine on the basis of Fe–Mg partitioning. Petrographical examination and melting experimental data for those basalts and HMAs further indicate their undifferentiated hence primitive nature [13,14,33,45]. Consequently, the basalts and HMAs used in this study have carried the mantle signatures, although shallow-level processes such as crustal contamination might have affected to some extent the chemical characteristics of these lavas.

Incompatible trace element compositions of Setouchi rocks are plotted in a multi-element diagram (Fig. 2). The elemental patterns are broadly similar

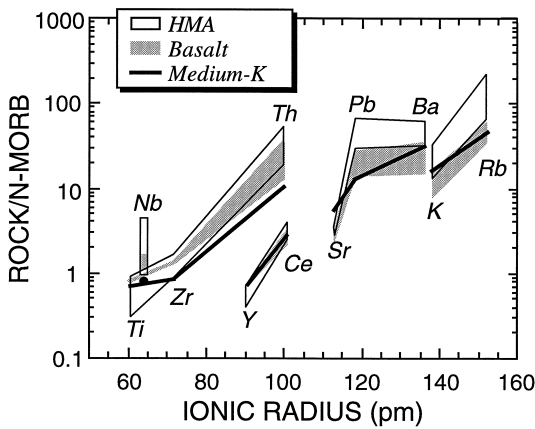


Fig. 2. Incompatible trace element characteristics of Setouchi HMA and basalts. Ce data for Setouchi rocks are after Ishizaka and Carson [28]. These samples are more enriched in an element with a larger ionic radius when comparing elements with an identical charge, which typifies subduction zone magma chemistry as shown by the average of medium-K subduction zone rocks (after Ref. [4]). It should be stressed that Setouchi rocks are distinct from a typical medium-K rock in the relative enrichment of Pb, suggesting the major contribution of the subducting sediment component.

to those of typical subduction zone lavas, showing progressive enrichment of elements with larger ionic radii of identical charge. A feature of the Setouchi rocks is the high Pb and low Sr and Y concentrations relative to medium- to high-K arc basalts.

Pb isotopic compositions for the Setouchi volcanic rocks (Fig. 3, upper and middle panel) clearly form a different trend from Pacific MORB and NHRL (Northern Hemisphere Reference Line; [46]), and are plotted on a mixing line between local

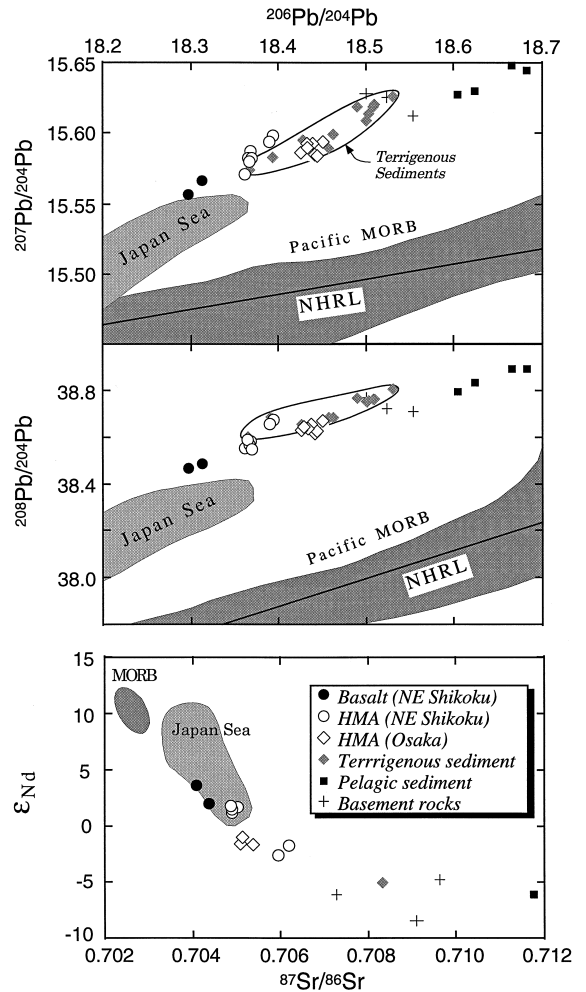


Fig. 3. Pb, Sr, Nd isotope compositions of Setouchi and oceanic samples. Pb isotope compositions of Setouchi HMAs overlap those of terrigenous sediments from the Shikoku Basin, supporting the mechanism including transportation of subduction components with slab melts rather than hydrous fluids.

oceanic sediments and the Japan Sea basalts [47,48]. Within a single mixing line, HMAs possess higher Pb isotopic compositions than basalts (Fig. 3). The HMAs from the Osaka area have the most radiogenic Pb isotopic compositions among the Setouchi HMAs, which overlap the range of terrigenous sediments on Pb–Pb diagrams (Fig. 3).

Terrigenous sediments show less radiogenic Pb isotopic signatures than pelagic sediments recovered from Philippine Sea (GDP 15–12), but are almost identical to that of the shales from the Shimanto belt, a subduction zone complex in SW Japan [29] and upper crustal basement rocks such as granite and gneiss. The isotopic compositions of the present pelagic sediment samples fall in the compositional range of the Pacific pelagic sediments, e.g. Ref. [49].

Since the basement rocks have isotopic compositions similar to those of terrigenous sediments (Fig. 3), a sedimentary origin for these granitic gneisses is suggested.

The Nd–Sr isotopic compositions of the Setouchi volcanic rocks (Fig. 3, bottom panel) exhibit a broad negative correlation similar to that documented earlier by Ishizaka and Carlson [28]. They are plotted between terrigenous sediments/upper crustal rocks and Japan Sea basalts/MORB (Fig. 3). In the same way as Pb isotopes, HMAs show more enriched Sr–Nd isotopic signatures than basalts.

## 5. Discussion

### 5.1. Original mantle compositions

The Setouchi volcanic belt was built by subduction of the Philippine Sea plate. In order to identify the subduction component, which governs geochemical characteristics of Setouchi magmas, estimating compositions of the original mantle before that subduction is required. The MORB-source mantle has been generally accepted as such sub-arc original mantle because of rather uniform chemistry of MORBs on the Earth and similarity in high-field-strength element ratios between MORBs and arc lavas [4,50–52]. On the other hand, the magma source for some arcs such as eastern Aleutian [53] and Mariana [54] would possess an enriched component possibly from the ocean island basalt source.

In case of continental arcs, furthermore, variably metasomatized subcontinental mantle materials may contribute to determining the original mantle compositions [55].

Compositions of Setouchi rocks are plotted on mixing lines between local oceanic sediments and Japan Sea backarc basin basalts (Fig. 3). Opening of the Japan Sea backarc basin and break-up of the eastern margin of the Eurasian lithosphere must have resulted in or been caused by replacement of pre-existing, rather enriched lithospheric mantle materials by asthenospheric materials possibly with more depleted compositions [55,56]. It is thus suggested that the magma source for Japan Sea backarc basin basalts is composed of at least such two end-member components. Further, the fact that Sr–Nd isotopic compositions of Japan Sea basalts completely overlap those of intraplate basalts in eastern China [57,58], which are produced undoubtedly with the involvement of the subcontinental lithosphere, suggests the possible contribution of such enriched components to forming the backarc basin basalt source. The Japan Sea basalt source should have variable compositions (Fig. 3), which is probably attributed to variable involvement of depleted asthenospheric and enriched subcontinental mantle materials.

There are rather compelling reasons for believing that compositions of the Setouchi original mantle are close to those for Setouchi basalt magma source: (1) Setouchi basalts have isotopic compositions very close to Japan Sea basalts (Fig. 3); (2) the Setouchi basalt magma source may contain much less H<sub>2</sub>O hence be much less metasomatized by hydrous slab-derived components than the HMA source as suggested by the results of melting experiments on Setouchi lavas [13,14]. In a strict sense, the above assumption is not valid, because the basalt source should also have been produced by addition of slab-derived, subduction components to the original mantle. In order to understand the relative role of slab components in production of the HMA magma source, however, the present assumption may be accepted. The interred original mantle compositions for Setouchi magmas can be then calculated based on compositions of a primitive basalt, SDSYB (Table 1), by assuming (1) appropriate distribution coefficients [59], and (2) 15% batch partial melting

Table 1  
Major and trace elements compositions

Locality	NE Shikoku													
	SDSYB	TK101	SD-261	SD407	SD411	SD812	MDYB-2	SH7201	JA-2	TGI-5	TGI-6	NBY-5	NJSB	NJIB
Sample	basalt	basalt	HMA	HMA	HMA	HMA	HMA	HMA	HMA	HMA	HMA	HMA	HMA	HMA
Rock type	basalt	basalt	HMA	HMA	HMA	HMA	HMA	HMA	HMA	HMA	HMA	HMA	HMA	HMA
SiO <sub>2</sub>	48.95	50.27	55.37	56.12	55.80	56.33	57.31	55.46	56.18	57.27	57.65	55.77	53.75	51.87
TiO <sub>2</sub>	1.02	0.95	0.65	0.62	0.61	0.61	0.59	0.70	0.67	0.42	0.44	0.39	1.08	0.76
Al <sub>2</sub> O <sub>3</sub>	14.69	17.06	15.55	15.38	15.41	16.48	15.81	15.54	15.32	14.26	14.42	13.98	16.62	15.48
Fe <sub>2</sub> O <sub>3</sub> *	10.21	7.92	6.92	6.87	6.84	6.19	6.43	6.71	6.95	6.19	6.29	6.81	7.94	8.29
MnO	0.17	0.13	0.17	0.14	0.14	0.11	0.14	0.13	0.11	0.12	0.12	0.13	0.15	0.14
MgO	11.79	8.76	6.89	7.61	7.77	7.19	6.24	9.33	7.68	9.45	9.23	10.93	6.64	9.54
CaO	8.75	9.00	7.04	6.87	6.92	6.97	6.46	6.94	6.48	6.31	6.21	6.96	8.18	8.14
Na <sub>2</sub> O	2.57	3.22	2.84	2.87	2.64	3.06	3.12	2.90	3.08	2.57	2.56	2.36	2.87	2.57
K <sub>2</sub> O	1.20	0.58	2.25	2.38	2.42	2.04	2.28	1.63	1.80	1.16	1.35	1.20	1.17	0.97
P <sub>2</sub> O <sub>5</sub>	0.27	0.14	0.17	0.16	0.16	0.16	0.17	0.16	0.15	0.10	0.10	0.09	0.18	0.12
Total	99.60	98.04	97.85	99.03	98.71	99.15	98.55	99.50	98.42	97.85	98.37	98.62	98.60	97.88
FeO <sup>*</sup> /MgO	0.78	0.81	0.90	0.81	0.79	0.78	0.93	0.65	0.81	0.59	0.61	0.56	1.08	0.78
Ba	219	95	195	211	213	263	221	288	317	336	301	378	275	233
Nb	4	2	5	4	4	5	5	8	10	3	3	2	5	3
Ni	207	124	148	132	126	151	123	132	142	179	178	254	32	194
Pb	8.3	4.3	17.4	18.3	17.7	17.8	17.9	17.7	19.3	13.1	11.1	11.2	13.6	9.0
Rb	33.2	19.2	113.6	119.3	121.3	68.4	120.6	60.5	68.0	44.7	51.6	47.5	41.8	36.5
Sr	277	223	267	249	253	299	274	245	252	308	296	284	301	274
Th	4.2	1.6	4.8	4.7	4.6	5.3	6.2	4.5	4.7	4.9	4.7	3.0	3.8	2.3
Y	18	19	15	16	16	13	16	16	18	11	11	11	18	14
Zr	99	96	80	82	82	109	92	107	119	94	93	68	116	80
<sup>206</sup> Pb/ <sup>204</sup> Pb	18.314	18.298	18.369	18.361	18.367	18.365	18.370	18.391	18.394	18.450	18.444	18.425	18.413	18.438
<sup>207</sup> Pb/ <sup>204</sup> Pb	15.566	15.556	15.587	15.571	15.580	15.582	15.582	15.594	15.598	15.594	15.584	15.586	15.572	15.593
<sup>208</sup> Pb/ <sup>204</sup> Pb	38.483	38.464	38.579	38.551	38.566	38.591	38.547	38.651	38.668	38.668	38.624	38.629	38.582	38.648
<sup>87</sup> Sr/ <sup>86</sup> Sr	0.70446 <sup>b</sup>	0.70413 <sup>b</sup>	0.70512 <sup>b</sup>	0.70522 <sup>b</sup>	0.70518 <sup>b</sup>		0.70510 <sup>b</sup>	0.706104	0.70637	0.70524 <sup>b</sup>	0.705154	0.70546 <sup>b</sup>		
<sup>87</sup> Sr/ <sup>86</sup> Sr <sup>c</sup>	0.70439	0.70408	0.7049	0.70502	0.70491		0.70487	0.70596	0.70621	0.70514	0.70507	0.70537		
<sup>143</sup> Nd/ <sup>144</sup> Nd	0.512747 <sup>b</sup>	0.512830 <sup>b</sup>	0.512700 <sup>b</sup>	0.512723 <sup>b</sup>	0.512717 <sup>b</sup>		0.512731 <sup>b</sup>	0.512502	0.512550	0.512588 <sup>b</sup>	0.512562	0.512553 <sup>b</sup>		
ε <sub>Nd</sub> <sup>d</sup>	2.1	3.7	1.2	1.7	1.5		1.8	-2.7	-1.7	-1.0	-1.5	-1.7		

Table 1  
(continued)

Locality	Nankai Trough, DSDP Leg 87, Site 582, terrigenous sediments								Philippine Sea, GDP15-12, pelagic clay				Nara Pref.		
	T-1	T-3	T-4	T-6	T-8	T-9	T-10	T-COM <sup>a</sup>	P-1	P-6	P-12	P-COM <sup>a</sup>	NBN-1 gneiss	SR-1 gneiss	NBR2-3 granite
SiO <sub>2</sub>	61.89	64.49	64.03	63.24	63.36	65.62	63.34	64.36	63.82	58.73	57.92	59.11	66.61	67.84	76.89
TiO <sub>2</sub>	0.80	0.77	0.78	0.79	0.80	0.69	0.78	0.76	0.61	0.81	0.90	0.87	0.60	0.63	0.12
Al <sub>2</sub> O <sub>3</sub>	18.28	17.47	17.81	18.00	18.40	16.23	18.12	17.47	16.40	19.45	18.93	18.84	16.41	15.61	13.59
Fe <sub>2</sub> O <sub>3</sub> <sup>*</sup>	7.60	6.65	6.89	7.02	7.06	6.12	7.59	6.69	6.13	8.13	8.93	8.59	4.63	4.54	1.30
MnO	0.13	0.09	0.11	0.11	0.09	0.10	0.09	0.10	0.54	0.76	0.73	0.72	0.12	0.09	0.03
MgO	2.90	2.60	2.60	2.96	2.88	2.55	2.77	2.69	2.26	2.85	3.25	3.11	1.65	1.89	0.30
CaO	2.32	1.80	2.29	2.54	1.79	3.62	1.48	2.36	1.75	1.89	1.32	1.53	2.90	3.86	1.86
Na <sub>2</sub> O	2.17	2.46	2.41	2.45	2.44	2.75	2.37	2.42	4.65	4.17	3.84	3.70	3.40	3.34	3.36
K <sub>2</sub> O	3.39	3.16	3.06	2.87	3.07	2.21	3.17	2.89	3.57	3.24	3.66	3.50	3.54	1.99	3.18
P <sub>2</sub> O <sub>5</sub>	0.16	0.40	0.16	0.16	0.19	0.13	0.15	0.18	0.20	0.26	0.23	0.22	0.15	0.16	0.05
Total	99.65	99.89	100.15	100.14	100.08	100.03	99.87	99.93	99.95	100.29	99.70	100.19	100.01	99.98	100.67
FeO <sup>*</sup> /MgO	2.36	2.30	2.38	2.14	2.21	2.16	2.46	2.24	2.44	2.56	2.47	2.48	2.52	2.16	3.83
Ba	490	456	443	387	438	400	501	449	886	744	855	665	544	320	1157
Nb	10	10	10	8	10	6	9	9	9	11	12	12	9	8	6
Ni	46	41	38	36	36	28	36	37	59	68	79	72	29	14	4
Pb	27.5	21.9	22.9	22.4	23.2	13.9	23.8	21.5	36.1	48.5	46.1	43.5	25.5	7.9	24.1
Rb	130.6	124.1	120.1	111.6	120.9	82.2	124.7	111.8	123.6	117.3	136.4	128.1	114.2	91.0	77.9
Sr	165	183	176	177	163	238	144	183	188	214	190	190	358	241	347
Th	13.1	12.0	12.7	10.6	11.5	7.6	11.2	10.8	13.9	15.3	15.7	14.8	9.2	–	5.0
Y	27	23	25	25	24	19	23	23	33	47	42	38	23	8	11
Zr 153	161	160	147	152	135	145	152	164	197	180	174	183	142	143	
<sup>206</sup> Pb/ <sup>204</sup> Pb	18.503	18.530	18.463	18.509	18.458	18.490	18.500	18.510	18.625	18.605	18.683	18.666	18.554	18.526	18.502
<sup>207</sup> Pb/ <sup>204</sup> Pb	15.614	15.626	15.599	15.619	15.589	15.619	15.609	15.620	15.629	15.627	15.644	15.648	15.611	15.624	15.626
<sup>208</sup> Pb/ <sup>204</sup> Pb	38.755	38.804	38.683	38.763	38.682	38.767	38.752	38.761	38.827	38.790	38.889	38.887	38.700	38.712	38.742
<sup>87</sup> Sr/ <sup>86</sup> Sr							0.708647				0.712118	0.709828	0.707508	0.709271	
<sup>87</sup> Sr/ <sup>86</sup> Sr <sup>c</sup>							0.70829				0.711173	0.70964	0.70729	0.70914	
<sup>143</sup> Nd/ <sup>144</sup> Nd							0.512383				0.512325	0.512386	0.512313	0.512195	
ε <sub>Nd</sub> <sup>d</sup>							–5.0				–6.1	–4.9	–6.3	–8.6	

Fe<sub>2</sub>O<sub>3</sub><sup>\*</sup> and FeO<sup>\*</sup>, total irons as Fe<sub>2</sub>O<sub>3</sub> and FeO, respectively.

<sup>a</sup> A composite sample was prepared by an even-mixture of sediment samples.

<sup>b</sup> Data from Ishizaka and Calson [28].

<sup>c</sup> Age corrected for 14 Ma.

<sup>d</sup> Bulk-earth <sup>143</sup>Nd/<sup>144</sup>Nd = 0.512638 from Jacobsen and Wasserburg (1980).



of a lherzolite with 55% olivine, 30% orthopyroxene, and 15% clinopyroxene.

### 5.2. Melting of subducting sediments

The linear trend of Pb isotopic compositions for Setouchi lavas strongly suggests the involvement of the subducting sediment component in the Setouchi magma genesis. The negative trend observed in the  $\epsilon_{\text{Nd}}$  vs.  $^{87}\text{Sr}/^{86}\text{Sr}$  diagram (Fig. 3, bottom panel) is also consistent with this scenario. These enriched isotopic characteristics in Setouchi HMAs contrast with depleted, rather MORB-like Pb–Sr–Nd isotopic compositions for western Aleutian HMAs [19]. The basement rocks for Setouchi lavas such as gneisses and granites with compositions broadly identical to oceanic sediments are candidates for the source of such enriched components in Setouchi HMAs. Assuming simple mixing between a Setouchi basalt magma and basement rocks as a contamination process for producing HMA magmas, such contaminated andesites should possess MgO and Ni contents much smaller than Setouchi HMAs and cannot crystallize Mg-rich olivine ( $\text{Fo}_{88-89}$ ; [33,45]). Such very primitive nature for HMAs may preclude great degrees of crustal contamination. However, it is impossible at the present stage to rule out the contribution of crustal contamination to forming Setouchi HMA geochemical characteristics.

Since HMAs have more enriched Pb–Sr–Nd isotopic characteristics than basalts, it is suggested that a greater amount of the slab-derived component has been overprinted onto the HMA magma source than the basalt magma source. This is a process consistent with experimental constraints which suggest that HMA magmas contain greater amounts of  $\text{H}_2\text{O}$  than basalt magmas [13,14]. However, the nature of such ‘enriched’ metasomatic agents, an  $\text{H}_2\text{O}$ -rich fluid produced by dehydration or a hydrous melt produced by partial melting of the subducted lithosphere, has been much debated. Both are capable of transporting slab-derived hydrous components to the original mantle wedge.

The Pb isotopic data demonstrated in Fig. 3 appear to be more consistent with a process including slab-melting than slab-dehydration, as Pb may be preferentially partitioned into a partial melt than an aqueous fluid [60,61]. In order to evaluate the nature

of the metasomatic agents, calculations of mixing between an interred original mantle (see Section 5.1) and hypothetical slab-derived melts/fluids have been conducted. Total melting of terrigenous sediments (T-COM, a composite sample in Table 1) is assumed for estimating Pb, Sr, and Nd abundance in subducting sediment-derived melt (20, 180, and 30 ppm, respectively) as: (1) high degrees of partial melting could be expected; and (2) such elements may be largely incompatible to residual phases during melting such as quartz, kyanite and clinopyroxene [62,63]. Compositions of sediment-derived aqueous fluid (10 ppm Pb, 18 ppm Sr, and 3 ppm Nd) are calculated based on experimental data for element transport during dehydration of terrigenous sediments [64].

The results of mixing calculations are shown in Fig. 4. The addition of several percent of a sediment-derived melt can account for the Sr–Nd–Pb isotope compositions of the HMA magma source. However, the sediment-derived fluid is unlikely for the metasomatic agent, because the amount of fluids required for obtaining Sr–Nd isotope compositions in the HMA magma source ( $\sim 40\%$ ) is much greater than that for obtaining Pb isotope compositions ( $\sim 10\%$ ).

The distribution of high-field-strength elements (HFSEs) can also provide strong constraints to the nature of the metasomatic agent, as HFSEs behave as incompatible elements during mantle melting but are not soluble into an aqueous fluid [65]. We examine HFSE compositions of HMAs and basalts from a small volcanic field in NE Shikoku, in order to avoid the effect of HFSE heterogeneity in the original upper mantle. Fig. 5 indicates that HMAs possess higher Zr/Ti and Nb/Ti ratios than basalts. This could be explained by difference in degrees of melting of an identical source (HMA > basalt magmas), because  $D_{\text{Zr}}$  and  $D_{\text{Nb}}$  are smaller than  $D_{\text{Ti}}$  [60]. If so, then Zr/Ti and Nb/Ti ratios would be positively correlated with Ti contents, but this is contrary to the observed negative correlation (Fig. 5). We suggest that the two types of magmas have tapped magma sources with distinctive HFSE abundance. If we assume a single original mantle before the imprint of slab-derived components, then the different HFSE ratios in the magma source would be reasonably attributed to greater degrees of metasomatism

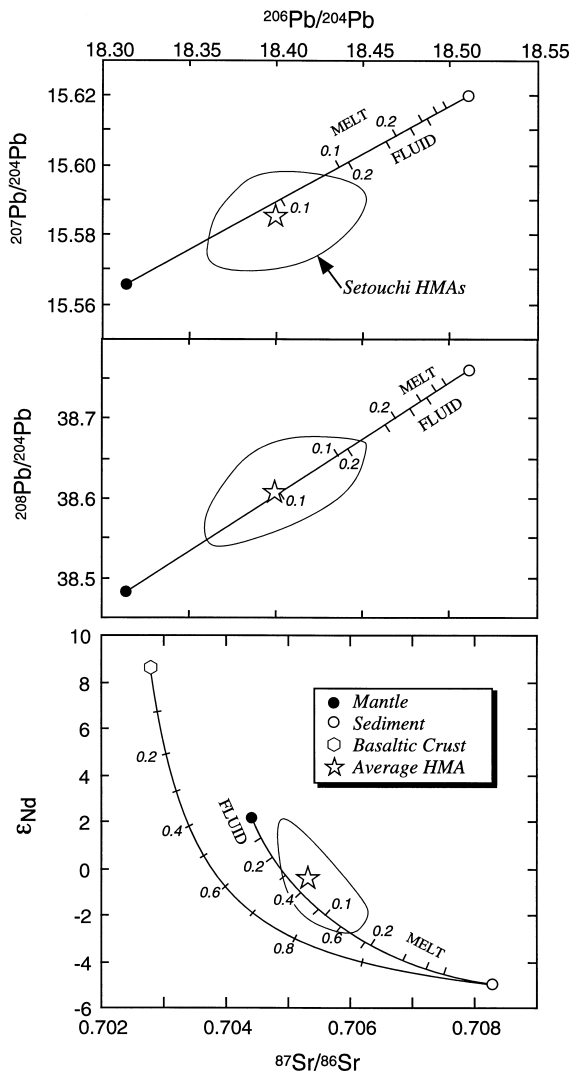


Fig. 4. Results of mixing calculations. Isotope compositions of Setouchi HMAs can be explained by the addition of several percent of sediment melts to an inferred original mantle, not by fluid addition. Involvement of basaltic crust in forming slab-derived component may not be likely, because such slab components are more depleted than expected.

by slab-derived partial melts for the HMA than for the basalt source.

HFSEs do not behave as incompatible elements during melting of the basaltic portion of the slab because of the presence of so-called TNT phases such as rutile [66,67]. This is consistent with the observation of relative depletion in HFSEs for Aleu-

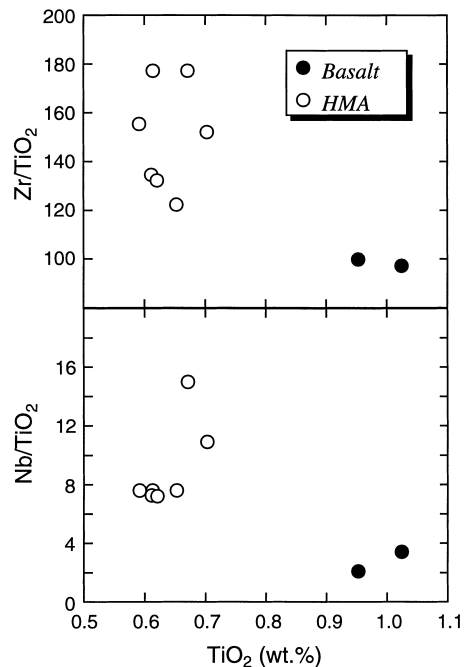


Fig. 5. High-field-strength element systematics for Setouchi HMAs and basalts. The observed negative correlation may suggest the major role of slab melts in determining the magma source characteristics.

tian adakites of slab melt origin. However, Setouchi HMAs possess Nb contents much higher than adakites, suggesting the absence of the TNT phase in the melting residues. This supports the present discussion suggesting a major role of melting of the sediments not basaltic portion of the subducting oceanic crust in the generation of Setouchi HMA magmas.

Yogodzinski et al. [19] reported HMAs with MORB-like, depleted isotopic characteristics from Piip Volcano, western Aleutian, and suggested that the subduction component overprinted onto the original mantle wedge is largely derived from the subducting basaltic crust, not from the sediment portion of the slab. This contrasts much with the case of HMA magma production in the Setouchi volcanic belt, where the slab components from the subducting basaltic crust may be little involved. This is confirmed by quantitative estimates shown in Fig. 4, which demonstrates that the involvement of the basaltic crust with Shikoku Basin basalt compositions [68] could form more depleted slab-derived

components than those required for Setouchi HMAs. This is supported by consideration of temperature distribution of the slab surface presented in the later discussion.

Plank and Langmuir [69] demonstrated that the volcanic outputs reflect the sediment inputs in some arc–trench systems. On the other hand, isotope and trace element characteristics of western Aleutian HMAs led Yogodzinski et al. [19] to the conclusion that sediments on the oceanic crust have been tripped out at shallow levels by the long, oblique subduction path beneath the Aleutian forearc. However, the depth to the slab surface beneath the Setouchi volcanic belt (40–50 km) would have been much shallower than that beneath western Aleutian (~100 km), enabling oceanic sediments to be subducted and to be molten beneath the Setouchi region.

Setouchi magmatism is also characterized by the occurrence of basalt lavas coeval with HMAs. We have simply assumed that the basalt source is little metasomatized by the slab-derived component. However, it is difficult to define the nature of such a metasomatic agent for the basalt source, because the geochemical characteristics of the original melt, possibly melting of subcontinental lithospheric mantle, has not been well constrained. Further, the mechanism responsible for the location of different temperatures at an identical pressure (~1300°C and ~1100°C at ~1.0 GPa for basalt and HMA magmas; [14]) is also an important but unsolved problem.

### 5.3. Adakite connection and mantle–melt interaction

Although most modern arc magmas are probably derived from melting of the mantle wedge, which has been metasomatized by hydrous fluids derived from the subducted lithosphere [4], some unusual arc magmas are believed to represent partial melts of the subducting oceanic crust. These unusual rocks were termed ‘adakites’ by Defant and Drummond [25], following the original description of such lavas from Adak Island in the Aleutian arc [19]. Adakites are characterized by steep rare earth element patterns, together with low Y concentrations and high Sr concentrations or Sr/Y ratios. These geochemical features can be explained by partial melting of amphibolitic oceanic crust at around amphibolite–eclogite

transition in the presence of amphibole/garnet and in the absence of plagioclase as residual phases. Defant and Drummond [25] and Drummond and Defant [27] demonstrated that the occurrence of adakites is limited to the arc–trench systems where a young and hot oceanic crust is subducting, although an exception was reported from western Aleutian [19], where one of the oldest lithosphere on the Earth is being subducted. The Philippine Sea plate with a minimum age of 15 Ma is one of such young lithosphere subducting into the upper mantle and could melt to produce unusual adakitic melts. Morris [24] demonstrated that andesite/dacite from Quaternary volcanoes along the SW Japanese volcanic front are chemically similar to adakites and suggested partial melting of the Philippine Sea plate beneath the region. The Setouchi volcanic belt was built also by melting of a subducting slab under such unusual tectonic setting. However, Setouchi HMAs have trace element characteristics quite different from those of adakites, with lower Sr/Y ratios and higher Y concentrations than adakites (Fig. 5). This may be consistent with our present model based on isotope signatures which proposes a major contribution of melting of sediments, not amphibolite, to forming Setouchi HMA magmas.

Although Y concentrations in Setouchi HMAs are higher than those in typical adakites, Setouchi HMAs are distinct from most arc lavas in their rather low Y concentrations (Fig. 6). Depletion of Y in adakites is generally attributed to the presence of garnet/amphibole in the melting residue within the subducting oceanic crust [25–27]. Melting phase relations for Setouchi HMAs, however, suggested that HMA magmas do not coexist with garnet nor amphibole [13,14]. One of the possible processes responsible for depletion of Y in Setouchi HMAs is the production of metasomatic slab melts in the presence of garnet/amphibole in molten sediments, which is consistent with melting phase relations for sediment systems [62,63]. Further, Setouchi HMAs are much more depleted in Sr than adakites, which results in low Sr/Y ratios in Setouchi HMAs (Fig. 6). Low concentration of Sr in Setouchi HMAs may also be attributed to the effect of residual phases in molten sediments; plagioclase could be present as a melting residual phase in sediment systems at pressures less than 1.5 GPa [62], a pressure roughly equivalent to

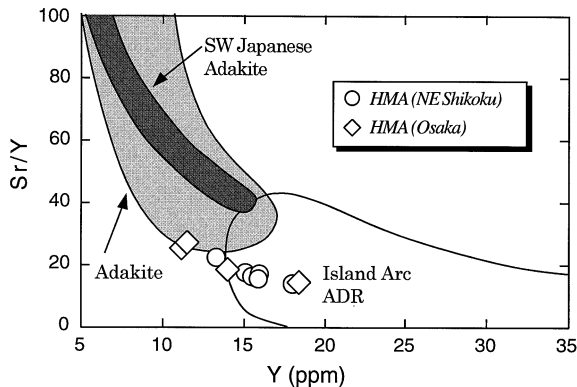


Fig. 6. A Sr/Y vs. Y diagram for Setouchi HMAs and adakites. Although both Setouchi HMAs and adakites may be produced by slab melting, they possess different signatures, which is probably caused by difference in the slab material that melts, sediments and amphibolite/eclogite crusts, respectively. Rather, Setouchi HMAs show Sr/Y similar to island arc andesite/dacite/rhyolite (ADR) [25–27].

the depth to the slab surface beneath the Setouchi region.

Melting of oceanic sediments should produce partial melts with silicic rather than andesitic/basaltic compositions. Such melts will not possess compositions of HMAs with high Mg and Ni contents. Since HMA magmas are finally equilibrated with mantle peridotite near the top of the subarc mantle wedge ( $\sim 1.0$  GPa; [13,14]), reactions between sediment-derived silicic melts and overlying mantle peridotites may occur during the melt ascent from the slab surface. Kay [41] proposed an attractive model for the origin of an Aleutian HMA (an adakite) in which hydrous melting of an eclogitic oceanic crust results in a small volume of dacitic melt which rises, together with aqueous fluids, into the hotter peridotite wedge and equilibrates with olivine and orthopyroxene under hydrous, probably  $H_2O$ -undersaturated, conditions. This process was experimentally investigated by Carroll and Wyllie [70], who show a decrease in silica content of derivative liquids and an increase in Mg/Fe ratios and Mg concentration, as a result both of olivine dissolution and reactions such as olivine +  $SiO_2 \rightarrow$  orthopyroxene. Kepezhinskas et al. [22] found the suite of xenoliths from Kamchatka displaying evi-

dence of variable degrees of metasomatic reactions between original mantle peridotites and felsic slab melts with a typical adakite composition. The occurrence of HMAs in the region as a host lava of such xenoliths may suggest the derivation of HMA magmas from such metasomatized peridotites. However, there is a critical difference between these reactions and those operated for the Setouchi HMA magmas; the slab melt beneath the Setouchi region is mostly derived from subducting sediments and should have left melting residues quite different from those after adakite melt production. Geochemical modeling of reaction between such sediment melts and mantle peridotite is not yet achieved, because experimental determination of melt composition during sediment fusion has been limited.

#### 5.4. Thermal regime

The paleo-depth to the surface of the subducting lithosphere beneath the Setouchi volcanic belt may have been  $\sim 50$  km as estimated from the present SW Japan subduction system. The subducting lithosphere was very young ( $< 5$  million years) at the time of Setouchi magmatism. Based on these tectonic constraints and a thermal model by Peacock [3], the temperature of the slab surface can be estimated at  $900$ – $1000^\circ C$ ,  $> 200^\circ C$  higher at the slab surface than a normal modern arc–trench system [71]. The upper part of a subducting lithosphere is composed of pelitic and basaltic rocks. The estimated temperature at the slab surface is well beyond the pelitic solidus under both  $H_2O$ -saturated and -undersaturated conditions ( $600^\circ C$  and  $800^\circ C$ , respectively, at 1.5 GPa; [62–64]). Thus, partial melting of the pelitic rock could have taken place, but melting of the amphibolite layer is not so well constrained by present estimations; the temperature at a  $\sim 50$  km depth is close to the amphibolite solidus. Even if amphibolite melting took place, the slab-derived partial melt should have been mainly composed of the sediment-derived component, a process more consistent with the present geochemical constraints.

Tatsumi and Maruyama [15] proposed that hydrous conditions required for HMA magma production at near-trench forearc mantle wedge can be attained by dehydration of serpentine within the downdragged hydrous peridotite layer at the base

of the mantle wedge. If the temperature distribution discussed above was correct, then dewatering of serpentine (at 600°C) must take place at much shallower depths. Thus, the simple model by Tatsumi and Maruyama [15] may not be applied for HMA magma genesis in the Setouchi volcanic belt.

## 6. Conclusion

A plausible process of production of HMA magmas in the Setouchi volcanic belt, SW Japan, which is consistent with unusual tectonic settings, melting phase relations of HMAs and isotopic/trace element compositions of HMAs and coeval basalts, is initial melting of subducting sediments on the young lithosphere, subsequent reactions of those hydrous silicic melts with overlying mantle peridotites, and final equilibration of a rising melt with uppermost mantle materials. Although the nature of Archean plate tectonics is uncertain, HMAs may have been more commonly produced in the Archean than at present simply due to possible slab melting associated with higher temperature distributions both in the subducting lithosphere itself and upper mantle. As Setouchi HMAs have compositions similar to igneous rocks that form a recognizable part of the continental crust [6], major parts of Archean dacites or tonalites, which are more common than andesites, may have formed by differentiation of Setouchi-type HMA (sanukitoid) magmas.

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helped establish the Pb isotope analytical techniques reported herein. [CL]

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