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ASPECTS OF MAGMA SOURCES AND PROCESSES IN THE HONSHU ARC

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Abstract

The volcanoes of the northern Izu – south-central Honshu and northeastern Honshu arcs, Japan, occur in a region where variables such as age, composition, and nature of the sediment cover of the subducting plate are relatively uniform. In this study, we attempt to isolate some of the variables associated with suprasubduction zone (SSZ) magma genesis, in order to provide insight into the nature of sources and petrogenetic processes. The chemical compositions of selected parental and evolved magmas in fifteen Plio-Pleistocene centers along the strike of the volcanic front allow us to assess the significance of over-riding lithospheric input for SSZ magmatism. These volcanoes are distributed across a number of major terrane boundaries, including the lithosphere-penetrating Tanakura Tectonic Line. Compositions range from basalt to rhyolite, with a preponderance of basaltic andesite and andesite; an exception is basalt-dominated Fuji. Most basalts are significantly fractionated, with low MgO (<7 wt%), Mg# <50, and low Ni (<50 ppm). Significant differences among volcanic suites are established on the basis of isotopic (Pb, Sr, and Nd), major- and trace-element data. The predominant source of these magmas is a relatively refractory (compared to mid-ocean ridge basalt) mantle-wedge area, with subchondritic Nb/Zr and Zr/Hf. A number of volcanoes also have low Zr/Y (< MORB), but several have both elevated Zr/Y (>3) and Dy/Yb, indicative of garnet involvement in their genesis. The Nd and Sr isotope ratios also indicate regional variations in chemical composition of the source(s) (long-term depleted to enriched). Pb isotopic data are distinctive in northern Honshu, with elevated $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ at specific $^{206}Pb/^{204}Pb$ (south *versus* north of the Tanakura Tectonic Line), are collectively elevated above the Northern Hemisphere Reference Line (and Izu–Mariana arcs), appear similar to portions of the Philippines and Tertiary basalts of eastern Asia, and probably reflect an Asian lithospheric heritage. The combined trace-element and isotope geochemistry of parental basalts distinguish different domains within the Izu–Bonin, central and northeastern Honshu arcs. The ultimate cause of these is most likely multicomponent, and some crustal assimilation is highly probable. However, these domains may in some part represent magma interaction with a subcontinental lithosphere dominated by Indian-Ocean-type mantle, or alternatively, derivation from an Indian-Ocean-type asthenosphere. The correlation of some magma compositional characteristics with nature of the basement terrane shows that the lithosphere plays a subtle but significant role in determining parental island-arc basalt characteristics. The longevity and character of the continental lithosphere in Asian margin arc systems, and its interaction with asthenosphere-derived melts, is an important process in island-arc basalt genesis.

Keywords: arc magmatism, petrogenesis, lithosphere, source, trace-element geochemistry, isotopic data, Honshu arc, Japan.

Sommaire

Les volcans des arcs du nord d'Izu – secteur sud-central de Honshu et du nord-est de Honshu, au Japon, sont situés dans une région où l'âge, la composition et la nature de la couche sédimentaire de la plaque en subduction semblent relativement uniformes. Nous essayons ici d'isoler quelques unes des variables associées à la genèse des magmas liés à la zone de subduction, afin de

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préciser leurs sources et la nature des processus pétrogénétiques. La composition chimique de certaines venues de magmas parentaux et évolués issus de quinze centres volcaniques plio-pléistocènes le long du front volcanique nous permet d'évaluer l'apport de la lithosphère au dessus de la zone de subduction. Cette lignée de volcans traverse plusieurs bordures importantes entre socles, dont la ligne tectonique de Tanakura, qui recoupe la lithosphère. Les compositions vont de basalte à rhyolite, avec une prépondérance de basaltes andésitiques et d'andésites; le mont Fuji, à dominance de basaltes, constitue une exception. La plupart des échantillons basaltiques sont relativement fractionnés, avec une teneur relativement faible en MgO (<7% en poids) et en Ni (<50 ppm), et un rapport $100Mg/(Mg + Fe^{2+})$ inférieur à 50. Des distinctions importantes parmi les suites volcaniques impliquant les éléments majeurs, les éléments traces, et les isotopes de Pb, Sr et Nd sont établies. La source la plus importante de ces venues de magma serait le coin de manteau, relativement réfractaire comparée à la source des basaltes des rides médio-océaniques. Ce domaine du manteau supra-subduction possède des valeurs de Nb/Zr et Zr/Hf inférieures à celles des chondrites. Plusieurs volcans possèdent en plus un faible rapport Zr/Y (par rapport aux basaltes des rides médio-océaniques), mais dans plusieurs cas, les rapports élevés de Zr/Y (>3) et Dy/Yb seraient une indication de l'implication du grenat dans leur genèse. De plus, les rapports isotopiques de Nd et de Sr indiquent des variations régionales dans la composition chimique des sources, soit appauvries ou enrichies à long terme. Les rapports isotopiques du plomb sont distincts dans le secteur nord de Honshu. Les valeurs de $^{208}Pb/^{204}Pb$ et $^{207}Pb/^{204}Pb$ sont élevées pour une valeur $^{206}Pb/^{204}Pb$ donnée dans le sud par rapport au nord de la ligne tectonique de Tanakura. Ces rapports sont tous élevés par rapport à la ligne de référence de l'hémisphère nord et aux arcs Izu–Mariana, ressemblent à des portions des Philippines et aux basaltes tertiaires de l'est de l'Asie, et refléteraient probablement un héritage lithosphérique asiatique. Une combinaison des éléments traces et des isotopes distinguent les différents domaines au sein des arcs de Izu–Bonin, du centre et du nord-est de Honshu. Leur cause ultime dépend de plusieurs composantes, et la probabilité d'une assimilation de la croûte semble réelle. Toutefois, ces domaines pourraient résulter de l'interaction d'un magma avec la lithosphère sous-continentale à caractéristiques de l'océan indien, ou bien à dérivation d'un asthénosphère de l'océan indien. D'après la corrélation entre certaines caractéristiques du magma et la nature du socle, la lithosphère jouerait un rôle subtil mais important dans l'établissement des caractéristiques du magma parental des suites à basaltes d'arc insulaire. La longévité et le caractère de la lithosphère continentale dans les systèmes d'arc en bordure de l'Asie, et son interaction avec les magmas issus de l'asthénosphère, seraient des facteurs importants dans la genèse des basaltes d'arcs insulaires.

(Traduit par la Rédaction)

Mots-clés: magmatisme d'arc, pétrogenèse, lithosphère, source, géochimie, éléments traces, données isotopiques, arc de Honshu, Japon.

INTRODUCTION

Understanding the petrogenesis of arc magmas has evolved from generalized conceptual models (*e.g.*, Ringwood 1974) to quantitative interpretations based on a broad spectrum of isotopic and geochemical data from individual volcanoes (*e.g.*, Edwards *et al.* 1994, Hunter & Blake 1995). Regional studies reveal the importance of slab geometry and composition, mantle domain, tectonic environment, and crustal thickness. The identification and assessment of different components [asthenophere, lithosphere (mantle and crust), slab-derived fluids] in arc magma genesis constitute a multi-faceted problem that involves interactions among minerals, melt and fluid. Confronted with a variety of mantle sources [Indian mid-ocean ridge basalt (MORB), Pacific MORB, ocean-island basalt (OIB), EMI, EMII, and High-Mu], subcontinental lithosphere, and crustal packages, the solution to this problem requires high-quality, comprehensive data-sets. Unfortunately, even with such an array of data, solutions in many cases are ambiguous.

Our greatest insight into mantle processes is provided through the examination of primary basalts, as they directly reflect the chemistry of their source (mantle). Primary basalts in the sense of derivation direct from (polybaric) equilibration with peridotitic assemblages are much sought after. However, even ultramafic-xenolith-bearing basalts (*e.g.*, southern Lesser Antilles, Solomon Islands, Kamchatka) are more likely primitive than primary (Thirlwall *et al.* 1996). Primitive basalts, defined as those with a Mg# ($100*Mg/(Mg + Fe^{2+})$ > 55, MgO > ~6 wt%, Ni and Cr contents greater than 100–200 ppm and parental to other basaltic and evolved magma-types in a given suite (BVSP 1981) are more common. More evolved basalts can be compositionally corrected (by addition of plausibly fractionated phases) to an arbitrary, relatively primitive reference-composition (*e.g.*, MgO of 6 wt%: Plank & Langmuir 1993) for purposes of inter-suite comparison. Nevertheless, it is important to realize that subtle changes in H_2O contents of melts can result in dramatically different sequences of crystallization in mafic magmas (Gaetani *et al.* 1993), so that these type of correction procedures are potentially flawed. Fortunately, some trace element *ratios* and, of course, isotopic characteristics are relatively robust through changes in sequences of olivine – pyroxene – plagioclase crystallization and can be used for purposes of source characterization (*e.g.*, Pearce & Parkinson 1993).

In this paper, we examine the chemistry of primitive and evolved magmas from volcanoes of the northern Izu, south-central Honshu, and northeastern Honshu arcs, Japan, to understand the nature of their sources. We initiated this study in an attempt to isolate some of the many variables involved in the genesis of suprasubduction-zone (SSZ) magmas. In situations where some of the variables such as age – composition – sediment cover are relatively uniform along restricted strike-lengths of the subducting plate, then other influences on the nature of the erupted magmas can be studied, such as mantle wedge heterogeneity (*e.g.*, Arculus *et al.* 1991) or crustal filter effects (*e.g.*, Hildreth & Moorbath 1988).

Scope of the Study and Background Information

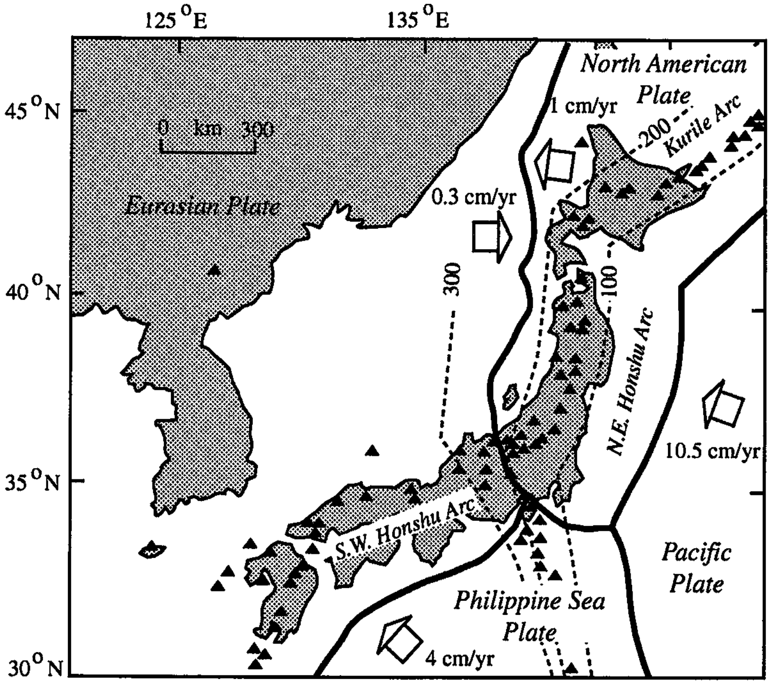
Although the volcanoes of the northern Izu – south-central Honshu – northeastern Honshu arc systems are well mapped, the geochemical database is fragmented; this study presents aspects of a new comprehensive regional petrological, geochemical and isotopic investigation of these Honshu volcanoes. We focus primarily on mafic magmas to address mantle-source issues. In the Honshu region, most basalts have relatively low MgO contents and Mg-numbers (typically <7.0 wt% and <55, respectively), have low Ni and Cr contents, and many are multiply-saturated with olivine, clinopyroxene and plagioclase. In fact, for most volcanoes (except Fuji and Oshima), basalts are rare. Thus, the primitive basalts discussed in this study are more evolved than primitive basalts from some other intra-oceanic arcs; we have not corrected our data to an even more primitive or a constant value. We recognize that our view of mantle sources and processes of Honshu basalts may be blurred by fractionation and crustal interaction (*cf.* Kersting *et al.* 1996). Our vision, although blurred, is perhaps not obscured. We note further, that some influence of crustal contamination can be detected even in the case of apparently primary, mantle-xenolith-bearing high-Mg alkali basalts from the southern Lesser Antilles (Thirlwall *et al.* 1996). Efforts to identify the sum of the individual inputs to arc magmas can clearly benefit from studies where distinctive heterogeneities in the crust (*e.g.*, ultramafic ophiolitic debris in Mt. Lamington in Papua; Arculus *et al.* 1983) or mantle wedge exist.

This study comprises a transect of fifteen different Plio-Pleistocene volcanoes that form the volcanic front of the northeastern portions of the Honshu arc [Tanakura Tectonic Line (TTL) transect] and the northern Izu – south-central Honshu arc [Asama – Yatsugatake – Fuji – Hakone – Oshima (A–Y–F–H–O; Fig. 1)]. Whereas both arcs result from the subduction of the Pacific Plate beneath the Eurasian – North American and Philippine Sea plates, they differ with regard to subduction-zone parameters, crustal structure and tectonic complexity. The selected transect of mature stratovolcanoes cross-cuts several terrane or tectonic boundaries of the overriding plate.

Variations in a number of important subduction-zone parameters are relatively restricted along the northeastern Honshu arc (TTL transect). For example, the age of the subducting Pacific Plate (~130 Ma), thickness of inbound sediments (800 m: von Huene & Culotta 1989), depth to the Wadati–Benioff Zone (~100–125 km) (Zhao *et al.* 1994), and crustal thickness (30 km: Zhao *et al.* 1994) are approximately constant from north to south. Some of the volcanoes of the northern Izu – south-central Honshu arc (*e.g.*, Fuji and Yatsugatake) overlie both the subducting Philippine Sea and Pacific plates, and the boundary between the Philippine Sea and Eurasian plates runs in a zone between Hakone and Fuji. Subduction parameters may differ with respect to the A–Y–F–H–O portion of the transect owing to the intersection of the Philippine and Pacific plates, deepening of the Wadati–Benioff Zone along strike from Oshima to Yatsugatake, and bending of the subduction zone to forrn the northern Izu – south-central Honshu arc.

The tectonic history of Japan is complex; see reviews by Uyeda (1991) and Isozaki (1996). Japan consists of accreted Paleozoic and Mesozoic terranes and continental arcs (granitic suites) that accumulated at the edge of the Asian craton (Ichikawa 1990, Faure & Natal'in 1992, Sato *et al.* 1992). Recent reconstructions suggest that northern Honshu and Hokkaido migrated from a position south of Korea, arriving in their present position around 100 Ma ago (Osozawa 1994). A change in plate geometry with the subduction of the Kula Ridge (40 Ma) and collision with the Izu–Bonin arc (25 Ma) split Japan from China about 25 Ma ago. The Sea of Japan is a pull-apart basin with a small amount of oceanic crust, caused primarily by dextral shear (Jolivet & Tamaki 1992). During the past 25 Ma, the volcanic front in northern Honshu migrated eastward and then westward, reaching its present position 3–5 Ma ago (Jolivet & Tamaki 1992, Finn *et al.* 1994). The northeastern Honshu arc is now located on the North American Plate and is currently in a stage of compression, with the subduction of the Pacific Plate along its eastern margin, subduction of the Philippine Plate in the southwest, and incipient thrusting of the Sea of Japan beneath northeastern Honshu (Uyeda 1991, Tamaki & Honza 1985). In the Kanto Plain, the Philippine Plate is poorly defined, and lies at rather shallow depths (Nakamura *et al.* 1984).

The volcanoes of Hakone and Oshima (part of the Izu–Bonin arc) overlie the Pacific Plate. To the west of the Y–F–H–O chain, the Itoigawa–Shizuoka Tectonic Line (ISTL) marks a terrane boundary and the western margin of the Fossa Magna; the Y–F–H–O volcanic centers erupted through the Chichibu (Y) and Shimanto (F–H–O) terranes. The strike of the Quaternary volcanic front makes a sharp turn between Yatsugatake and Asama (Fig. 1). On the basis of geochemical similarities, we have grouped Asama (located on the Sambagawa Terrane) with the Y–F–H–O volcanic centers in this study. In central Honshu, the volcanic front crosses several terrane boundaries, the most significant of which is the TTL or shear zone (Fig. 1). The TTL is a fundamental Mesozoic terrane boundary separating northeastern from southwestern Honshu; it was reactivated as a lithosphere-penetrating transcurrent fault during the Oligocene–Miocene opening of the Japan Sea (Jolivet *et al.* 1995). Volcanoes south of the TTL (*e.g.*, Akagi, Nikko, Nantai, Nyoho, Takahara, Nasu;



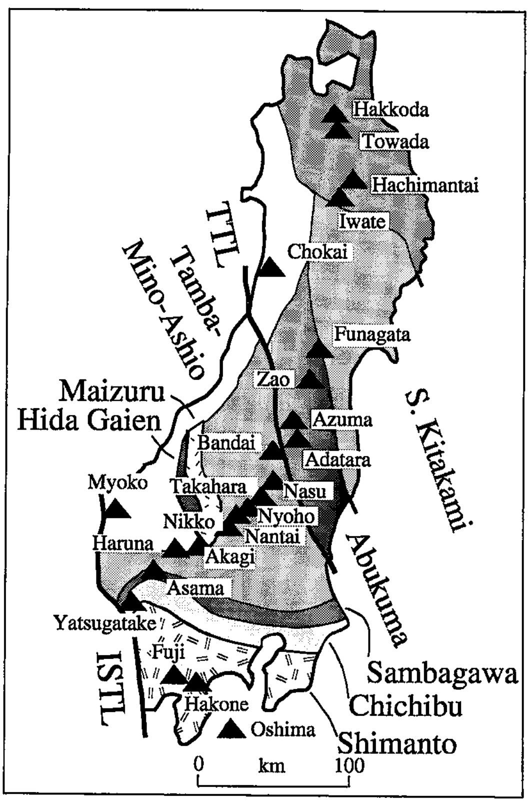


FIG. 1. Above, simplified tectonic location of Japan, with relative plate-motion vector, and to the left, terrane map of northeastern Honshu, after Ichikawa (1990). Locations of volcanoes studied (and others) indicated by triangles. Major terrane boundaries indicated by heavy lines. Abbreviations are: TTL: Tanakura Tectonic Line; ISTL: Itoigawa Shizuoka Tectonic Line.

collectively, STTL) overlie the Tamba – Mino – Ashio terrane, which comprises the central part of southwest Honshu. These terranes were welded to Asia prior to the Jurassic (Faure & Natal'in 1992), and may include a Precambrian lithospheric basement. Volcanoes north of the TTL (*e.g.*, Adatara, Azuma, Zao, Funagata; collectively, NTTL) overlie the Abukuma terrane, once part of a microcontinent that collided with Asia during the early Cretaceous (Faure & Natal'in 1992). Suites of granitic rocks are younger (~60–100 Ma) and more radiogenic in terms of $^{87}Sr/^{86}Sr$ (~0.708–0.710) south of the TTL than those to the north (100–110 Ma; <0.706, respectively) (Sato *et al.* 1992).

ANALYTICAL TECHNIQUES

Samples were analyzed for: major and trace elements by automated X-ray fluorescence spectrometry at the University of New England (UNE) (Siemens SRS300) and the Australian National University (ANU) (SRS300 and Philips PW1400); rare-earth and other trace elements by inductively coupled plasma – mass spectrometry at Monash University, and instrumental neutron-activation analysis (INAA) at the ANU. Separation of Sr and Nd at UNE was followed by determination of isotopic ratios by thermal ionization mass spectrometry (TIMS) at the jointly funded CSIRO–ARC Centre for Isotope Studies at North Ryde. Separation of Pb was followed by determination of isotopic ratios by TIMS at Lawrence Livermore National Laboratory.

Results

The data-set consists of results of approximately 400 major- and trace-element analyses, 40 rare-earth element (*REE*) analyses, 40 Sr and Nd isotope analyses, and 25 Pb isotopic analyses. All published data on these volcanoes have been compiled for comparison. The entire data-set is available from the Depository of Unpublished Data, CISTI, National Research Council, Ottawa, Ontario K1A 0S2, Canada. Representative results of analyses are presented in Tables 1 and 2.

The combined Honshu volcanic suite consists dominantly of tholeiitic basalts with low- to medium-K andesite and dacite (Fig. 2). The rock sequences of a number of the volcanoes include both tholeiitic and calc-alkaline suites in terms of the Miyashiro (1974) criterion of FeO*/MgO *versus* SiO_2 (Fig. 3). Both suites appear to merge to a common, relatively high-Mg parent containing 50 wt% SiO_2. There does appear to be a natural division between suites, with relatively high and low trends in terms of FeO*/MgO *versus* SiO_2, but interestingly, Miyashiro's division appears to be somewhat misplaced at low FeO*/MgO in the low SiO_2 range (Fig. 3). In total alkali – total Fe (expressed as FeO*) – MgO (AFM) plots, there is no clear break between tholeiitic and calc-alkaline suites, and a complete overlap of the Irvine & Baragar (1971) discriminant boundary.

Some suites include both low- and medium-K rocks (*e.g.*, Adatara, Zao, Nantai, Nasu, Nyoho), whereas others are generally restricted to low-K (*e.g.*, Funagata, Hakone, Oshima) or medium-K (*e.g.*, Azuma, Takahara, Yatsugatake, Fuji). Furthermore, some volcanoes are dominantly tholeiitic (*e.g.*, the most active, high-magma-flux volcanoes, like Fuji and Oshima), whereas others include both tholeiitic and calc-alkaline types (*e.g.*, Hakone, Nantai, Nyoho, Akagi, Adatara). Note that there is no simple coupling between K content and the tholeiitic *versus* calc-alkaline character on the basis of FeO*/MgO *versus* SiO_2 (Figs. 2, 3).

Overall, there are extensive variations in major-element composition at specific SiO_2 contents in the Honshu volcanic suites (Fig. 4). For example, a spread exists in MgO concentration at any specific SiO_2 content by a factor of 3. The overall trends on Harker plots of Al_2O_3 and CaO variation (Fig. 4) appear to indicate the initiation of plagioclase fractionation after that of olivine and clinopyroxene. Projections of normative components from plagioclase onto the olivine – clinopyroxene – quartz plane for the majority of the Honshu volcanic suites demonstrate significant displacements from the one-atmosphere cotectics, generally systematically displaced toward the olivine apex, *i.e.*, higher-pressure conditions (Fig. 5).

All of these Honshu samples have the characteristic positive Ba/Nb and K/La "spikes" of island-arc basalts and associated rocks. For example, N-MORB-normalized plots (Fig. 6) of the most primitive Honshu basalts ($7.4 \le$ MgO wt% < 5.4) exhibit patterns typical of many island-arc tholeiites, with enrichments in the large-ion lithophile elements (*LILE*), Nb, Ti depletions, and large enrichment spikes in Pb, alkaline earths and Li (see Fig. 6 for examples from Funagata, Zao, Nasu, Nantai, Asama, Yatsugatake, and Fuji). The *REE* abundances of basalts and basaltic andesites from the NTTL volcanoes are generally depleted relative to N-MORB (*e.g.*, Fig. 6; see also Togashi *et al.* 1992). A few samples have a very slight negative Eu anomaly, but generally lack any Ce anomaly. Some samples from STTL volcanoes are similar to NTTL samples, but others are enriched in the light rare-earth elements (*LREE*) relative to N-MORB. The overall spread of *REE* abundances is greater in the STTL basalt – basaltic andesite suites than in the NTTL samples. The overall *REE* abundances of Asama – Yatsugatake – Fuji are similar to some of the STTL group (*e.g.*, Fig. 6), whereas some of those of Hakone and Oshima have essentially flat patterns (Fujimaki 1975).

There are, however, some other systematic features of the trace-element geochemistry of the Honshu suites that merit attention and indicate some differences between the various sources of magma involved. For example, examination of the relative abundances of fluid-immobile but incompatible trace-elements (determined by ICP–MS and INAA) in order of increasing residual-mantle compatibility (Nb > Zr > Hf > Y; see Fig. 6) indicates ratios of abundances of less compatible to more compatible elements (*e.g.*, Nb/Zr, Zr/Hf) that are mostly strongly to weakly sub-chondritic (Fig. 7). On the other hand, Zr/Y is mostly super-chondritic (Fig. 7), but ranges from values ~2, equivalent to the highly depleted Zr/Y of the West Philippine backarc basin, through the N-MORB value of 3, to the relatively high values of 5 characteristic of the Daito Basin (one of several basins forming the Philippine Sea Plate; Fig. 8).

Low Nb/Zr and Zr/Hf values are indicative of magma derivation from a more depleted mantle source than that sampled by N-MORB. In contrast, however, the relatively high Zr/Y of much of the Honshu suite appears to reflect an intrinsically more fertile mantle-source (in the sense of magma extractability) than that tapped by N-MORB. We interpret this contradictory feature to reflect strong depletion in Y in some of the sample suites, most likely due to retention of Y in a residual phase during melt generation. Modeling of details of the *REE* abundance patterns following the

TABLE 1. REPRESENTATIVE COMPOSITIONS OF ROCKS FROM THE IZU – HONSHU ARC

Sample	Fun A	Fun B	6Z21	7AZ4	7AZ17	8AD4	8AD7	10NS1	10NS4	10NS12	11T2	11T4	14NO5	14NO10	12NT3
SiO_2	50.26	51.42	49.01	55.30	56.74	57.91	55.83	56.25	54.57	53.60	54.43	55.03	50.86	55.50	52.73
TiO_2	0.63	0.71	0.86	0.79	0.76	0.80	0.95	0.69	0.71	0.71	0.76	0.75	0.68	0.92	0.80
Al_2O_3	19.60	18.42	18.35	17.21	16.52	16.71	17.41	16.83	16.54	17.46	17.71	17.33	20.75	17.85	18.86
Fe_2O_3	2.24	2.86	3.15	2.36	1.83	1.92	3.71	2.97	2.15	4.44	3.05	2.86	3.36	2.96	2.75
FeO	6.73	6.73	7.19	6.21	6.27	6.08	5.89	5.11	6.59	4.73	5.65	5.65	5.60	7.07	6.78
MnO	0.16	0.17	0.17	0.15	0.14	0.14	0.17	0.14	0.15	0.15	0.14	0.14	0.14	0.18	0.16
MgO	5.42	5.11	7.36	4.84	4.75	4.15	3.52	5.08	6.48	6.16	5.09	5.02	4.74	3.83	5.21
CaO	11.87	11.06	11.10	8.46	8.14	7.87	8.50	8.37	8.93	9.14	9.09	9.28	11.20	8.75	9.90
Na_2O	1.48	1.70	1.48	1.85	2.10	2.13	2.33	1.91	1.84	1.67	1.81	1.92	1.52	2.57	1.93
K_2O	0.09	0.17	0.23	0.88	1.03	1.17	0.37	0.73	0.68	0.44	0.67	0.82	0.24	0.50	0.39
P_2O_5	0.05	0.05	0.08	0.09	0.08	0.09	0.15	0.06	0.09	0.06	0.11	0.11	0.11	0.15	0.09
Ba	33	68	175	265	320	308	156	311	239	263	301	277	153	183	179
Rb	2	2	7	28	32	40	9	19	22	13	15	25	9	14	11
Sr	179	171	269	235	225	232	278	249	245	233	269	267	297	274	299
Y	15	26	16	22	25	21	31	21	18	16	19	20	14	24	18
Zr	22	34	40	93	109	111	67	75	61	53	85	84	46	68	56
Nb	1	1	4	6	5	6	6	4	4	3	5	4	3	4	2
Pb	0	2	6	5	10	10	5	8	8	7	10	7	6	8	5
Th	1	1	5	5	6	8	4	7	6	4	8	6	3	4	3
U	0	2	3	1	3	2	3	3	1	2	2	3	3	2	3
Sc	51	53	39	35	33	31	44	29	31	27	32	36	37	39	36
V	267	297	319	247	224	220	211	219	239	220	278	249	253	245	282
Ni	18	15	37	30	38	17	9	47	62	50	27	29	25	13	25
Cr	107	87	87	84	84	39	26	130	262	208	84	87	59	24	74
Cu	65	64	57	48	34	41	39	48	36	51	53	73	66	66	48
Zn	70	77	81	81	78	78	102	78	83	90	80	78	77	100	90
Ga	15	15	19	19	18	20	21	18	18	20	19	19	22	23	21
La	5	6	12	4	10	11	8	14	4	5	17	11	5	17	3
Ce	1	0	11	28	29	24	18	27	14	16	25	24	18	26	19
Nd	4	4	8	17	15	14	14	16	11	13	16	14	11	17	11
La	1.73	3.22	3.38	7.09	7.80	8.26	6.37	9.61	6.22	5.12	9.49	10.37	5.37	7.52	6.29
Ce	5.45	6.97	9.08	16.82	18.42	19.11	14.32	21.95	14.84	13.07	20.78	22.24	12.94	17.55	14.66
Pr	0.89	1.23	1.42	2.29	2.45	2.53	2.32	3.07	2.06	1.86	2.82	2.99	1.86	2.54	2.05
Nd	3.70	5.45	6.06	9.72	10.16	10.34	10.61	13.22	8.48	7.84	11.60	12.63	7.51	11.35	8.64
Sm	1.41	1.83	1.87	2.65	2.73	2.73	3.03	3.45	2.29	2.35	2.88	3.10	1.98	3.06	2.23
Eu	0.56	0.67	0.70	0.74	0.72	0.70	0.97	0.95	0.74	0.79	0.83	0.88	0.70	1.00	0.75
Gd	1.75	2.45	2.27	3.00	2.97	3.00	3.72	3.86	2.61	2.72	3.04	3.44	2.20	3.67	2.52
Tb	0.33	0.47	0.40	0.52	0.52	0.51	0.64	0.66	0.46	0.49	0.52	0.59	0.38	0.66	0.44
Dy	2.37	3.27	2.56	3.34	3.38	3.27	4.18	4.02	2.87	3.14	3.08	3.64	2.37	4.11	2.76
Ho	0.55	0.76	0.57	0.74	0.74	0.72	0.94	0.83	0.61	0.69	0.67	0.76	0.51	0.88	0.59
Er	1.40	2.01	1.58	2.07	2.09	2.02	2.57	2.23	1.64	1.88	1.79	2.09	1.35	2.41	1.59
Tm	0.24	0.34	0.24	0.34	0.34	0.34	0.40	0.34	0.26	0.29	0.29	0.33	0.22	0.39	0.26
Yb	1.58	2.22	1.75	2.29	2.33	2.25	2.62	2.14	1.70	1.83	1.94	2.09	1.41	2.42	1.62
Lu	0.26	0.37	0.27	0.37	0.37	0.35	0.42	0.35	0.27	0.30	0.30	0.34	0.23	0.40	0.26
As	2	2	2	5	6	6	5	4	5	5	2	4	3	2	4
Li	3.46	4.43	4.08	9.80	12.37	12.41	6.28	8.62	7.86	7.19	7.45	7.34	4.07	5.64	6.33
Hf	0.76	1.03	1.32	2.79	2.91	2.98	1.72	2.30	1.81	1.71	2.21	2.50	1.36	1.94	1.48
Ta	0.63	0.62	0.31	0.54	0.58	0.79	0.33	0.38	0.65	0.60	0.30	0.54	0.42	0.42	0.35
Pb	2.24	2.80	4.52	8.14	8.77	8.65	4.32	7.44	6.75	7.48	5.63	7.76	5.52	6.58	5.02
Th	0.08	0.48	1.09	3.78	3.94	4.16	1.09	3.32	2.51	1.80	2.58	2.61	1.08	1.50	1.22
U	0.03	0.07	0.36	1.03	1.02	1.09	0.35	0.83	0.69	0.53	0.58	0.70	0.36	0.48	0.40
Sc	42.7	44.3	39.0	30.1	28.3	27.8	34.1	26.0	28.9	31.7	33.0	29.5	27.1	30.7	31.9
V	270.9	299.3	317.0	242.5	202.5	215.9	199.8	207.0	223.1	222.7	270.1	224.5	243.4	232.8	258.9
Cr	86.8	71.4	69.3	63.1	63.8	25.1	14.2	112.5	229.3	185.8	67.7	61.5	45.6	13.0	52.5
Ni	20.7	20.2	33.3	30.7	38.3	15.4	5.9	43.2	64.2	47.6	25.9	25.1	19.6	9.2	24.3
Cu	60.6	62.6	39.9	39.4	22.1	29.2	27.0	34.5	24.7	41.8	40.2	57.2	46.7	47.4	37.6
Zn	63.6	71.7	67.9	78.0	77.3	80.3	107.0	68.7	76.0	78.0	71.4	71.3	73.5	98.1	85.2
Ga	15.6	16.6	15.2	16.8	16.5	17.4	19.8	15.5	15.7	15.6	16.5	16.3	17.5	19.3	18.5
Ge	1.4	1.6	1.5	1.3	1.5	1.4	1.6	1.1	1.1	1.2	1.4	1.2	1.3	1.4	1.5
Rb	2.0	2.5	7.2	22.4	33.0	37.2	9.6	20.6	22.3	13.9	16.1	23.8	8.6	12.9	11.0
Sr	191.8	188.6	284.1	228.2	215.9	217.3	258.2	250.6	241.0	233.7	253.9	261.1	293.7	257.8	288.8
Y	15.2	24.5	16.6	20.9	22.6	21.7	28.2	20.5	16.1	16.6	19.1	19.0	13.1	22.8	15.9
Zr	27.9	37.2	39.5	83.1	95.0	95.6	55.5	67.2	51.5	47.5	78.4	73.9	39.9	58.2	48.3
Nb	0.9	1.3	1.5	3.1	3.5	3.9	3.8	2.2	1.6	1.5	3.0	2.9	1.6	2.4	2.0
Ba	49.7	75.7	127.0	233.9	261.9	269.6	139.5	255.8	212.7	156.3	239.1	248.9	115.1	164.5	153.8
Cs	0.05	0.06		1.68	1.93	2.24	0.38	0.94	1.24	0.74	0.91	0.63	0.47	0.21	0.46

The data are presented in three blocks. The first presents results of major-element analyses, quoted in weight % of the relevant oxides (X-ray fluorescence). The second block presents concentrations of trace elements, expressed in ppm (X-ray fluorescence). The third block presents concentrations of trace elements, expressed in ppm (ICP–MS). The region or volcano and the terrane are listed here for all samples: Fun A and Fun B: Funagata, Abukuma; 6Z21: Zao, Abukuma; 7AZ4, 7AZ17: Azuma, Abukuma; 8AD4, 8AD7: Adatara, Abukuma; 10NS1, 10NS4, 10NS12: Nasu, Ashio; 11T2, 11T4: Takahara, Ashio; 14NO5, 14NO10: Nyoho, Ashio; 12NT3: Nantai, Ashio. Isotopic data are presented in Table 2.

TABLE 1. REPRESENTATIVE COMPOSITIONS OF ROCKS FROM THE IZU – HONSHU ARC (continued)

Sample	12NT13	12NT17	16AK4	17AS1	17AS5	86-8-29-1	86-8-30-1	86-8-31.9	85-10-8-4	86-8-21-3	83-5-14-12	84-4-14-13	84-4-14-21	85-10-14-3	85-10-15-4
SiO_2	56.35	52.75	53.72	56.52	57.06	53.82	55.91	52.21	50.77	52.93	52.52	52.36	51.63	52.27	52.01
TiO_2	0.82	0.76	0.72	0.91	0.88	1.17	0.97	1.31	1.59	0.92	0.75	0.73	0.71	1.15	1.03
Al_2O_3	17.96	18.32	20.39	17.43	17.17	19.40	15.89	18.05	16.21	20.70	19.06	21.63	19.63	14.76	17.47
Fe_2O_3	2.25	3.24	3.39	2.34	2.72	3.13	2.31	3.09	2.18	3.26	1.82	3.40	3.33	4.29	3.29
FeO	6.39	6.01	4.64	5.64	5.11	4.74	5.32	6.05	9.06	4.93	7.16	4.31	5.80	8.80	8.29
MnO	0.15	0.16	0.15	0.13	0.13	0.14	0.13	0.16	0.18	0.15	0.16	0.13	0.16	0.22	0.19
MgO	4.07	5.53	3.75	4.37	4.42	4.06	6.19	4.66	5.64	2.93	5.41	2.55	5.56	5.15	4.21
CaO	8.41	9.56	9.79	8.42	8.15	8.10	7.52	9.30	9.24	9.86	9.66	11.23	10.01	9.85	10.41
Na_2O	2.55	1.92	2.19	2.77	2.75	3.66	3.65	3.29	2.80	3.09	2.16	2.53	2.12	1.96	1.71
K_2O	0.88	0.44	0.31	0.80	0.85	0.95	1.33	0.94	0.93	0.53	0.27	0.34	0.21	0.41	0.39
P_2O_5	0.15	0.12	0.13	0.14	0.13	0.29	0.18	0.26	0.39	0.15	0.08	0.13	0.08	0.16	0.09
Ba	330	212	149	240	331	219	262	145	244	92	84	41	55	124	104
Rb	25	12	8	19	18	19	29	19	17	6	2	4	2	7	5
Sr	291	311	395	371	357	609	499	641	391	432	278	373	334	176	194
Y	24	17	13	20	21	13	15	14	30	15	12	11	13	22	19
Zr	86	59	45	85	89	76	111	84	132	61	37	42	41	48	42
Nb	6	4	2	5	3	2	1	2	1	0	1	0	0	0	0
Pb	8	7	8	5	6	1	6	4	3	1	0	1	2	2	3
Th	5	4	8	4	5	0	0	0	0	0	0	0	0	0	0
U	3	1	3	2	2	0	0	0	0	0	0	0	0	0	0
Sc	31	34	1	30	26	20	19	17	34	22	33	29	32	50	42
V	221	254	181	274	251	233	216	260	334	214	262	256	262	589	489
Ni	16	38	14	20	21	3	98	7	49	5	26	6	29	20	13
Cr	44	102	26	45	46	10	215	0	83	0	73	0	57	35	28
Cu	56	62	29	72	73	19	46	14	273	67	89	38	65	327	289
Zn	87	85	72	78	73	73	69	78	101	74	63	58	67	98	85
Ga	22	19	20	22	21	21	16	16	18	19	14	15	13	17	14
La	21	10	9	10	13	6	8	4	5	0	0	0	0	0	0
Ce	33	21	15	23	28	19	20	24	27	8	1	5	6	0	4
Nd	19	15	10	13	15	12	27	19	34	5	3	7	0	19	13
La	10.80	7.80	5.79	6.84	7.59	11.23	10.97	10.05	10.13	4.67					
Ce	23.49	17.16	12.10	16.46	18.36	27.35	25.66	24.32	25.21	12.06					
Pr	3.02	2.32	1.79	2.40	2.62	3.68	3.57	3.60	3.84	1.98					
Nd	12.61	9.52	7.31	10.70	11.43	18.50	15.71	17.42	18.84	8.71					
Sm	3.08	2.33	1.96	2.81	3.02	4.27	3.63	4.30	5.04	2.49					
Eu	0.89	0.74	0.68	0.84	0.89	1.40	1.02	1.45	1.43	0.90					
Gd	3.36	2.52	2.01	3.05	3.11	3.70	3.26	4.79	5.08	2.61					
Tb	0.56	0.43	0.33	0.48	0.51	0.58	0.47	0.69	0.85	0.46					
Dy	3.48	2.61	2.14	3.13	3.28	3.23	2.79	4.14	5.11	2.74					
Ho	0.73	0.55	0.46	0.67	0.67	0.64	0.55	0.82	1.09	0.60					
Er	2.01	1.51	1.18	1.73	1.83	1.62	1.47	2.03	2.84	1.59					
Tm	0.34	0.24	0.18	0.27	0.28	0.24	0.21	0.31	0.45	0.25					
Yb	2.12	1.57	1.29	1.78	1.84	1.61	1.39	1.96	2.86	1.66					
Lu	0.33	0.25	0.20	0.28	0.29	0.25	0.22	0.31	0.43	0.26					
As	5	2	2	5	5										
Li	8.64	5.09	7.10	9.36	8.07	11.46	9.93	8.63	7.94	5.15					
Hf	2.19	1.55	1.14	2.21	2.25	2.12	2.73	2.91	3.23	1.54					
Ta	0.49	0.36	0.34	0.46	0.34	0.98	1.00	1.38	1.29	1.09					
Pb	7.21	5.51	3.34	5.19	4.62	4.11	6.24	4.66	6.89	3.76					
Th	2.51	1.71	0.58	1.26	1.43	1.95	2.66	1.26	1.39	0.44					
U	0.70	0.51	0.21	0.42	0.48	0.52	0.80	0.40	0.56	0.21					
Sc	27.3	26.5	22.9	27.5	26.5	23.1	23.7	25.4	29.6	26.5					
V	207.2	223.2	192.0	289.4	270.6	264.1	261.9	349.6	399.3	237.7					
Cr	30.6	82.3	13.4	34.4	40.4	22.6	251.7	13.9	110.4	2.3					
Ni	14.8	37.1	10.6	17.7	18.7	7.7	96.6	8.8	53.5	11.2					
Cu	40.3	49.1	21.4	57.5	52.8	26.9	54.2	27.4	207.5	63.4					
Zn	83.5	83.5	64.1	71.0	65.7	79.4	72.2	84.7	94.9	74.3					
Ga	18.6	18.3	16.5	17.4	16.0	21.1	18.3	19.9	16.7	20.9					
Ge	1.3	1.6	1.2	1.1	1.0	1.2	1.2	1.3	1.4	1.3					
Rb	26.3	13.3	8.0	19.0	18.6	21.4	34.6	20.4	18.0	8.6					
Sr	277.9	291.2	381.0	379.6	342.4	635.6	550.2	681.6	345.2	457.6					
Y	20.9	15.0	12.6	19.5	20.0	16.4	17.4	18.3	31.6	18.3					
Zr	74.2	48.4	41.2	78.4	82.9	71.3	106.9	80.4	115.9	55.0					
Nb	3.2	2.2	2.2	2.6	2.7	4.1	4.0	4.4	3.3	1.4					
Ba	263.5	183.2	119.9	216.1	230.6	270.5	304.0	211.2	263.2	165.5					
Cs	0.65	0.52	0.36	1.02	0.55	0.43	1.74	0.92							

The data are presented in three blocks. The first presents results of major-element analyses, quoted in weight % of the relevant oxides (X-ray fluorescence). The second block presents concentrations of trace elements, expressed in ppm (X-ray fluorescence). The third block presents concentrations of trace elements, expressed in ppm (ICP–MS). The region or volcano and the terrane are listed here for all samples: 12NT13, 12NT17: Nantai, Ashio; 16AK4: Akagi, Ashio; 17AS1, 17AS5: Asama, Ashio (?); 86-8-29-1, 86-8-30-1, 86-8-31-9: yatsugatake, North Kitakami; 85-10-8-4, 86-8-21-3: Fuji, Shimanto; 83-5-14-12, 84-4-14-13, 84-4-14-21: Hakone, Shimanto; 85-10-14-3, 85-10-15-4: Oshima, Philippine Plate. Isotopic data are presented in Table 2.

TABLE 2. ISOTOPIC DATA FOR REPRESENTATIVE SAMPLES OF VOLCANIC ROCKS FROM THE IZU – HONSHU ARC, JAPAN

Sample	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Fun A	0.704218	0.512945	18.42	15.55	38.4
Fun B	0.704237	0.512894	18.48	15.58	38.51
6Z21	0.703847	0.512900	18.37	15.54	38.32
7AZ4	0.704638	0.512764	18.48	15.59	38.55
7AZ17	0.704568	0.512747	18.45	15.57	38.47
8AD4	0.705082	0.512730	18.47	15.57	38.49
8AD7	0.705669	0.512650	18.48	15.58	38.52
10NS1	0.705034	0.512650	18.43	15.58	38.54
10NS4	0.704980	0.512750	18.41	15.54	38.47
10NS12	0.704491		18.42	15.58	38.53
11T2	0.705653	0.512610	18.41	15.58	38.54
11T4	0.705587	0.512610	18.43	15.59	38.58
14NO5	0.706054	0.512590			
14NO10	0.705775	0.512620			
12NT3	0.706011	0.512560	18.38	15.57	38.5
12NT13	0.706053	0.512520	18.39	15.56	38.54
12NT17	0.705945	0.512490	18.42	15.59	38.58
16AK4	0.706348	0.512570			
17AS1	0.703838	0.512933			
17AS5	0.703847	0.512927			
86-8-29-1	0.703743	0.512886			
86-8-30-1	0.703668	0.512948			
86-8-31-9	0.703676	0.512932			
85-10-8-4	0.703422	0.513053			
86-8-21-3	0.703424	0.513073			
83-5-14-12	0.703547	0.513098			
84-4-14-13	0.703507	0.513093			
84-4-14-21	0.703493	0.513054			
85-10-14-3	0.703659				
85-10-15-4	0.703652				

The region or volcano and the terrane are listed here for all samples: Fun A, Fun B: Funagata, Abukuma; 6Z21: Zao, Abukuma; 7AZ4, 7AZ17: Azuma, Abukuma; 8AD4, 8AD7: Adatara, Abukuma; 10NS1, 10NS4, 10NS12: Nasu, Ashio; 11T2, 11T4: Takahara, Ashio; 14NO5, 14NO10: Nyoho, Ashio; 12NT3, 12NT13, 12N17: Nantai, Ashio; 16AK4: Akagi, Ashio; 17AS1, 17AS5: Asama, Ashio (?); 86-8-29-1, 86-8-30-1, 86-8-31-9: yatsugatake, North Kitakami; 85-10-8-4, 86-8-21-3: Fuji, Shimanto; 83-5-14-12, 84-4-14-13, 84-4-14-21: Hakone, Shimanto; 85-10-14-3, 85,10-15-4: Oshima, Philippine Plate.

approach of Thirlwall *et al.* (1994) indicates probable involvement of garnet in the mantle source of Fuji, Yatsugatake, and Asama (Fig. 9).

A notable feature of the Honshu suites is the range of Th/U, from values close to that of N-MORB (*e.g.*, Asama – Yatsugatake – Fuji – Oshima) to relatively high values (~4; Fig. 10). Given the potential relative enrichment of U with respect to Th in slab-derived fluids, high Th/U, particularly of the NTTL and STTL suites, is a distinctive feature consistent with their elevated $^{208}Pb/^{204}Pb$ at specific $^{206}Pb/^{204}Pb$ (see below).

A major contrast in trace-element characteristics among these Honshu–Izu suites is the spectacular dichotomy in the behavior of the chalcophile elements Cu and Pb, and the covariation of these elements with respect to major lithophile elements such as K (Fig. 11). In general, the extreme enrichment of Cu with respect to either Pb or K occurs in the Asama – Yatsugatake – Fuji – Hakone – Oshima suites, whereas Cu is negatively correlated with these elements in most of the NTTL and STTL suites (together with some examples from Hakone).

Isotopic ratios clearly distinguish the various Honshu suites (*e.g.*, Kersting *et al.* 1996, Gust *et al.* 1996). With respect to Sr and Nd isotopic ratios, the STTL,

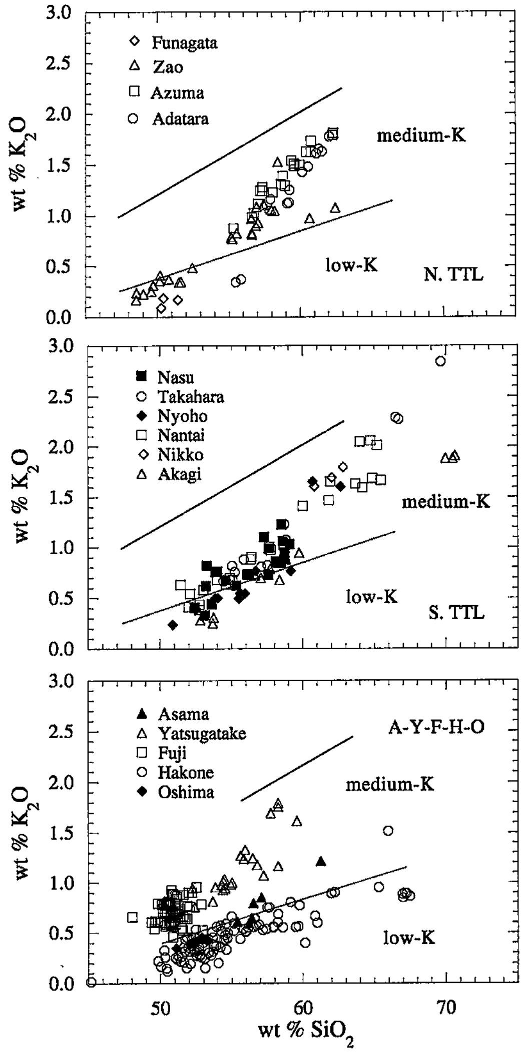


FIG. 2. Variation of wt% K_2O *versus* SiO_2 for the entire northern Izu – southern central Honshu and northeastern Honshu suites. High-, medium- and low-K discriminants are from Gill (1981). Collectively, the volcanoes are grouped into northern (N), southern (S) TTL, and northern Izu – south-central Honshu (Asama – Yatsugatake – Fuji – Hakone–Oshima) suites.

NTTL, Asama – Yatsugatake – Fuji – Hakone – Oshima suites are distinct (Fig. 12). In detail, the Fuji – Hakone – Oshima volcanoes have the lowest $^{87}Sr/^{86}Sr$ (~0.7034) and highest $^{143}Nd/^{144}Nd$ (~0.51305) values. Yatsugatake is characterized by similar $^{87}Sr/^{86}Sr$ (~0.7036), but slightly lower $^{143}Nd/^{144}Nd$ (~0.5129). It overlaps with NTTL volcanoes in these respects. STTL volcanoes have elevated $^{87}Sr/^{86}Sr$ and systematically lower $^{143}Nd/^{144}Nd$ (Fig. 12). The change in isotopic

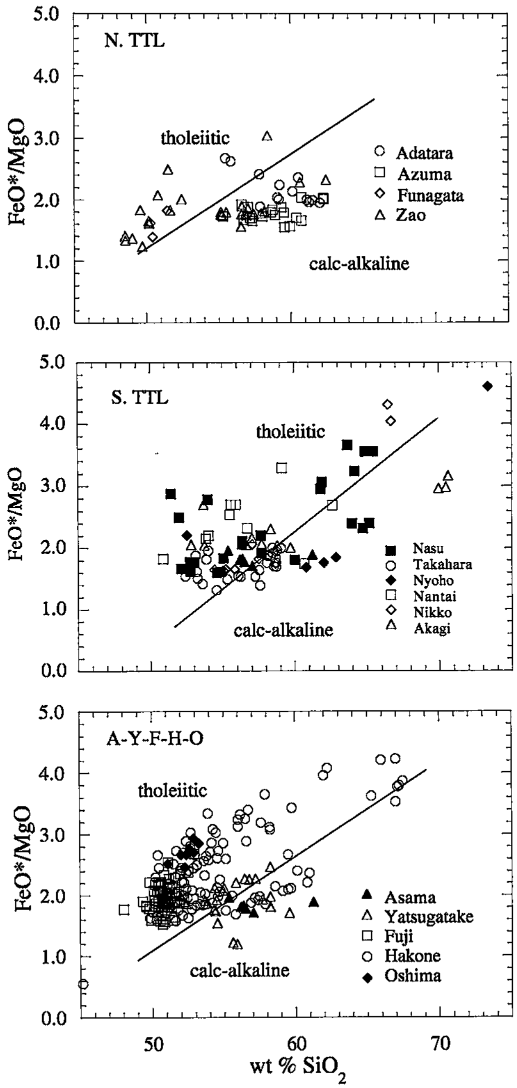


FIG. 3. Variation of total Fe as FeO*/MgO *versus* SiO_2 of the entire northern Izu – southern central Honshu and north-eastern Honshu suites. Discriminant line (tholeiitic *versus* calc-alkaline) after Miyashiro (1974). Groupings as in Figure 2.

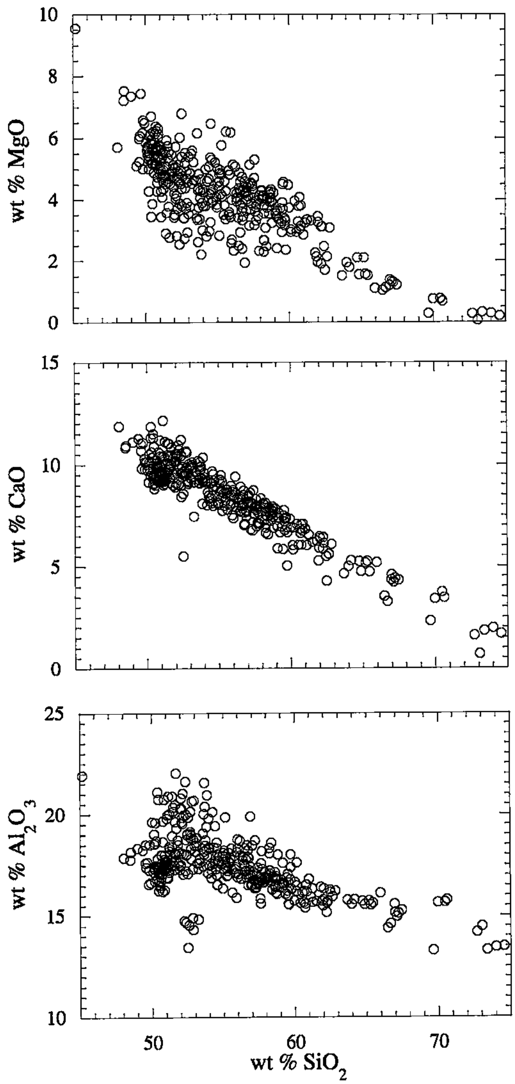


FIG. 4. Variation of selected major oxides *versus* SiO_2 for the entire northern Izu – southern central Honshu and north-eastern Honshu suites of samples.

composition from NTTL to STTL is systematic with respect to geographic location. Akagi, the most southerly STTL volcano, is the most enriched in terms of $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$.

Pb isotopic ratios (Fig. 13) are also distinctive with respect to geography. STTL rnagmas are systematically more enriched in $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ at specific $^{206}Pb/^{204}Pb$ than the NTTL (Kersting *et al.* 1996), which are again more enriched than the Asama – Yatsugatake – Fuji – Hakone – Oshima volcanoes. Three distinct arrays are formed on $^{208}Pb/^{204}Pb$ *versus* $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ *versus* $^{206}Pb/^{204}Pb$ for the different groups of volcanoes.

DISCUSSION

The geochemical characteristics of the A–Y–F–H–O, STTL and NTTL volcanic suites indicate that local

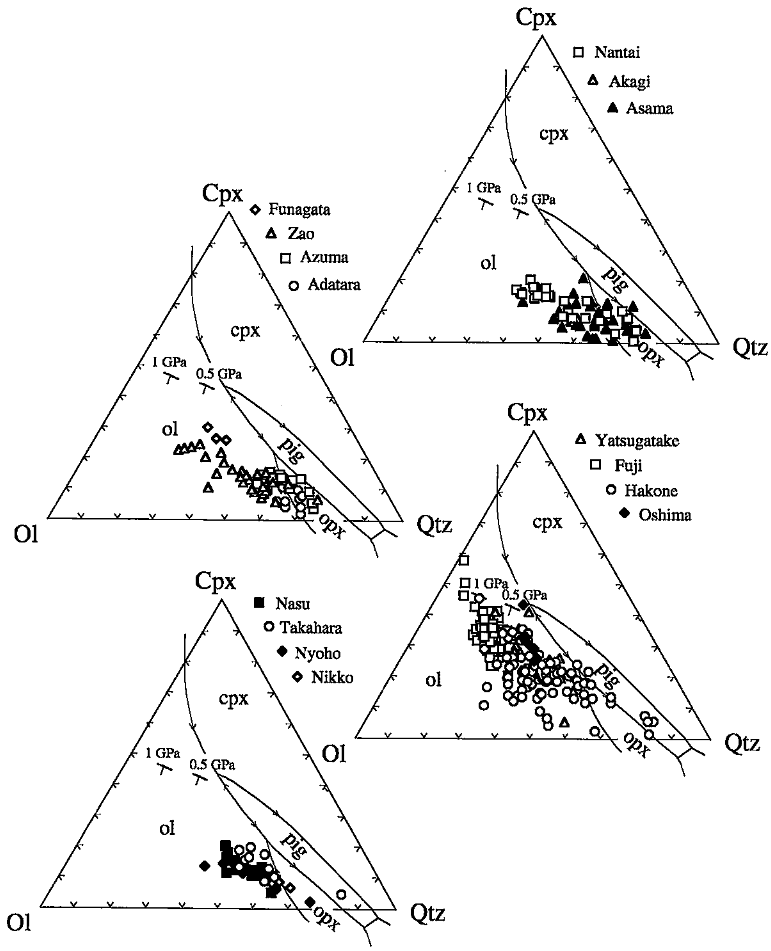


FIG. 5. Oxygen-weighted molar projections of individual sample suites from the northern Izu – southern central Honshu and northeastern Honshu arcs in the system olivine (Ol), clinopyroxene (Cpx), silica (Qtz). Approach, 1-atmosphere cotectics and primary phase fields after Grove *et al.* (1982). The data for Akagi are projected together with a subset of the STTL group to avoid clutter on the Y–F–H–O projection.

heterogeneities in source or petrogenetic process (or both) exist in the northern Izu – south-central Honshu and northeastern Honshu arcs. Analysis of the most primitive rock types of these volcanic suites suggests that certain geochemical characteristics define a regionally consistent framework. In this discussion, we focus on possible causes and implications of this regional framework, and in particular, examine the nature of and the interaction between asthenosphere and lithosphere in the arc environment. Several major components need to be considered with regard to the Honshu volcanic suites. These include: i) the downgoing plate(s), particularly the Pacific oceanic lithosphere plus sedimentary cover, ii) supra-subduction-zone sources, comprising the advecting mantle-wedge, asthenospheric section and Honshu lithospheric mantle, and iii) the Honshu crust.

Slab-derived components

The Honshu primitive basalts possess chemical signatures that are distinctive of SSZ systems worldwide. Plank & Langmuir (1993) concluded that the agents of mass transfer in subduction zones are melts from subducted sediment, and aqueous fluids from the basaltic layers of the subducted crust. These interact with the mantle wedge to provide a composite geochemical signature to arc magmas (*e.g.*, Arculus & Johnson 1981). It is clear that the Pb, Sr, and Nd isotopic characteristics

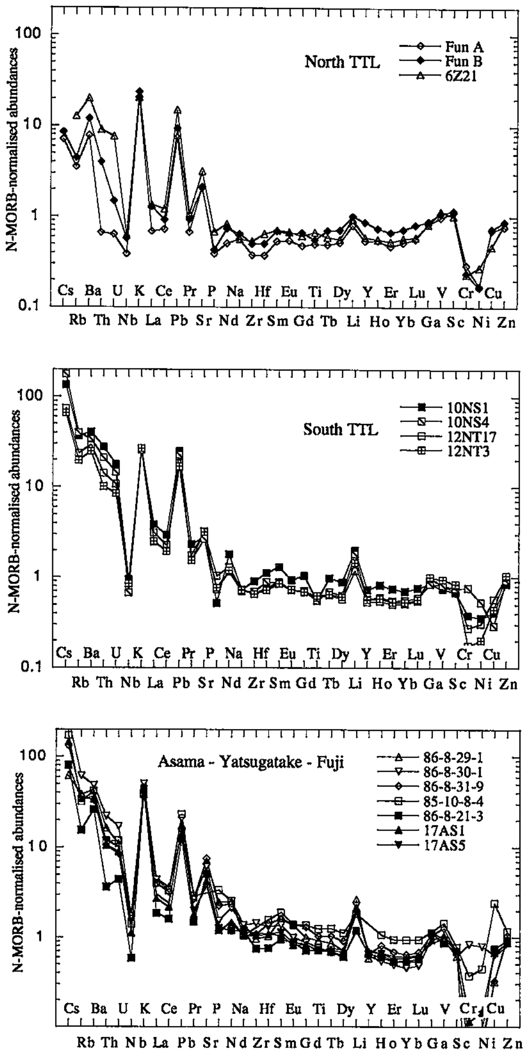


FIG. 6. Primitive mantle-normalized trace-element abundances for representative Izu–Honshu suites. Abbreviations are as follows: Fun: Funagata; Z: Zao; NS: Nasu; NT: Nantai; 86–8–29–1, 30–1, and 31–9 are from Yatsugatake; 85–10–8–4 and 86–8–21–3 are from Fuji; AS: Asama. Abundances used for normalization after Sun & McDonough (1989).

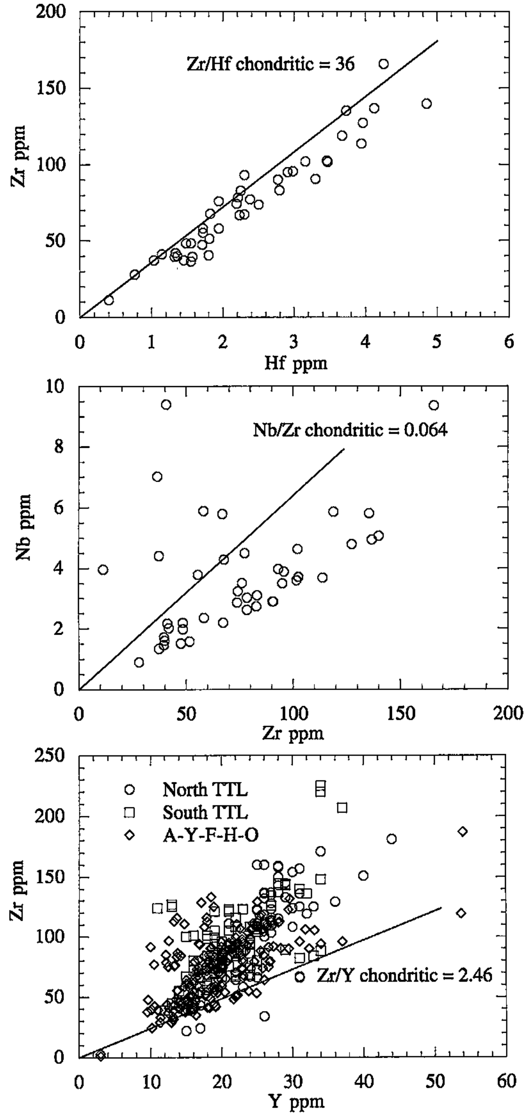


FIG. 7. Abundances of Zr *versus* Hf and of Nb *versus* Zr (by ICP–MS), and Zr *versus* Y (by XRF) for sample suites from the northern Izu – south-central and northeastern Honshu arcs.

of these Izu–Honshu magmas are not simply accounted for by slab-dominated elemental budgets. We argue that the *LILE* and *REE* enrichment in the Honshu basalts most likely results from the net complexities of slab-derived *and* wedge-remobilized SSZ fluid (plus melt), which promoted leaching and anatectic processes (*e.g.*, Hawkesworth *et al.* 1991).

The northern Izu – south-central Honshu and northeastern Honshu arcs are defined by the subduction of Pacific Ocean lithosphere. To a first approximation, therefore, the flux from this slab, be it fluid or melt or both, should be similar for each arc. Examination of normalized diagrams reveals *limited* systematic differences among these volcanic systems, for example the apparent greater abundances of highly mobile lithophile elements such as Cs and Rb in the NTTL magmas compared with the more southerly suites (Fig. 6). However, distinct differences exist in the case of Sr, Nd and

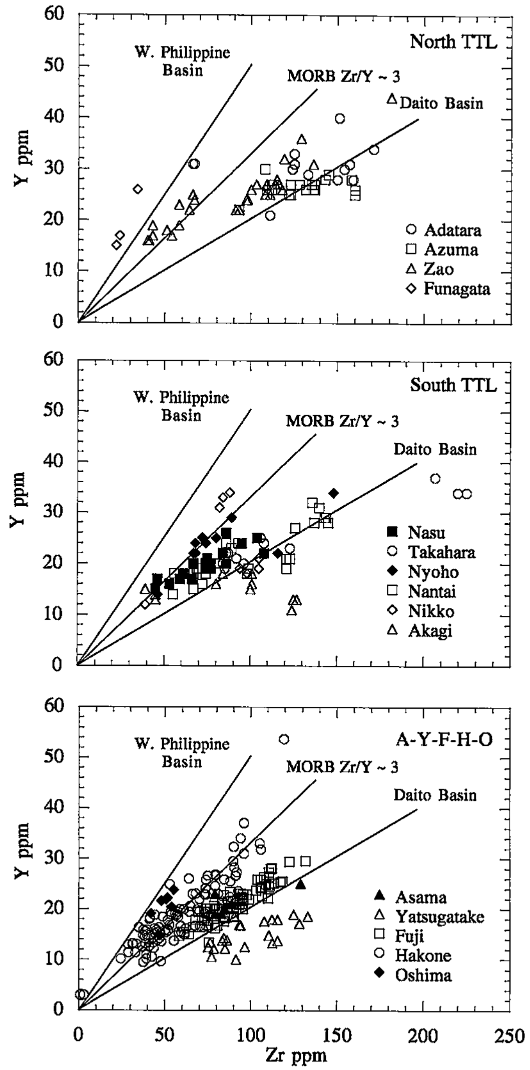


FIG. 8. Abundances of Y *versus* Zr (XRF data) for individual suites of samples from the northern Izu – south-central and northeastern Honshu arcs. Values for Western Philippine and Daito Basins are from Arculus *et al.* (1995). N-MORB and chondritic values from Sun & McDonough (1989).

Pb isotopic data (Figs. 12, 13). The $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ values are lower and higher, respectively, for A–Y–F–H–O magmas than for STTL magmas, whereas the isotopic compositions of the NTTL magmas are intermediate between these two groups. Geochemical flux arguments (Arculus & Powell 1986, Hawkesworth *et al.* 1991) suggest that a significant fraction (~80%) of the "excess" Sr in arc magmas is derived by leaching of the advecting mantle-wedge, with the balance provided by the subducted slab. Similar arguments can be advanced for the light *REE*, including Nd. Consideration of these two components indicates that the slab + wedge contribution must be highly variable in this region, and that the mantle wedge must differ significantly along the arc.

Pb may be a "reliable" element, equivalent to Ba and U, for tracing sediments through the subduction-induced recycling process (Plank & Langmuir 1993). This reliability is a function of the strong contrast in abundances between subducted sediments and mantle (or basalt), but is dependent on the absence of significant contamination by the upper crust. The variation in Pb isotopic characteristics of the Honshu basalts is of interest in this respect. A number of investigators have argued generally that a significant proportion of Pb in arc magmas is derived from subducted sediment (Ben Othman *et al.* 1989, Woodhead 1989), but Kersting & Arculus (1995) proposed an alternative interpretation.

The Honshu basalts (normalized to N-MORB) have elevated Pb abundances, similar to many arc basalts. A first-order observation is that the Pb isotopic values do not clearly trend toward the broad (imprecise) field defined by Pacific sediments (Fig. 13). In basalts with MgO > 5.5 wt%, $^{208}Pb/^{204}Pb$ or $^{207}Pb/^{204}Pb$ increases with increasing Pb, Th, and Ba. With respect to these samples, the variation observed is systematic from NTTL to STTL primitive basalts. Do these data imply a significant role for sediment in the NTTL and STTL magmas? Kersting *et al.* (1996) considered this question and noted that the possible Pb isotopic range for sediment subducted at Honshu greatly exceeds that observed in the arc magmas. The variation in Pb isotope composition for *all* Honshu basalts is much greater than for the few primitive basalts. Correlations among Pb isotopes and Ba, Th, and Pb enrichment and geography are not well defined in this larger data-set. If the northeastern Honshu Pb isotopic signature is derived primarily from sediment subduction, then this contribution is erratic within a volcano, as well as among volcanoes.

Mixing arrays on Pb–Pb isotope diagrams are sensitive to choice of end members. NTTL and STTL magmas define distinct arrays with different slopes and, thus, require distinct end-members. When compared with other arcs in the region, a wide variety of mantle – sediment end-members are required (Figs. 13, 14). Although the NTTL and Izu–Bonin suites seem to allow mixing of Pacific MORB (defined by the Northern Hemisphere Reference Line) and sediment, two of the most depleted samples in the region, Funagata (NTTL) and Torishima (Izu–Bonin) have the lowest $^{208}Pb/^{204}Pb$ or $^{207}Pb/^{204}Pb$ values. These samples, which should be the most sensitive to sediment mixing, record minimal sediment Pb signatures. STTL magmas define trends that are *irreconcilable* with simple "two-component" mixing, whereas Fuji–Oshima and Miocene volcanic rocks (Hanawa area) might be accounted for by mixing of mantle typical of the Sea of Japan (with Indian

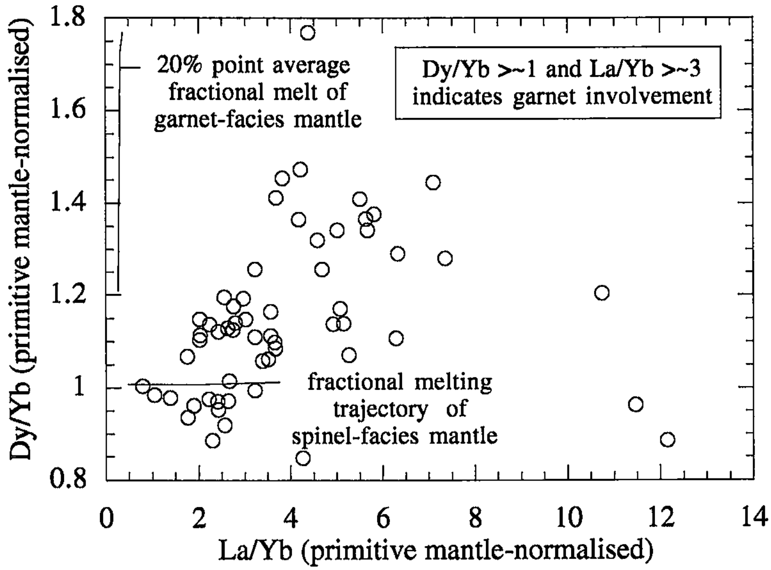


FIG. 9. Primitive-mantle-normalized Dy/Yb *versus* La/Yb for sample suites from the northern Izu – south-central and northeastern Honshu arcs. The melting trajectories for spinel- and garnet-peridotite fractional melting are from Thirlwall *et al.* (1994). For both spinel and garnet peridotite, increased degree of melting trends to lower Dy/Yb and La/Yb. Abundances used for normalization after Sun & McDonough (1989).

Ocean MORB-like Pb isotopic characteristics; Fig. 14) and sediment. If subducted sediment is responsible for the Pb isotopic characteristics of the Honshu basalts, then its involvement is extremely erratic.

Geological considerations are relevant to this discussion. The systematic variation observed in the isotopic ratios (particularly Pb) of the volcanoes correlates with their position relative to the TTL. It seems fortuitous that sediment mixing could explain the systematics of the observed Pb isotope variation on either side of this lithosphere-penetrating fault. As subduction occurs at an oblique angle to the arc and nearly perpendicular to the TTL, the distinct change in Pb isotope signature at the TTL cannot be explained solely by input from the subducted Pacific Plate. We argue that the composition of the sediments and SSZ processes should be uniform over this restricted, along-strike portion of the volcanic front. A sediment component may contribute (minimally) to the overall character of the TTL magmas, *but it is not the cause* of the isotopic differences among NTTL, STTL, and A–Y–F–H–O magmas.

Lithosphere – asthenosphere components

The interaction of basaltic magmas with the lithosphere beneath an arc has received considerable attention (*e.g.*, Kelemen *et al.* 1990). The simple division of the lithosphere into crust and mantle complicates the assessment of this interaction. In the Honshu arc, the crust may consist of two extremes, recently generated (Mesozoic–Tertiary) "arc" crust, or "ancient" (Proterozoic) Sino-Korean crust. The lithospheric mantle may be relatively depleted Pacific Ocean or relatively enriched EMI, EMII, or Indian Ocean (as tapped by east Asian basalts) type. On the basis of radiogenic and stable isotope data, Kersting *et al.* (1996) considered the mixing of basalt with distinct reservoirs in the lower crust to be an important process in the petrogenesis of the Honshu basalts. Other work in the Honshu arc [Tawada volcano: Hunter & Blake (1995), Matsuhisa & Kurasawa (1983), Notsu *et al.* (1985)] indicates that assimilation of crust is essential in explaining the evolution of the tholeiitic and calc-alkaline suites. The isotopic characteristics of felsic (dacitic and rhyolitic) magmas in the vicinity of the TTL (*e.g.*, Takahara, Nantai) indicate a role for crustal anatexis. Therefore, *crustal assimilation is a viable explanation* for some of the character and variability seen in the volcanic rocks of northeastern Honshu. However, it is also possible that other processes or sources contribute to the petrogenesis of the Honshu basalts. Evaluating the relative importance of each of these is at best a difficult task, owing to the numerous parameters that must be estimated. In the discussion that follows, we explore the possibility that the isotopic and chemical characteristics of the NTTL and STTL magmas reflect in part their mantle parentage.

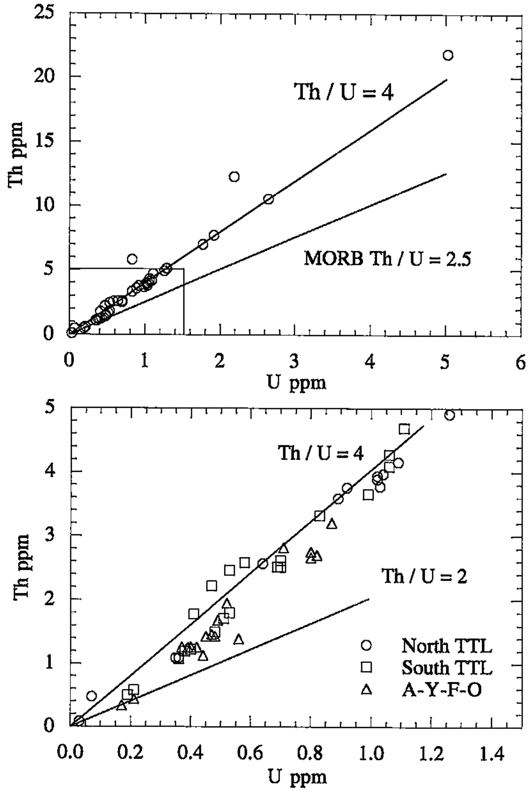


FIG. 10. Abundances of Th *versus* U (ICP–MS data) for suites of samples from the northern Izu – southern central Honshu and northeastern Honshu arcs. Note change in scale between upper and lower parts of the figure. Abbreviations are as in previous captions. Values for N-MORB from Sun & McDonough (1989).

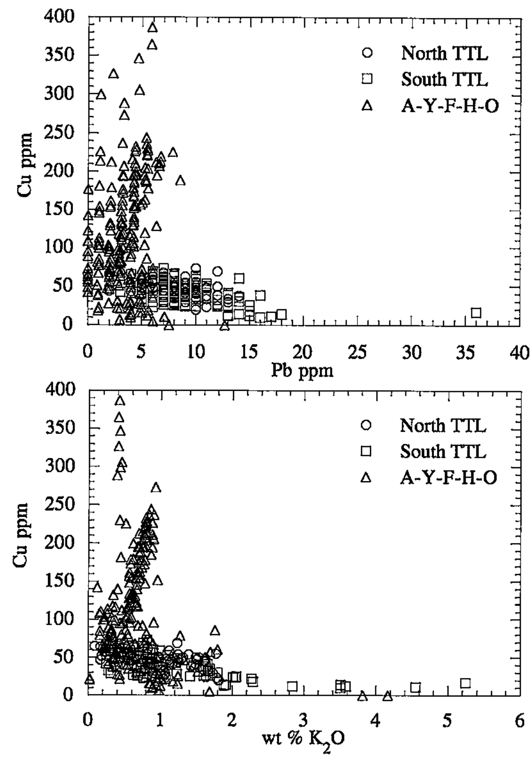


FIG. 11. Abundances of Cu *versus* Pb and K_2O (XRF data) for suites of samples from the northern Izu – southern central Honshu and northeastern Honshu arcs. Abbreviations are as in previous captions.

Pb isotopic ratios of ore minerals in major ore deposits in Honshu (Doe & Zartman 1979, 1982, Sato 1975, Sato & Sasaki 1980, Sato *et al.* 1981, Sasaki *et al.* 1982) provide a bulk estimate of Honshu crustal (lithospheric?) Pb composition [*i.e.*, the plumbotectonics approach of Zartman & Haines (1988); Fig. 14]. The lead in these ores, which come from a variety of Phanerozoic Besshi- and Kuroko-type deposits, records a temporal change in isotopic composition. Paleozoic Besshi-type deposits have Pb isotopic ratios that are similar to modern Pacific MORB, that is, they lie close to the Northern Hemisphere Reference Line. Mesozoic (Jurassic and Cretaceous) Besshi-type deposits are displaced to higher $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ at specific $^{206}Pb/^{204}Pb$ values. Tertiary Besshi and Kuroko deposits are even more elevated in $^{208}Pb/^{204}Pb$ and encompass and exceed the range present in the NTTL and STTL magmas.

The extreme $^{208}Pb/^{204}Pb$ signature of Tertiary ore Pb is significant for our understanding of the Honshu magmas for several reasons. Firstly, it indicates the presence of an ancient high-(Th/U) source in the Honshu lithosphere. Secondly, the ore Pb is significantly different from North Pacific sediment Pb and cannot be derived solely from it. Thirdly, it provides possible end-members with Indian Ocean MORB-type-source mantle for mixing curves within which both NTTL and STTL magmas may lie. In this respect, we note that the Pb isotopic ratios of the northeastern Honshu volcanic rocks overlap with the local Tertiary ore Pb, suggesting that both NTTL and STTL groups (and Tertiary ores) derive their Pb from the same source.

Potentially, the primitive basalts of the Honshu and northern Izu–Bonin can yield more information on the nature of the involvement of other sources. The important issue here centers on the composition of the asthenosphere in the Honshu arc. Is it Indian-Ocean-type mantle? If it is, where is it, when did it arrive, and how was it "emplaced"? Ultimately, we must focus on the

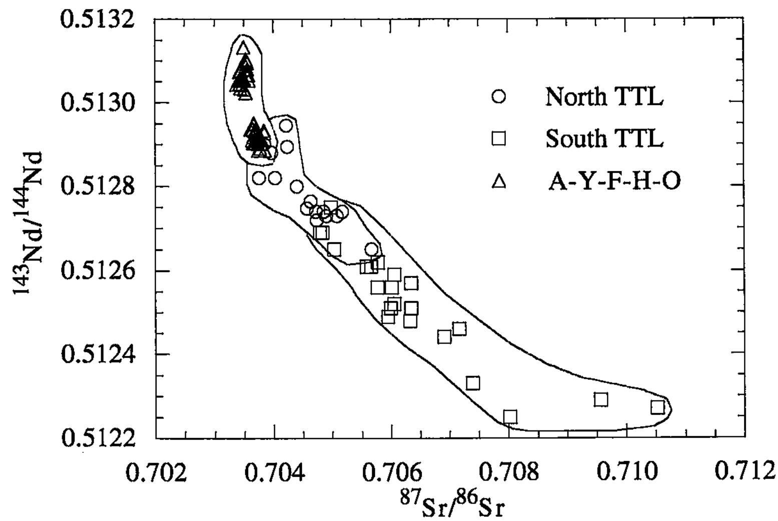


FIG. 12. $^{143}Nd/^{144}Nd$ *versus* $^{87}Sr/^{86}Sr$ for suites of samples from the northern Izu – southern central Honshu and northeastern Honshu arcs. Abbreviations are as in previous captions.

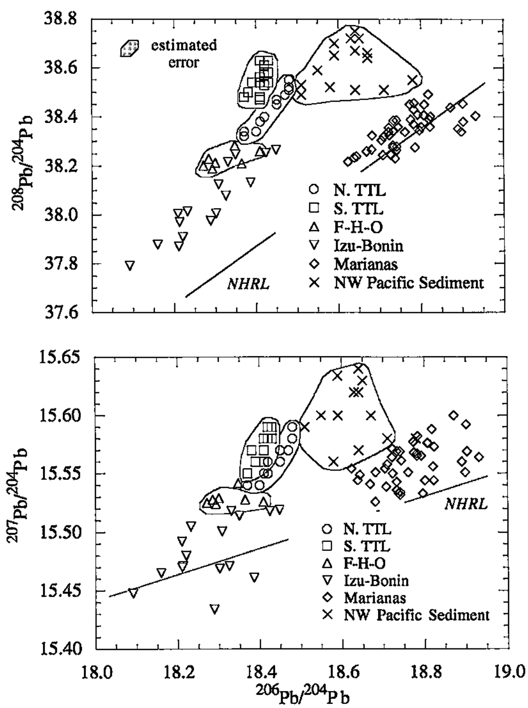


FIG. 13. $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ *versus* $^{206}Pb/^{204}Pb$ for suites of samples from the northern Izu – south-central Honshu and northeastern Honshu arcs, together with volcanic samples from the Izu–Bonin and Mariana arcs, and northwestern Pacific sediments. NHRL: Northern Hemisphere Reference Line. Other abbreviations are as in previous captions. Data sources cited in text.

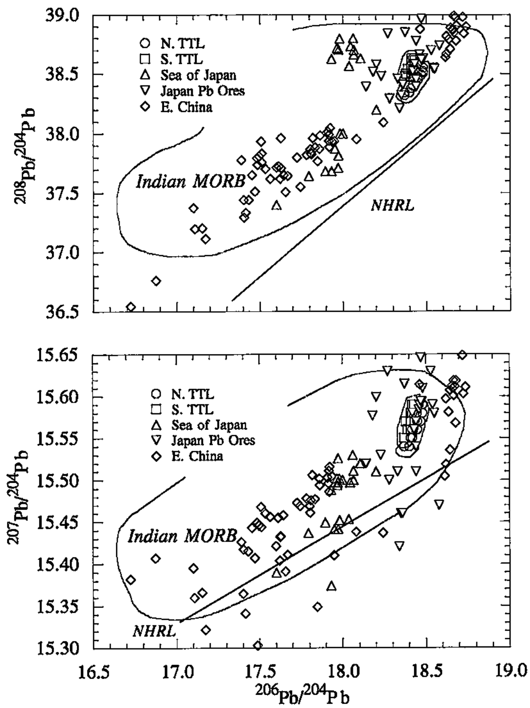


FIG. 14. $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ *versus* $^{206}Pb/^{204}Pb$ for suites of samples from the northern Izu – southern central Honshu and northeastern Honshu arcs, together with volcanic samples from the Sea of Japan, eastern China intraplate and sulfide ore deposits. Abbreviations are as in previous captions. Data sources cited in text.

nature of the boundary between mantle sources of Pacific Ocean and Indian Ocean types (*e.g.*, Hickey-Vargas 1991).

Indian Ocean asthenosphere is identified by its Dupal anomaly, being generally more enriched in $^{87}Sr/^{86}Sr$, $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ at specific $^{206}Pb/^{204}Pb$, and more depleted in $^{143}Nd/^{144}Nd$ than Pacific- and Atlantic-type MORBs (Dupré & Allègre 1983, Hart 1984, 1988, Zindler & Hart 1986). The ubiquitous presence of mantle of Indian Ocean type has been documented in all of the backarc basins of the western and southwestern Pacific (Hickey-Vargas *et al.* 1995).

The northeastern Honshu arc is isotopically quite unlike the majority of other arcs of the western Pacific (Kersting & Arculus 1995). The exceptions are some basalts of the Philippine arcs (Mukasa *et al.* 1987, Vidal *et al.* 1989). Conversely, the isotopic characteristics of some of the backarc basins and intraplate volcanoes of eastern Asia [*e.g.*, Sea of Japan: Tatsumoto & Nakamura (1991), southern China: Flower *et al.* (1992), Tu *et al.* (1991, 1992)] are similar with respect to Pb, Sr and Nd isotopic ratios (Fig. 14). Magmas from these regions are interpreted to be derived from a combination of EMI, EMII or Indian Ocean-like asthenosphere or subcreted lithosphere. Thus, the isotopic signature of the NTTL and STTL basalts, if not solely a result of crustal contamination, may reflect the presence of one or more of these mantle components as either asthenospheric or lithospheric mantle beneath the Honshu arc.

Volcanoes located at the intersection of the Izu–Bonin and Honshu arcs (Fuji, Hakone, Oshima) are distinct from the northeastern Honshu magmas; their isotopic signatures are more similar to Pacific MORB and Pacific arcs [*e.g.*, the Izu–Bonin arc: Pearce *et al.* (1992), Gill *et al.* (1994)]. The collision of the Izu–Bonin and Honshu arcs potentially juxtaposes two distinct mantle sources (Pacific and Indian Ocean) near central Japan. Unfortunately, the appropriate isotopic data do not exist to chart the spatial and temporal development of the isotopic character of the Honshu volcanic arc. Tectonic models for the area indicate that the position of the Quaternary Honshu volcanic arc was formerly in a fore-arc, and then backarc position over the past 30 Ma (Finn *et al.* 1994). Recent aeromagnetic evidence reveals that a substantial Early Cretaceous magmatic arc (represented by the Kitakami batholith) forms almost half of the modern Japan forearc basement (Finn 1994). Thus the lithosphere of the Quaternary Honshu arc has, in essence, been positioned behind the active arc for much of the past 70 million years.

Coupled with the opening of the Sea of Japan at about 25 Ma (Jolivet *et al.* 1995), this "backarc" environment may have experienced significant tectonic erosion by an injection of a hotter and chemically distinct asthenosphere (Nohda *et al.* 1988). Although asthenosphere injection may have ceased at 10 Ma when the Sea of Japan stopped opening (Jolivet *et al.* 1995), the mantle injected by that process could have been retained. Allowed to slowly cool, this asthenosphere may have become lithosphere (Tatsumi *et al.* 1992). Thus the Indian-Ocean-type isotopic signature of the NTTL and STTL magmas may have resulted in part from a "failed" spreading event and replacement of pre-existing lithosphere.

This model suggests that more Indian Ocean mantle would be present where greater spreading occurred in the Sea of Japan. Examination of magnetic anomalies within the Sea of Japan indicates that the greatest amount of spreading occurred immediately to the west of a northerly trending narrow strike-slip margin (extension of the TTL) (Jolivet & Tamaki 1992), and propagated westward. Thus the portion of the Honshu lithosphere most likely to be affected by Sea of Japan asthenosphere is that which lies west of the TTL.

Conclusions

We conclude that the trace-element and isotopic geochemistry of "primitive" basalts defines different domains within the Izu–Bonin, central Honshu and northeastern arcs. The ultimate cause of these is most likely multicomponent. Although the fundamental geochemical characteristics of the Honshu arc result primarily from SSZ processes, it seems clear that variations among volcanoes in these arc segments must derive from other factors. For example, strong arguments can be advanced for crustal assimilation (Kersting *et al.* 1996). These investigators pointed out the fact that geographic position correlates strongly with isotopic character. We suggest that these domains may also represent, in some part, interaction with a subcontinental lithosphere dominated by Indian-Ocean-type mantle or derivation from an Indian-Ocean-type asthenosphere. It is also clear from relative abundances of trace elements with varying incompatibilities in spinel peridotite or garnet peridotite assemblages that a dominant (previous) melt-depleted wedge source must be involved; the involvement of garnet appears to be restricted to a few centers on the volcanic front (Fuji, Yatsugatake, and Asama) located over relatively deep (~150–200 km) parts of the subducted Pacific Plate.

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