Tamaki, K., Suyehiro, K., Allan, J., McWilliams, M., et al., 1992
Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 127/128, Pt. 2

57. ND AND SR ISOTOPIC STUDY OF LEG 127 BASALTS: IMPLICATIONS FOR THE EVOLUTION OF THE JAPAN SEA BACKARC BASIN[1]

Susumu Nohda,[2] Yoshiyuki Tatsumi,[3] Shigeru Yamashita,[4] and Toshitsugu Fujii[4]

ABSTRACT

Sr and Nd isotopic compositions are reported for basaltic rocks collected during ODP Leg 127 from the Yamato Basin, a rifted backarc basin in the Japan Sea. The basalts are classified into two groups in terms of Nd isotopic composition: the upper sills at Site 797 are characterized by higher $^{143}Nd/^{144}Nd$ ratios (0.513083–0.513158, ε_{Nd} = 8.68–10.14) and the basalts from Site 794 and the lower sills at Site 797 have lower $^{143}Nd/^{144}Nd$ ratios (0.512684–0.512862, ε_{Nd} = 0.90–4.37). All of the basalts show higher Sr isotopic compositions than those of the mantle array, which is attributed to seawater alteration. The basalts with lower Nd isotopic values ranging in age from 20.6 to 17.3 Ma have tapped an enriched subcontinental upper mantle (SCUM) with the minor involvement of a depleted asthenospheric mantle (AM). Subsequent change in composition through the physical replacement of SCUM by AM yielded the basalts of the upper sills of higher Nd isotopic compositions. This event within the upper mantle was associated with the breakup of the overlying lithosphere during the rifting of the Japan Sea backarc basin.

INTRODUCTION

This report presents the Nd and Sr isotopic compositions of basalts collected from the Japan Sea floor during Leg 127 of the Ocean Drilling Program (ODP) (Fig. 1). Based on the isotopic data, we examine the geochemical evolution of the upper mantle beneath the terrain during the rifting/opening process of the Japan Sea backarc basin.

The opening of the Japan Sea had been, hitherto, inferred from magnetic anomalies in the Japan Sea (Isezaki, 1986; Kono, 1986) and a sharp change in marine faunas from warm to cold water in the early Miocene deposits dated at about 15 Ma along the Japan Sea coast (Chinzei, 1986). Rapid clockwise rotation of the southwest Japan arc sliver and counterclockwise rotation of the northeast Japan sliver were suggested from paleomagnetic studies of Tertiary volcanic rocks of the Japan arc (Otofuji and Matsuda, 1983; Otofuji et al., 1985b). The rotational movement of the arc slivers resulted in the fan-shaped opening of the Japan Sea at about 15 Ma (Otofuji et al., 1985a). Alternatively, Lallemand and Jolivet (1985) proposed a pull-apart basin model to explain the opening of the Japan Sea. Tamaki (1985) pointed out the existence of multirifts during the opening of the Japan Sea Basin. As for the commencement of rifting in the Japan Sea, an age of about 30 Ma, which is older than the age of rotation of the arc slivers, was estimated on the basis of stratigraphy, basement depth, and heat-flow data by Tamaki (1986). The ^{40}Ar-^{39}Ar dates of three dredged samples from the slope of the Japanese Islands in the basin yielded ages of 23–24 Ma and an age of 26 Ma for an andesite from the Yamato Bank (Kaneoka and Yuasa, 1988).

Nohda and Wasserburg (1986) and Nohda et al. (1988) reported Nd and Sr isotopic compositions for Tertiary volcanic rocks from the northeast Japan arc and documented secular variation in the isotopic composition of the enriched to depleted signature of the magma source region through time. This secular variation was considered in the framework of backarc opening in the Japan Sea and attributed to the growth of depleted asthenospheric materials into the preexisting enriched upper mantle. Nohda et al. (1988) and Tatsumi et al. (1989) proposed a hypothetical model of asthenospheric injection to explain the initiation of backarc opening in the Japan Sea. Tatsumi et al. (1990) and Tatsumi and Kimura (in press) inferred that some backarc and continental rift systems are triggered by the injection and/or upwelling of asthenospheric mantle materials.

The basalts recovered during ODP Leg 127 are representative of magmatic activity during the rifting and opening of the Japan Sea and as such were imprinted with the evolutionary milestones of the mantle through the tectonic event. In this paper we analyze the Nd and Sr isotopic compositions of nine basalt samples from Site 797, three samples from Site 794, and one from Site 795 (Fig. 2). The results may provide important constraints on mantle evolution through the rifting and opening of the Japan Sea backarc basin.

SAMPLES

Samples were recovered from basement at Sites 794 and 797 in the Yamato Basin and from Site 795 in the Japan Basin. The Japan Basin is considered by Ludwig et al. (1975) to be composed of oceanic crust. The seismic velocity of the crust of the Yamato Basin is intermediate between that of the continent and the ocean (Hirata et al., 1987). It should be stressed that the crust of the basin is twice as thick as ordinary oceanic crust (Hirata et al., 1989). The velocity characteristics of Site 794 show a more continental signature than other areas of the Yamato Basin (Shinohara et al., this volume). The lithology and petrography of the basalts from Sites 794, 795, and 797 are given elsewhere (Tamaki, Pisciotto, Allan, et al., 1990).

The Japan Basin basalts (Site 795) are heavily altered (Allan and Gorton, this volume) and the original chemistry may not be preserved. The basalts from Site 794 in the Yamato Basin are also variably altered, with loss on ignition (LOI) ranging from 1.7% to 5.6% (Allan and Gorton, this volume). The samples from Site 794 are tholeiitic basalts, based on their chemistry and quench-margin prealteration mineralogy of plagioclase, olivine, and Cr-spinel (Tamaki, Pisciotto, Allan, et al., 1990). Some samples appear to be quite primitive, but care must be taken as even the contents of the major elements have been affected by alteration (Allan and Gorton, this volume). All of the samples from Hole 794C show a slight enrichment in the light rare earth elements (LREEs) and large-ion lithophile elements (LILEs) against N-MORB abundance (Allan and Gorton, this volume). $^{40}Ar/^{39}Ar$ ages of the Site 794 basalts indicate intrusion at about 20 Ma (Kaneoka et al., this volume).

Drilling at Site 797 recovered the deepest core, which may cover a wider time span than that from Site 794. The basalts from Site 797 are also altered to varying degrees, with LOI values ranging from

---

[1] Tamaki, K., Suyehiro, K., Allan, J., McWilliams, M., et al., 1992. *Proc. ODP, Sci. Results,* 127/128, Pt. 2: College Station, TX (Ocean Drilling Program).

[2] Kyoto Sangyo University, Kamigamo-Motoyama, Kita-ku, Kyoto 603, Japan.
[3] Department of Geology and Mineralogy, Kyoto University, Kitashirakawa-Oiwakecho, Sakyo-ku, Kyoto 606, Japan.
[4] Earthquake Research Institute, University of Tokyo, Yayoi 1-1-1, Bunkyo-ku, Tokyo 113, Japan.

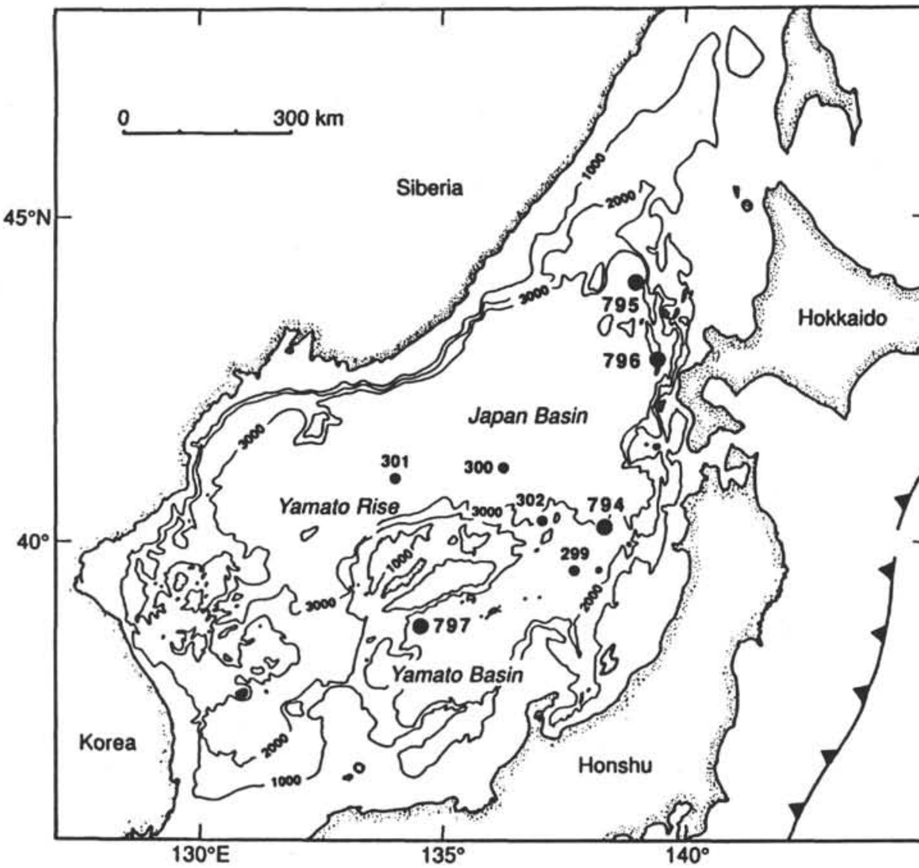

Figure 1. Topographic features of the Japan Sea. Numbered sites were drilled during ODP Leg 127 and Deep Sea Drilling Project Leg 31.

1.6% to 8.4% (Allan and Gorton, this volume). The rocks were classified into two groups: high-alumina basalts in the upper section (Units 1–9) and enriched tholeiites in the lower one (Units 10–21) (Tamaki, Pisciotto, Allan, et al., 1990). Distinctive geochemical characteristics of the basalts in the upper group are the flat chondrite-normalized patterns exhibited for the rare earth elements (REEs) with slight relative depletions in the LREEs and lower concentrations than those of typical N-MORBs in all of the incompatible elements except for Sr (Allan and Gorton, this volume). Because of the extremely low concentrations of potassium, no reliable isotopic ages could be obtained for the upper group (Kaneoka et al., this volume).

The lower group of units clearly differs in composition from the upper group, being more evolved and having higher amounts of incompatible elements (Allan and Gorton, this volume). Chondrite-normalized REE patterns are characterized by substantial LREE enrichment. Most of the LILEs and high-field-strength elements are enriched in respect to N-MORB. These N-MORB-normalized element patterns of the lower group are quite different from those of the upper group and require a disparate mantle source. ^{40}Ar-^{39}Ar ages ranging from 17.3 to 19.0 Ma (Kaneoka et al., this volume) may indicate the time of intrusion of the lower sills.

ANALYTICAL PROCEDURE

The Sr and Nd isotopic compositions were analyzed using a Finnigan MAT 261E mass spectrometer at Kyoto Sangyo University, following the analytical procedure described in Nohda et al. (1988) with minor modifications as follows. Splits of the powdered samples weighing about 100 mg were decomposed in HF and $HClO_4$ mixtures in Teflon vials. The clean sample solutions were passed first through a small cation-exchange column (2-mL resin volume Biorad 50WX12) using 2.5N HCl and 4.0N HCl, and then the fractions of Rb, Sr, and the REEs were eluted through a second column (5-mm inside diameter, 2-mL resin volume Biorad 50WX8) to purify the Sr and LREEs. The LREEs were loaded onto a microcolumn (2.5-mm inside diameter × 13-cm-long Biorad 50WX8) and treated with 0.2M MLA adjusted to a pH of 4.50 with ammonium hydroxide. Further purification of the Nd fraction was carried out on a second microcolumn (2.5-mm inside diameter × 6-cm-long Biorad 50WX4). Such minor modifications enabled us to reduce the total amount of HCl to separate the Sr and Nd and were effective in lowering the chemistry blank. The total chemistry blank run during the period of analysis was estimated to be <1 ng Sr, <30 pg Nd, and about 4 pg for Sm. No isotopic correction is needed from the present blank.

Sr isotopic ratios were normalized to $^{86}Sr/^{88}Sr = 0.1194$, and Nd isotopic ratios to $^{146}Nd/^{144}Nd = 0.7219$. Recent average values of standard samples are $^{87}Sr/^{86}Sr = 0.710181 \pm 0.000018$ ($n = 13$) for NBS987, 0.707943 ± 0.000027 ($n = 5$) for Eimer & Amend $SrCO_3$, and $^{143}Nd/^{144}Nd = 0.511866 \pm 0.000009$ ($n = 15$) for La Jolla Nd. For BCR-1, $^{87}Sr/^{86}Sr = 0.704967 \pm 0.000025$ ($n = 6$) and $^{143}Nd/^{144}Nd = 0.512629 \pm 0.000011$ ($n = 5$) were obtained.

For five selected samples from Site 797, we determined concentrations of Nd and Sm by adding ^{150}Nd and ^{147}Sm spikes to the aliquot sample solutions (Table 1).

In this study, we analyzed the powdered samples usually without any washing treatment. In order to examine the effect of alteration after the emplacement of basalts, two representative samples were washed with 4N HCl at 60°C for 24 hr (Table 1).

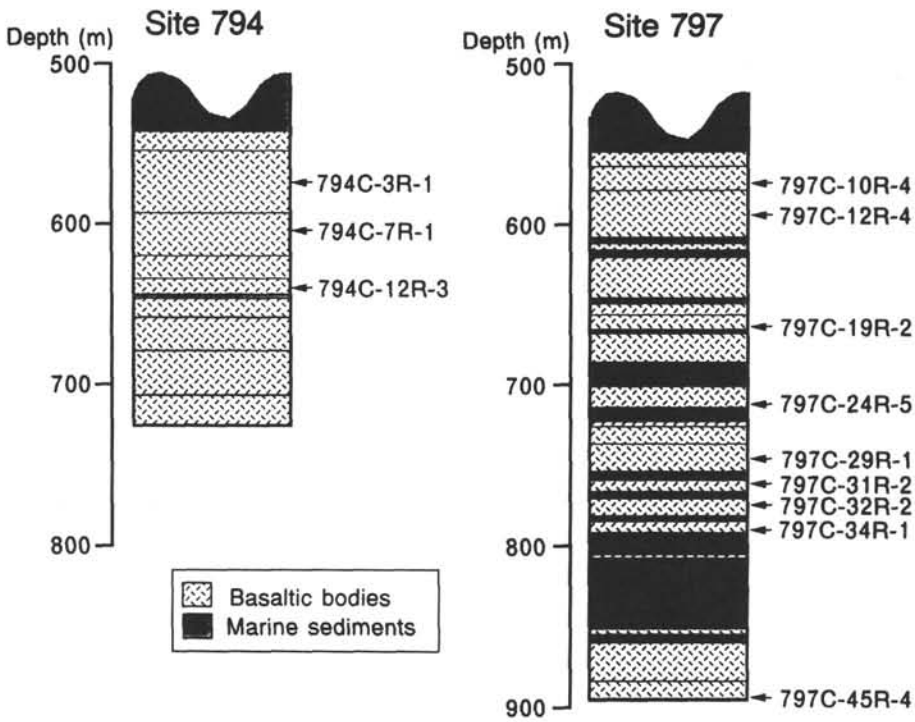

Figure 2. Columnar sections and analyzed samples for Sites 794 and 797.

RESULTS AND DISCUSSION

The Sr and Nd isotopic data are listed in Table 1 with some of the trace element concentrations reported by Tamaki, Pisciotto, Allan, et al. (1990).

Effect of Seawater Alteration

Basalts recovered from oceanic environments are subjected generally to seawater alteration, which is typically reflected by their higher Sr isotopic signatures (e.g., Hart and Nalwalk, 1970; Dasch et al., 1973; Hart et al., 1974). Acid leaching is commonly employed in order to determine the original Sr isotopic ratio (e.g., Volpe et al., 1987; White et al., 1990).

All of the samples analyzed in the present work are altered to varying degrees. The interstitial mesostasis is partially to completely replaced by clays. The LOI data suggest that even major elements such as K_2O, MgO, and CaO are strikingly affected by alteration. The coupled increase in MgO and decrease in CaO may be related to the formation of mixed-layer secondary clays (Allan and Gorton, this volume).

We washed two representative samples (127-797C-19R-1 and 127-797C-34R-1) with 4.0N HCl at 60°C for 24 hr. The density of the HCl and the washing time seemed sufficient to eliminate the Sr from the altered part. The washed samples show slightly lower values of Sr isotopes than those of the unwashed (0.704361–0.704200, 2.3 ε_{Sr} units for Sample 127-797C-19R-1; 0.704904–0.704637, 3.8 ε_{Sr} units for Sample 127-797C-34R-1), but do not give enough lower $^{87}Sr/^{86}Sr$ values identical to the range of mantle array defined by DePaolo and Wasserburg (1979). The HCl solutions used in the washing treatment were also analyzed and show higher $^{87}Sr/^{86}Sr$ ratios than the unwashed samples (127-797C-19R-1: 0.704471, 127-797C-34R-1: 0.705634), which implies that the enriched components were involved during alteration of the samples. Sample 127-797C-34R-1 was severely altered, with an LOI of 6.31% (Allan and Gorton, this volume) and removal of 35% of its Sr by HCl washing. The $^{87}Sr/^{86}Sr$ ratio of the HCl-washed-fraction (0.704637) was lowered 0.000267 (3.8 ε_{Sr} units) and plots in a higher range than that expected from its Nd isotopic value. On the other hand, LOI is variable for samples from Core 127-797C-19R: 2.40% for Sample 127-797C-19R-2 and 7.86% for Sample 127-797C-19R-4 (Allan and Gorton, this volume). Fifty-seven percent of the Sr in Sample 127-797C-19R-1 was removed by HCl washing, but $^{87}Sr/^{86}Sr$ was lowered only 0.000161 (2.3 ε units). Thus, the amount of removed Sr and the lowering of $^{87}Sr/^{86}Sr$ may not be proportional to the LOI values. The $^{87}Sr/^{86}Sr$ ratios of the unwashed samples (Table 1) are not representative of the original magmatic values. However, even if we employ thorough HCl washing of the samples, the $^{87}Sr/^{86}Sr$ obtained would not represent the original values and show the resultant values of contamination occurring during the magmatic process. The present Sr isotopic compositions may be attributed to seawater alteration during the magmatic process so that isotopic modification from mantle characteristics is observed only in Sr isotopic compositions (DePaolo and Wasserburg, 1977).

No effect from 4.0N HCl washing was observed in the $^{143}Nd/^{144}Nd$ ratios. The present $^{143}Nd/^{144}Nd$ values for the basalts thus may represent the magmatic values, that is, the present Nd isotopic compositions may be useful for consideration.

Nd and Sr Isotopes of the Yamato Basin Basalts

Four basalt samples from the upper part of Site 797 have higher Nd isotopic ratios indicative of derivation from a geochemical reservoir that was depleted in LREEs relative to the bulk Earth for a considerable period of time, like the MORB source (Fig. 3). The Nd and Sm concentrations are similar to those of MORB, and the slightly variable Sm/Nd ratios do not give a consistent model age, implying a recent modification of REE concentration in the depleted mantle source. The present Sr-Nd isotopic characteristics are consistent with the abundance of REEs and incompatible elements reported by Allan and Gorton (this volume). On the other hand, sills from the lower part of Site 797 and the three samples from Site 794 are clearly distinguished from the upper four samples from Site 797 (Fig. 3). The lower Nd and higher Sr isotopic compositions suggest the involvement of

Table 1. Analytical results for basalts from the Yamato and Japan basins.

Core, section, interval (cm)	$^{87}Sr/^{86}Sr$	ε_{Sr}	$^{143}Nd/^{144}Nd$	ε_{Nd}	Sr	Sm	Nd	Ba	TiO_2
127-794C-									
3R-1, 77–79	0.704217 ± 0.000018	−4.02	0.512862 ± 0.000015	4.37	424			129	1.14
7R-1, 46–48	0.705044 ± 0.000018	7.72	0.512684 ± 0.000018	0.90	273			166	1.26
12R-3, 71–73	0.704757 ± 0.000023	3.65	0.512806 ± 0.000018	3.28	278			98	1.19
127-797C-									
10R-4, 90–92	0.703900 ± 0.000022	−8.52	0.513106 ± 0.000020	9.13	275	3.22	10.22	23	1.06
12R-2, 81–83	0.703753 ± 0.000024	−10.60	0.513117 ± 0.000016	9.34	239	3.01	8.57	14	0.95
19R-2, 42–44	0.704361 ± 0.000026	−1.97	0.513158 ± 0.000021	10.14	179	2.07	8.30	17	0.88
[a]19R-2	0.704200 ± 0.000027	−4.26	0.513158 ± 0.000036	10.14	75.7				
[b]19R-2	0.704471 ± 0.000023	−0.41							
24R-5, 34–36	0.704336 ± 0.000022	−2.33	0.513083 ± 0.000019	8.68	217	2.95	8.38	4	0.92
29R-1, 57–59	0.705228 ± 0.000023	10.33	0.512739 ± 0.000018	1.97	274			242	2.02
31R-2, 46–48	0.704949 ± 0.000030	6.37	0.512843 ± 0.000016	4.00	276			181	1.65
32R-2, 15–17	0.704588 ± 0.000024	1.25	0.512838 ± 0.000021	3.82	329			145	1.75
34R-1, 33–35	0.704904 ± 0.000025	5.73	0.512830 ± 0.000018	3.75	297	5.42	21.30	167	1.24
[a]34R-1	0.704637 ± 0.000023	1.94	0.512850 ± 0.000033	4.14	192				
[b]34R-1	0.705634 ± 0.000018	16.10							
45R-4, 15–17	0.704743 ± 0.000022	3.54	0.512913 ± 0.000015	5.36					
127-795B- (Japan Basin)									
41R-1, 107–109	0.704324 ± 0.000026	−2.50	0.512845 ± 0.000016	4.06					

Note: ε_{Sr} and ε_{Nd} determined following DePaolo and Wasserburg (1979). $^{87}Sr/^{86}Sr_{bulk earth} = 0.7045$ and $I(0)_{CHUR} = 0.512638$. Element concentration in ppm except for TiO_2 in wt%.
[a]Samples washed by HCl.
[b]HCl after washing.

an enriched component to the magmas. The chondrite-normalized REE patterns and abundances of the incompatible elements (Allan and Gorton, this volume) suggestive enrichment in these elements, consistent with the implication of the Nd and Sr isotopes.

The clear isotopic distinction between the two groups implies that at least two different magma sources in the mantle of the terrain were involved in the volcanic activity during the opening of the Yamato Basin. This observation is consistent with the distinctive patterns of the incompatible elements and REEs between the upper and the lower sills at Site 797 (Allan and Gorton, this volume). The former group shows characteristic depleted patterns of these elements relative to those of MORB, and the latter, enriched. This is further supported by the correlation between the Nd isotopes and TiO_2, as shown in Figure 4. The upper sills show consistently high ε_{Nd} with low TiO_2, and the lower sills have low ε_{Nd} with variable TiO_2. The correlation between the Nd isotopes and TiO_2 may be valid because the TiO_2 contents do not show any variation with LOI (Allan and Gorton, this volume). Ba and MgO contents also seem to be useful for distinguishing the upper and lower sills, but LOI suggests migration of these elements during alteration (Allan and Gorton, this volume). A single data set of Nd and Sr isotopes obtained from the lowest part at Site 795, dated at 20 Ma, falls in the range of the lower sills at Site 797 in the Nd and Sr isotopic correlation diagram. Further analytical work is required to define the isotopic signature for this site.

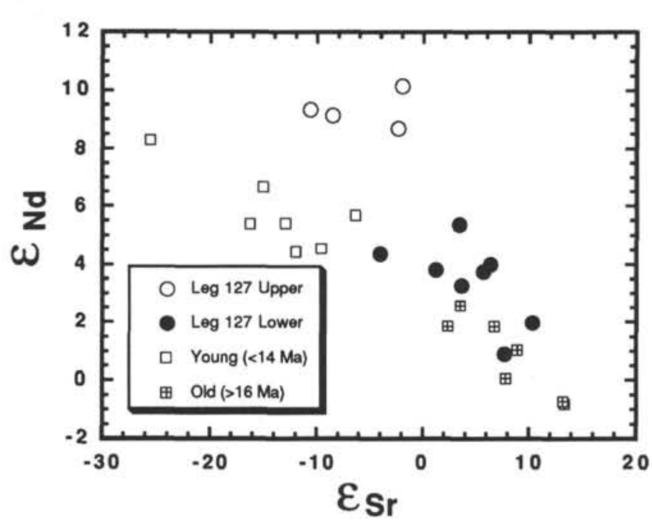

Figure 3. Sr-Nd isotopic composition of basalts from Site 794 and the lower sills at Site 797 (open circles) and the upper sills at Site 797 (solid circles). Data for on-land Tertiary volcanic rocks from the northeast Japan arc (Nohda et al., 1988) are also plotted (squares).

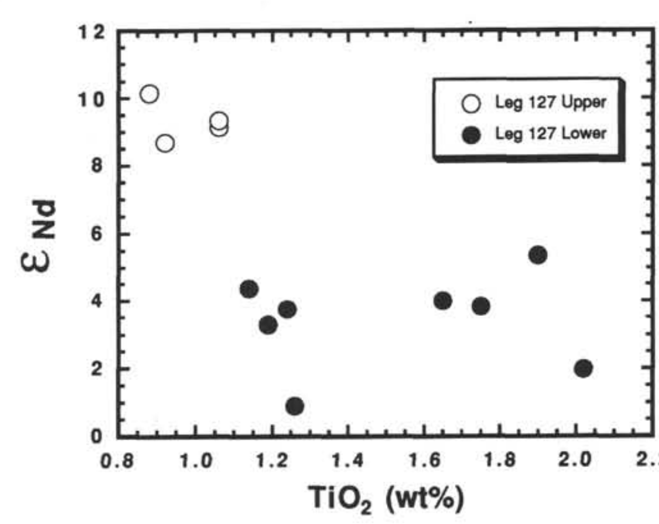

Figure 4. ε_{Nd} vs. TiO_2 concentration in basalts from Sites 794 and 797 in the Yamato Basin. Symbols are the same as for Figure 3.

Evolution of the Upper Mantle

The basalts from the upper part of Site 797 show a depleted Nd isotopic signature equivalent to those of the MORB source and within the same range as those of backarc basin basalts from intraoceanic island arcs such as the Scotia Sea (Hawkesworth et al., 1977) and Lau Basin (Volpe et al., 1988). ^{40}Ar-^{39}Ar data were not obtained for this unit because of the extremely poor concentration of K_2O (I. Kaneoka, pers. comm., 1991). Basalts from the lower part of Site 797 are dated from 19.0 to 17.3 Ma (Kaneoka et al., this volume), and their ε_{Nd} values vary from 2.0 to 5.4. The basaltic sills at Site 794 are dated at about 20 Ma (Kaneoka et al., this volume) and correspond to the ε_{Nd} values of the lower sills at Site 797. In spite of the distinctive isotopic and geochemical differences between the upper and lower sills, there may be little difference in the time of intrusion of these two units, because the sediments at Site 797 have been interpreted by the Leg 127 Shipboard Scientific Party as rapidly deposited (Tamaki, Pisciotto, Allan, et al., 1990). However, it may be possible that the upper sills at Site 797 are younger than the sills at Site 794 and the lower sills Site 797. If so, the abrupt and distinctive change of the mantle magma reservoirs between the upper and lower sills may be related to the rapid opening process inferred from paleomagnetic evidence from the Japan arc (Otofuji et al., 1985a).

It is interesting to compare the present Nd-Sr isotopic variations with the isotopic trend documented for Tertiary lavas found on land in the northeast Japan arc (Nohda and Wasserburg, 1986; Nohda et al., 1988) (Fig. 3). These lavas are grouped in terms of isotopic composition (i.e., more enriched and less enriched). It should be stressed that this geochemical grouping corresponds to the difference in age of the lavas. The older rocks (>16 Ma) have more enriched isotopic compositions and the younger (<14 Ma) less enriched or depleted compositions. A possible geochemical reservoir with enriched isotopic characteristics may be the continental crust. However, Nohda et al. (1988) examined mechanisms that can operate to produce the secular variation and emphasized the minor involvement of continental crustal materials. Therefore, the secular variation in the isotopic composition of rocks in the northeast Japan arc may be elucidated by a mixing of two end-member components, the enriched subcontinental upper mantle (SCUM) with low ε_{Nd} values and the depleted asthenospheric mantle (AM) with high ε_{Nd} values. The older magmas with enriched geochemical characteristics may tap mainly the SCUM reservoir, and the younger magmas may contain a greater involvement of AM. If so, then the isotopic secular variation could be explained by a mechanism including replacement of SCUM by AM during the process of backarc rifting. It should be stressed that a clear gap in isotopic compositions is recognized between the older and younger magmas (Fig. 3). It is thus possible to speculate that SCUM was drastically replaced by AM.

At present, we have no direct evidence that the upper sills at Site 797 in the Yamato Basin are derived from the identical mantle source as the depleted and younger lavas in the northeast Japan arc. However, the geochemical characteristics of the Site 797 basalts are consistent with the range of the Akita-Yamagata "oil-field" basalts (Allan and Gorton, this volume). Thus, we may correlate the older lavas of northeast Japan with the lower sills at Site 797 and the younger lavas with the upper sills at Site 797.

Tectonic Implications

The present study reveals that backarc rifting of the Japan Sea was accompanied by changes in composition in the magma source region in the upper mantle. Geochemical variations observed in basaltic rocks in continental rift systems are also attributed to both mantle stratification and secular change of the magma source through physical replacement of upper mantle materials (e.g., Perry et al., 1988; Nohda et al., 1991).

Tatsumi et al. (1990) reviewed four possible models of backarc spreading in the Japan Sea. The models may be classified into two groups: plate kinematics and mantle dynamics. The former denotes the interaction of major plates of outward trench migration due to sinking and rollback of the subducted lithosphere (Uyeda and Kanamori, 1979; Dewey, 1980). The latter includes mantle diapirism caused by melting of the subducted slab or the base of the mantle wedge (e.g., Karig, 1971), induced convection (e.g., McKenzie, 1969; Andrews and Sleep, 1974; Toksöz and Hsui, 1978), and injection of asthenosphere unrelated to the subduction process (Miyashiro, 1986; Nohda et al., 1988; Tatsumi et al., 1989). The model of plate kinematics, however, fails to explain backarc extension in the New Hebrides, Tonga, and South Sandwich arcs. Backarc extension in those regions takes place even though the remnant arc plates have a large component of motion directed toward the trench; some dynamic forces are required to initiate backarc spreading (Taylor and Karner, 1983). As discussed by Dewey (1980), the underriding plate passively sinks and rolls back relative to the overriding plate to produce extension in the backarc region. However, the stress gradient observed in Tertiary strata in the northeast Japan arc (Nakamura and Uyeda, 1980) may be a disadvantage to applying plate kinematics, because backarc opening due to plate kinematics would have resulted in a rather invariable stress field in the arc-backarc region of northeast Japan.

As for the plate dynamic models, mantle diapirism and induced asthenospheric convection cannot adequately explain the temporal and spatial distribution of the backarc basins (Taylor and Karner, 1983) or the observation that backarc extension occurs behind only a limited number of arc-trench systems whereas induced convective currents and diapirs are likely to occur in all subduction zones (Tatsumi et al., 1989). Thus, the injection of asthenosphere may be a plausible model for explaining backarc opening in the Japan Sea. This model should be examined in consideration of the tectonic setting.

The Cenozoic volcanic and tectonic development of the Japan arc and the adjacent areas is interpreted as follows (Tatsumi et al., 1990). The Cenozoic volcanism in northeast China may not be related to the subduction process and is inferred to be intraplate volcanism resulting from upwelling of the asthenosphere or mantle pluming (e.g., Miyashiro, 1986; Song et al., 1990; Nohda et al., 1991). If this is the case, vertical currents associated with mantle pluming collide with the base of the lithosphere, change direction to horizontal movement at the top of the asthenosphere, and rush toward the Japan arc-trench system. Asthenospheric materials injected into the mantle wedge were consequently dammed by the subducted Pacific plate and pushed the slab oceanward with a slab-steepening event (Tatsumi et al., 1989). The overriding lithosphere of the mantle wedge came under the extensional stress field induced by the trench retreating. The extensional stress finally broke up the lithosphere along the internally weakest part, which might be located beneath or just behind the volcanic front, as a higher geotherm of 1400°C occurs at the shallowest point beneath the volcanic front (Tatsumi et al., 1983).

In the case of the northeast Japan arc, the volcanic front at the preopening stage (~30 Ma) was located along the western coastline of the present arc, which suggests that the breakup of the continental arc took place at or just behind the volcanic front. Because rifting of the lithosphere results in the upwelling of higher temperature mantle materials, the base of the lithosphere or SCUM may have partially melted to produce relatively enriched magmas. Thus, the rift-related volcanism of this stage may be characterized by low ε_{Nd} values (basalts from Site 794, lower sills at Site 797, and older on-land lavas). The breakup of the lithosphere including SCUM resulted in the major role of the depleted AM in producing magmas, which are represented by the upper part at Site 797 and the younger on-land lavas with higher ε_{Nd} values.

ACKNOWLEDGMENTS

We thank Dr. J. F. Allan and two anonymous reviewers for their helpful and constructive comments on the manuscript. Drs. K. Tamaki and I. Kaneoka are thanked for their countless discussions.

REFERENCES

Andrews, D. J., and Sleep, N. H., 1974. Numerical modeling of tectonic flow behind island arcs. *Geophys. J. R. Astron. Soc.*, 38:237–251.

Chinzei, K., 1986. Opening of the Japan Sea and marine biogeography during the Miocene. *J. Geomagn. Geoelectr.*, 38:487–494.

Dasch, E. J., Hedge, C. E., and Dymond, J., 1973. Effect of sea water interaction on strontium isotope composition of deep-sea basalts. *Earth Planet. Sci. Lett.*, 19:177–183.

DePaolo, D. J., and Wasserburg, G. J., 1977. The source of island arcs indicated by Nd and Sr isotopic studies. *Geophys. Res. Lett.*, 4:465–468.

————, 1979. Petrogenetic mixing models and Nd-Sr isotopic patterns. *Geochim. Cosmochim. Acta*, 43:615–627.

Dewey, J. F., 1980. Episodicity, sequence and style at convergent plate boundaries. *In* Strangeway, D. (Ed.), *The Continental Crust and Its Mineral Resources.* Geol. Assoc. Can., Spec. Rep., 553–574.

Hart, S. R., Erlank, A. J., and Kable, E.J.D., 1974. Sea floor alteration: some chemical and Sr isotope effects. *Contrib. Mineral. Petrol.*, 44:219–230.

Hart, S. R., and Nalwalk, A. J., 1970. K, Rb, Cs and Sr relationships in submarine basalts from the Puerto Rico trench. *Geochim. Cosmochim. Acta*, 34:145–155.

Hawkesworth, C. J., O'Nions, P. K., Pankhurst, R. J., Hamilton, P. J., and Evensen, N. M., 1977. A geochemical study of island-arc and back-arc tholeiites from the Scotia Sea. *Earth Planet. Sci. Lett.*, 36:253–262.

Hirata, N., Kinosita, H., Suyehiro, K., Suematsu, M., Matsuda, N., Ouchi, T., Katao, H., Koresawa, S., and Nagumo, S., 1987. Report on DELP 1985 cruises in the Japan Sea, Part II: seismic refraction experiment conducted in the Yamato Basin, southwest Japan Sea. *Tokyo Daigaku Jishin Kenkyusho Iho*, 62:347–365.

Hirata, N., Tokuyama, H., and Chung, T. W., 1989. An anomalously thick layering of the crust of the Yamato Basin, southeastern Japan Sea. *Tectonophysics*, 165:303–314.

Isezaki, N., 1986. A magnetic anomaly map of the Japan Sea. *J. Geomagn. Geoelectr.*, 38:403–410.

Kaneoka, I., and Yuasa, M., 1988. ^{40}Ar-^{39}Ar age studies on igneous rocks dredged from the central part of the Japan Sea. *Geochem. J.*, 22:195–204.

Karig, D. E., 1971. Origin and development of marginal basins in the western Pacific. *J. Geophys. Res.*, 76:2542–2561.

Kono, M., 1986. Magnetic anomalies in the Sea of Japan: a speculation on the tectonic history. *J. Geomagn. Geoelectr.*, 38:411–426.

Lallemand, S., and Jolivet, L., 1985. Japan Sea: a pull-apart basin? *Earth Planet. Sci. Lett.*, 76:375–389.

Ludwig, W. J., Murauchi, S., and Houtz, R. E., 1975. Sediments and structure of the Japan Sea. *Geol. Soc. Am. Bull.*, 86:651–664.

McKenzie, D. P., 1969. Speculations on the consequences and causes of plate motions. *Geophys. J. R. Astron. Soc.*, 18:1–32.

Miyashiro, A., 1986. Hot regions and the origin of marginal basins in the western Pacific. *Tectonophysics*, 122:195–216.

Nakamura, K., and Uyeda, S., 1980. Stress gradient in arc-backarc regions and plate subduction. *J. Geophys. Res.*, 85:6419–6428.

Nohda, S., Chen, H., and Tatsumi, Y., 1991. Geochemical stratification in the upper mantle beneath NE China. *Geophys. Res. Lett.*, 18:97–100.

Nohda, S., Tatsumi, Y., Otofuji, Y., Matsuda, T., and Ishizaka, K., 1988. Asthenospheric injection and back-arc opening: isotopic evidence from Northeast Japan. *Chem. Geol.*, 68:317–327.

Nohda, S., and Wasserburg, G. J., 1986. Trends of Sr and Nd isotopes through time near the Japan Sea in northeastern Japan. *Earth Planet. Sci. Lett.*, 78:157–167.

Otofuji, Y., and Matsuda, T., 1983. Paleomagnetic evidence for the clockwise rotation of southwest Japan. *Earth Planet. Sci. Lett.*, 61:349–359.

Otofuji, Y., Matsuda, T., and Nohda, S., 1985a. Opening mode of the Japan Sea inferred from the paleomagnetism of the Japan Arc. *Nature*, 317:604–607.

————, 1985b. Paleomagnetic evidence for the Miocene counter-clockwise rotation of Northeast Japan—rifting process of the Japan Arc. *Earth Planet. Sci. Lett.*, 75:265–277.

Perry, F. V., Baldridge, W. S., and DePaolo, D. J., 1988. Chemical and isotopic evidence for lithospheric thinning beneath the Rio Grande rift. *Nature*, 332:432–434.

Song, Y., Frey, F. A., and Zhi, X., 1990. Isotopic characteristics of Hannuoba basalts, eastern China: implication for their petrogenesis and the composition of subcontinental mantle. *Chem. Geol.*, 85:35–52.

Tamaki, K., 1985. Two modes of back-arc spreading. *Geology*, 13:475–478.

————, 1986. Age estimation of the Japan Sea on the basis of stratigraphy, basement depth and heat flow data. *J. Geomagn. Geoelectr.*, 38:427–446.

Tamaki, K., Pisciotto, K., Allan, J., et al., 1990. *Proc. ODP, Init. Repts.*, 127: College Station, TX (Ocean Drilling Program).

Tatsumi, Y., and Kimura, N., in press. Backarc rifting vs. continental breakup: petrological aspects for active rifting. *Tectonophysics.*

Tatsumi, Y., Maruyama, S., and Nohda, S., 1990. Mechanism of backarc opening in the Japan Sea; role of asthenospheric injection. *Tectonophysics*, 181:299–306.

Tatsumi, Y., Otofuji, Y., Matsuda, T., and Nohda, S., 1989. Opening of the Sea of Japan back-arc basin by asthenospheric injection. *Tectonophysics*, 166:317–329.

Tatsumi, Y., Sakuyama, M., Fukuyama, H., and Kushiro, I., 1983. Generation of arc magmas and thermal structure of the mantle wedge in subduction zones. *J. Geophys. Res.*, 88:5815–5825.

Taylor, B., and Karner, G. D., 1983. On the evolution of marginal basins. *Rev. Geophys. Space Phys.*, 21:1727–1741.

Toksöz, M. N., and Hsui, A. T., 1978. Numerical studies of back-arc convection and the formation of marginal basins. *Tectonophysics*, 50:177–196.

Uyeda, S., and Kanamori, H., 1979. Back-arc opening and the mode of subduction. *J. Geophys. Res.*, 84:1049–1062.

Volpe, A. M., Macdougall, J. D., and Hawkins, J. M., 1987. Mariana Trough basalts (MTB): trace element and Sr-Nd isotopic evidence from mixing between MORB-like and arc-like melts. *Earth Planet. Sci. Lett.*, 82:241–254.

————, 1988. Lau basin (LBB): trace element and Sr-Nd isotopic evidence for heterogeneity in backarc basin mantle. *Earth Planet. Sci. Lett.*, 90:174–186.

White, W. M., Cheatham, M. M., and Duncan, R. A., 1990. Isotopic geochemistry of Leg 115 basalts and inferences on the history of the Réunion mantle plume. *In* Duncan, R. A., Backman, J., Peterson, L. C., et al., *Proc. ODP, Sci. Results*, 115: College Station, TX (Ocean Drilling Program), 53–61.

Date of initial receipt: 18 March 1991
Date of acceptance: 4 October 1991
Ms 127/128B-207