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ASTHENOSPHERIC INJECTION AND BACK-ARC OPENING ISOTOPIC EVIDENCE FROM NORTHEAST JAPAN [1]

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Abstract : Nd and Sr isotopic compositions were determined for the Tertiary volcanics from the back-arc side of the NE Japan arc. Sr isotopes show a linear trend through time from an enriched signature ($^{87}Sr/^{86}Sr$ = 0.705437) to a depleted signature ($^{87}Sr/^{86}Sr$ = 0.70270). In a complementary fashion, Nd isotopes start at low value ($\epsilon_{Nd} = -0.80$) and show a gradual increase ($\epsilon_{Nd} = 8.3$) with decreasing age. Isotopic change of Nd and Sr from the enriched signature to the depleted one is synchronous with the opening of the Japan sea at ~15 Ma. This synchronism indicates that the opening of the Japan Sea was initiated by the injection of the asthenosphere. During the pre-opening stage, the mantle wedge was composed of a two-layered structure : the sub-continental lithosphere and the underlying asthenosphere. The volcanics of this stage characterized by an enriched isotopic signature were derived from a source with a higher proportion of sub-continental lithosphere. The sub-continintal lithosphere of the back-arc side was thinned by the injection of the depleted asthenosphere, which accelerated the growth of the MORB source within the mantle wedge of the back-arc side and resulted in magma generation with the depleted isotopic signature of Nd and Sr at the post-opening stage.

Key words : Asthenospheric injection, Back-arc opening, Isotopic composition, Northeast Japan

Introduction

The NE Japan arc and its back-arc basin (the Japan sea) consist of one geotectonic unit in the framework of plate tectonics (Fig. 1). The Japan Sea basin is considered to have formed by back-arc spreading (Isezaki, 1986). Recent paleomagnetic work indicates that NE Japan has rotated counter-clockwise through 47° between 21 and 14 or 11Ma (Otofuji et al., 1985a) and SW Japan was subjected to a clockwise rotation of 60° at ~15Ma (Otofuji and Matsuda, 1983). These differential rotations are inferred to have caused the opening and formation of the Japan sea basin (Otofuji *et al.*, 1985a).

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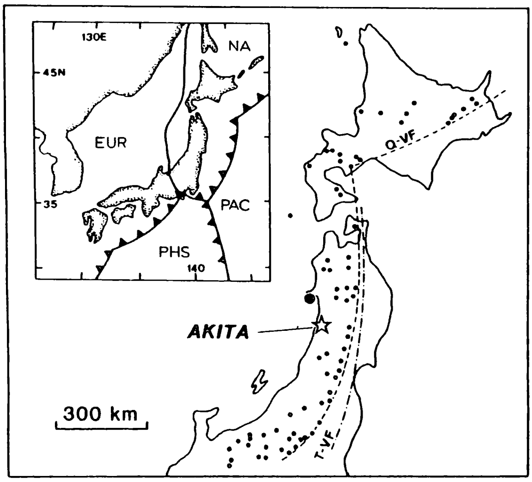

Fig. 1. Index map of NE Japan. Localities of sampling sites are represented by the star marked AKITA. Small solid circles indicate Quaternary volcanoes. The larger solid circle denotes the Kampuzan volcano. NA = North American plate ; EUR = Eurasian plate ; PC = Pacific plate ; PHS = Philippine Sea plate.

It suggests that NE Japan had been a part of the eastern margin of the Asian continent before the rotation.

The opening of the Japan sea implies a change of the Japan region from continental margin environment to the present island arc setting. A large amount of mass movement must have taken place in the upper mantle of the spreading region during the back-arc opening (Garfunkel et al., 1986) , and this movement would have changed the structure of the mantle and crust beneath the Japan region. Such structural and compositional changes should be seen in the isotopic and geochemical characteristics of the volcanic rocks generated during the event. Nohda and Wasserburg (1986) reported the presence of age-dependent variations in the Nd and Sr isotopic compositions of the Tertiary volcanic rocks from the bask-arc side of the NE Japan arc, and attributed it to the process of crustal thinning accompanying the back-arc opening of the Japan Sea.

To confirm the temporal variation of Nd and Sr isotopes found by Nohda and Wasserburg (1986), we made further analyses on the samples collected from the same area. Based on the results, we present injection of the asthenosphere into the mantle wedge and the subsequent thinning process of the sub-continental lithosphere in order to explain the temporal variation Nd and Sr isotopes of the Tertiary volcanics from the back-arc side of the NE Japan arc.

Geologic background

The concept of back-arc opening is established in intraoceanic arcs such as the Mariana and Scotia arcs (Kobayashi and Nakada, 1987 ; Barker and Hill, 1981 ; Hussong and Uyeda, 1981 ; Chamot-Rooke *et al.*, 1987), where the spreading initiated just beneath the volcanic arc. In constant, the Japan Sea basin formed as a result of rifting and lateral movement of the continental fragment. The rifting had initiated just behind the volcanic arc. As a result, successive volcanic records are preserved in the coast region of the Japan Sea in NE Japan. In relation with tectonic transition of the NE Japan arc, we divide the volcanic activity of the region into three stages : pre-opening (>16 Ma), syn-opening (16-14 Ma), and post-opening (<14 Ma).

Table 1 Major-element compositions and Nd, Sr isotopic compositions of the volcanics from the Japan Sea of the NE Japan arc.

Sample No.	AKT *12.2*	AKT *2.3*	NS-*833*	AKT. *7*	NS-*839*	HS-27
Formation	Ukibuta basalt in Sugota Fm.	Daisenyama	Kanotsume	Taikura basalt in Hatamura Fm.		Sanzugawa
Locality: lat. (° ′ ″N)	39 19 01	39 02 37	39 19 26	39 10 14	39 09 52	39 00 02
Locality: long. (° ′ ″E)	140 21 20	140 21 38	140 11 53	140 17 42	140 17 20	140 28 49
Rock type	olivine basalt	olivine basalt	olivine basalt	aphyric basalt	olivine basalt	hypersthene augite andesite
Age (Ma)*1	22	(20)	20.9	17.6	(10)	4.7
SiO_2	50.24	50.74	52.04	48.88	48.15	60.05
TiO_2	0.98	2.07	1.69	1.85	1.11	0.87
Al_2O_3	16.42	16.59	16.72	16.54	16.72	17.30
Fe_2O_3*2	8.91	10.23	8.98	10.47	8.80	7.26
MnO	0.14	0.17	0.12	0.14	0.16	0.24
MgO	8.44	4.72	4.84	5.51	7.49	1.79
CaO	9.22	8.45	7.36	8.50	9.64	6.28
Na_2O	2.66	3.10	3.48	3.31	2.67	4.34
K_2O	0.54	1.43	1.36	0.77	0.71	1.28
P_2O_5	0.19	0.64	0.48	0.49	0.24	0.26
Σ	97.74	98.14	97.07	96.46	95.69	99.67
Sr (ppm)	285	456	488	491	308	334
Rb (ppm)	7	27	28	9	11	28
$^{87}Sr/^{86}Sr_p$*3	0.705149±0.000020	0.705476±0.000019	0.705099±0.000015	0.704674±0.000021	0.703452±0.000016	0.703840±0.000026
$^{87}Sr/^{86}Sr_i$	0.705127	0.705428	0.705051	0.704661	0.703438	0.703824
$^{143}Nd/^{144}Nd$*3	0.512676±0.000029	0.512586±0.000017	0.512626±0.000018	0.512718±0.000016	0.512964±0.000029	0.512855±0.000027
ϵ_{Nd}	1.05	−0.70	0.08	1.87	6.67	4.55
ϵ_{Sr}	8.90	13.17	7.82	2.29	−15.07	−9.60

*1K-Ar age reported for the geologic unit; ( ) is estimated from the stratigraphic sequence.
*2Total Fe as Fe_2O_3.
*3The errors are 2σ of the mean.

The area on the southeast of Akita (30×60 km) is mapped in detail and offers the best field for the present purpose (Ozawa *et al.*, 1979 a, b). Volcanic activity of the region is summarized as follows. The pre-opening stage is characterized by having a larger volume of rhyolitic welded tuff than the contemporaneous andesite with a minor amount of basalt (Sugimura *et al.*, 1963). There are scarcely any reliable age data for the volcanic activity of the syn-opening stage. In the post-opening stage, andesitic products were abundant with minor amounts of basalt and welded tuff. Further investigation is required for the mutual genetic relationship among the various rock types in each stage. We have collected samples from almost all the basaltic rocks that appear fresh and suitable for the present purpose, and it seems that no more useful data points can be obtained from this region.

Analytical procedure

Rock samples of 5-10 kg were roughly crushed. Fresh fragments were selected, rinsed in distilled water, and crushed in an agate mortar. Major elements, Rb and Sr concentrations were determined by Rigaku symaltics 3530 and 3080 XRF (X-ray fluorescence) spectrometers. Powdered samples of ~100mg were dissolved and chemically separated for mass-spectrometric anaysis. Nd was measured as the metal species by a double Re filament with a Finnigan MAT 261 E mass spectrometer at Kyoto Sangyo University. The measured $^{143}Nd/^{144}Nd$ ratios were normalized to $^{146}Nd/^{144}Nd$ of 0.7219 and trace contributions from ^{144}Sm were checked by monitoring ^{147}Sm. The average La Jolla standard value obtained during the study was $^{143}Nd/^{144}Nd = 0.511845 + 0.000010$ (n = 7). The Nd isotopic ratio of BCR-1 was 0.512626 + 0.000031 (n = 2). Sr was measured on a double Re filament or a Ta single filament. We obtained $^{87}Sr/^{86}Sr$ ratios of 0.710220 ± 0.000014 (n = 3) for NBS-987, 0.707992 + 0.000006 (n = 4) for Emer & Amend $SrCO_3$ and 0.704980 + 0.000018 (n = 2) for BCR-1. The total blanks of the chemical procedures were negligible.

Isotopic ratios are expressed in the notion where $\epsilon_{Nd}(0)$ is the measured (m) deviation in parts in 10^4 of the $^{143}Nd/^{144}Nd$ ratio from the present-day chondritic value which is calculated to be 0.512622 by assuming that La Jolla Nd standard ($^{143}Nd/^{144}Nd = 0.511845$) corresponds to $\epsilon_{Nd} = -15.15$ (Wasserburg et al., 1981). Similarly, ϵ_{Sr} (0) is the deviation in parts in 10^4 of the measured $^{87}Sr/^{86}Sr$ ratio from the inferred reference value of 0.7045 corresponding to a present-day model undifferentiated mantle reservoir (UR).

Results

Because of the young ages of the samples, no corrections for in situ decay of Nd have been made. Analytical results are listed in Table I. Nd and Sr isotopic data are plotted on an ordinary $\epsilon_{Nd} - \epsilon_{Sr}$ correlation diagram in Fig. 2. Nd and Sr isotopes show a substantial variation ranging from −0.8 to 8.3 and from −25.6 to 13.3 ϵ-units, respectively. The most depleted value is found in

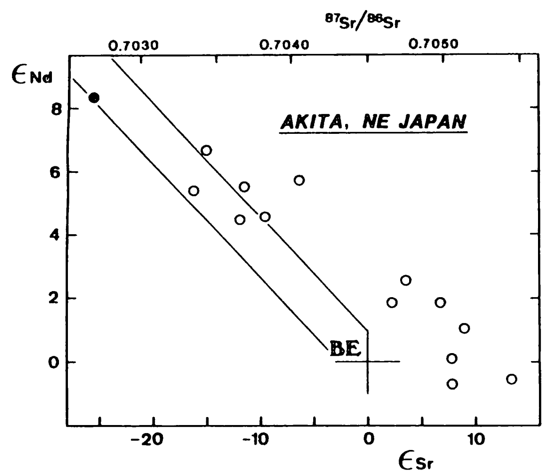

Fig. 2. Plots of ϵ_{Nd} vs. ϵ_{Sr} of the volcanic rocks of the back-arc side in NE Japan arc (open circles = Tertiary volcanics ; Solid circles = Quaternary volcanics ; BE = bulk Earth) . Data from Nohda and Wasserburg (1981, 1986) are also plotted.

the Quaternary Kampuzan lava which shows ϵ_{Nd} of 8.3 and ϵ_{Sr} of -25.6 (data from Nohda and Waserburg, 1981) . It implies that the Kampuzan magma is derived from a very depleted source similar to MORB (mid-ocean ridge basalt) . The most enriched values are found in AKT2.3 ($\epsilon_{Nd} = -1$, $\epsilon_{Sr} = 13$) and NS-428 (data from Nohda and Wasserburg, 1986) . Except for samples with $\epsilon_{Sr} > 0$, they plot approximately along the mantle array. Fig. 3a and b shows the relationships between ϵ_{Nd} and ϵ_{Sr} and geologic age of the samples. As pointed out by Nohda and Wasserburg (1986), Nd and Sr isotopic ratios are regular functions of geologic age ; the volcanic samples of the early Miocene show an enriched isotopic signature, but a continuous shift to depleted values is observed in the younger lavas. It should be stressed that the present results are not brought by geographic heter-

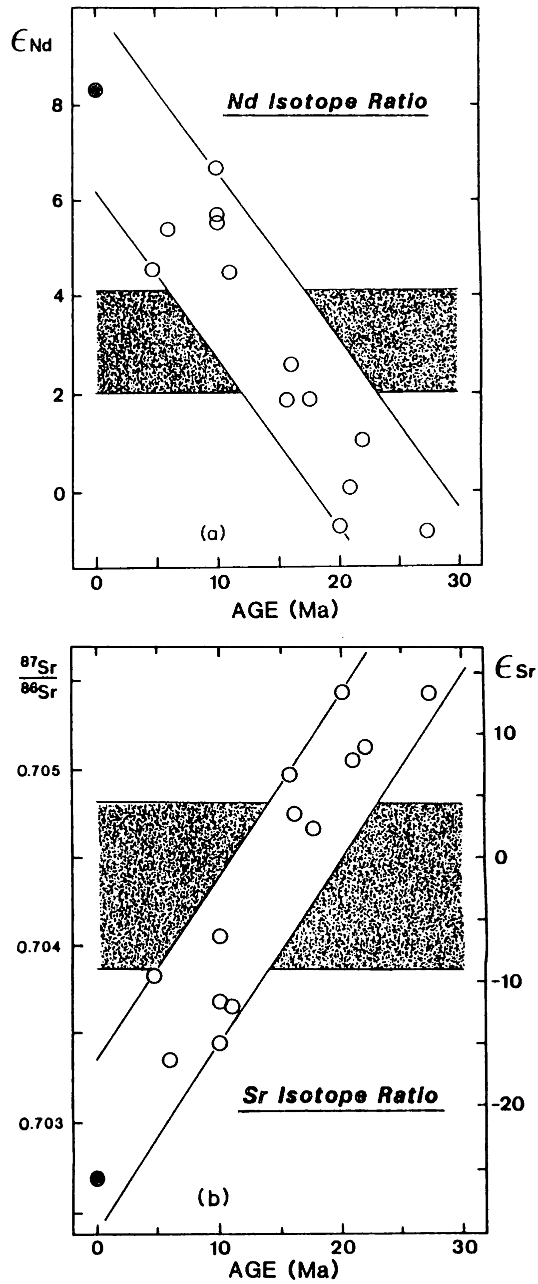

Fig. 3. Nd and Sr isotopic ratios vs. age for the volcanic rocks from the back-arc side of the NE Japan arc. Symbols are the same as those in Fig. 2. The isotopic compositions show contrasting temporal variations from enriched to depleted, in comparison with the constant isotopic compositions of the volcanic rocks along the volcanic front of the same arc (dotted areas).

ogeneity because the samples are obtained in a very limited area of 30×60km in the back-arc side of NE Japan.

Discussion

The temporal variation of Nd and Sr isotopes is synchronous with the opening of the Japan Sea inferred from paleomagnetic evidence (Otofuji *et al.*, 1985a), magnetic anomalies in the Japan Sea (Isezaki, 1986 ; Kono, 1986) and a sharp change in marine fauna (Chinzei, 1986) . This synchronism indicates that there is a common cause for the opening of the Japan Sea and the temporal variation of Nd and Sr isotopes of the volcanics. During the opening of the Japan Sea, the arc-trench system retreated from the Asian continent toward the Pacific side, which implies a possibility of compositional change of the mantle wedge through tectonic transition. The temporal variation of Nd and Sr isotopes is considered in terms of the change of the megatectonic structure related to the opening of the Japan Sea basin.

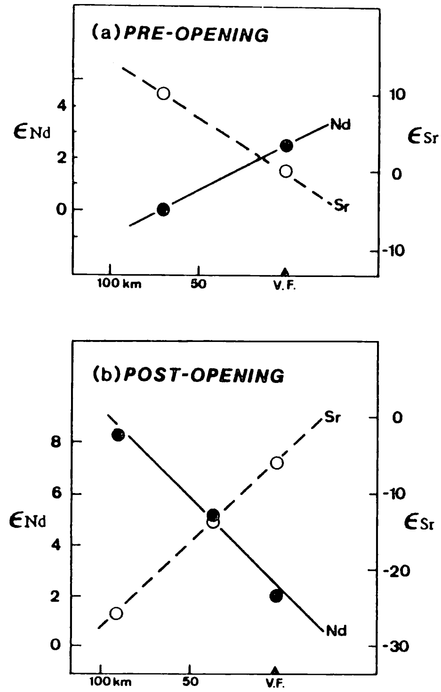

Fig. 4. a. Nd and Sr isotopic profile across NE Japan at 20Ma during the pre-opening stage, estimated from Fig. 3a and b. Sr isotopic compositions increase towards the back-arc side.
b. Nd and Sr isotopic profile across NE Japan along 40°N of the Quaternary volcanics (Nohda and Wasserburg, 1981).

Crustal contamination

The narrow linear array of the present data on an ϵ_{Nd} - ϵ_{Sr} correlation diagram indicates a mixing process between enriched and depleted components in the magma source region throughout the period. Nohda and Wasserburg (1986) considered involvement of two endmember components for magma generation : a depleted component similar to a MORB-type source (MORB source) and an enriched one represented by the continental crust. The isotopic shift was then attributed to the change in degree of crustal contamination and inferred from the proportions of the contribution of these two components due to a thinning process of the continental crust accompanying the back-arc opening of the Japan Sea.

Although crustal thinning seems to have been a substantial process for the region around the spreading center of the Japan Sea basin, the present thickness of the crust is observed as ~30km at around Akita (Yoshii, 1979) and is equivalent to that of the Sikhote Alin and the eastern part of the

Asian continent (Soller *et al.*, 1982 ; Tan, 1987). These data suggest that NE Japan had not been subjected to crustal thinning. In addition, the ultramafic nodules found at the Quaternary volcanics of Ichinomegata show a depleted Nd and Sr isotopic signature similar to the nearby Quaternary lavas of the Kampuzan and Moriyoshiyama volcanoes (Nohda and Wasserburg, 1986). It may be unrealistic to claim that only the Tertiary volcanics were subjected to crustal contamination. Thus, we attribute the major governing factor of the temporal variation of Nd and Sr isotopes to a chemical transition of the upper mantle during the opening of the Japan Sea.

Nature of the mantle wedge during the pre-opening stage

We estimated the chemical structure of the mantle wedge of the NE Japan region during the pre-opening stage from the Nd and Sr isotopic data. We can make use of the unchanged Nd and Sr isotopic data from the tholeiitic basalts that are ranging from 22 Ma to the present and found along the present volcanic front of NE Japan (dotted area of Fig. 3a and b ; Tatsumi *et al.*, 1988). With these data we can infer an isotopic profile of Nd and Sr across the NE Japan region for the pre-opening stage as shown in Fig. 4a which is similar to those of the continental margin obtained at California, U. S. A. (DePaolo, 1981a) and Patagonia, Argentina (Hawskesworth *et al.*, 1979), and also to the central section of Japan (Nohda and Wesserburg, 1981). There, the volcanics show a more enriched isotopic signature of Nd and Sr with increasing distance from the trench. Such an isotopic profile seems to be characteristic for the continental margin volcanic arc, and requires an explanation from the viewpoint of the mantle structure.

The mantle wedge of the continental margin is composed of sub-continental lithosphere (SCL) which is chemically more enriched than the MORB source (Allègre *et al.*, 1982 ; Hawkesworth *et al.*, 1983 ; Pearce, 1983). Before the opening of the Japan Sea, the mantle wedge of NE Japan was composed of SCL that was thickened towards the back-arc side from the trench side. During the subduction of the oceanic plate, the depleted asthenosphere underlay the SCL. Therefore, we propose the most probable structure of the mantle wedge of NE Japan for the pre-opening stage, as shown in Fig. 5a. Such a two-layered structure of the upper mantle is characteristic of a continental arc.

A petrogenetic model is already discussed elsewhere for the volcanics of NE Japan (Tatsumi, 1986 ; Tasumi *et al.*, 1988). Here we emphasize that the Nd and Sr isotopic signatures of the continental margin volcanic arcs are mainly determined by the ratio of thickness between SCL and the underlying MORB source. The partially molten mantle diapir would initiate within the depleted part of the mantle wedge by addition of the enriched fluid originally extracted from the downgoing slab, then would upwell through the high-temperature region ($>1400°C$) and release a primary basalt magma at a depth of ~30km. During upwelling, the mantle diapir was chemically in open-system conditions, and had a chance to react with the overlying SCL mantle (DePaolo, 1981b). Consequently the Nd and Sr isotopic compositions of the lavas are determined by the enriched fluid extracted from the slab and the volume ratio between the SCL and the MORB source within the mantle wedge.

The fluid extracted from the downgoing slab is originally related to seawater and oceanic sediments and is enriched in incompatible elements with larger ionic radii, but their isotopic composition is not known (Tatsumi *et al.*, 1986) . Seawater enriches Sr isotopes but is not effective for Nd (DePaolo and Wasserburg, 1977) . Except for the continental crust, oceanic sediment is the most effective candidate to lower the Nd isotopic composition in island-arc environments, but considerable amounts are required to alter the depleted Nd isotopic value to an undepleted value (Nohda and Wasserburg, 1981) . It is known that basalts of the intra-oceanic arc (A-type arc of Nohda, 1984) show an average ϵ_{Nd} of 8.1 which is lower than those of N-type MORB ($\epsilon_{Nd} = 10$) . The mantle wedge of an A-type arc is composed of the oceanic mantle, the MORB source. Since the fluid from the downgoing slab is the only possible component to lower the ϵ_{Nd} of lavas, we can thus estimate the degree of the fluid effect to the mantle wedge as being 1.9 ϵ-unit lowering of Nd isotopes. The average ϵ_{Nd} of the trench side basalts of NE Japan is 2.8, which means that the original mantle wedge (SCL mantle + MORB source) had a ϵ_{Nd} of 4.7 [$2.8-(-1.9)=4.7$] before the fluid addition. The Nd and Sr isotopic compositions of the SCL are not arbitrarily determined from this value because the Nd and Sr contents in the SCL are not known. But we can conclude that the SCL of NE Japan is characterized by the enriched isotopic signature.

The enriched signature of the SCL of NE Japan is also supported by trace-element data. Tertiary volcanics of NE Japan define a constant Hf/La ratio, while Quaternary volcanics are scattered with large variation but show generally higher Hf/La ratios (Ebihara *et al.*, 1984) . The older volcanic rocks of the La/Yb ratio with decreasing age is reported (Ebihara *et al.*, 1984) . Such geochemical observations give further confirmation of the enriched characteristics of the mantle wedge of NE Japan during the pre-opening stage.

Characteristics of the post-opening NE Japan arc

The Nd and Sr isotopic profile for the post-opening stage is represented by the Quaternary volcanics across NE Japan (Nohda and Wasserburg, 1981), and reproduced in Fig. 4b. It shows a regular increase in ϵ_{Nd} and decrease in ϵ_{Sr} from the volcanic front to the back-arc side, and has quite opposite sense with those of the pre-opening and active continental margins. If we suppose s homogeneous and depleted MORB source for the mantle wedge of NE Japan, the undepleted or less-depleted isotopic signature of Nd and Sr from the volcanics of the trench side strictly requires an involvement of the enriched crustal component. Sakuyama and Nesbitt (1986) , however, deny such crustal contamination to explain the chemical characteristics such as those in Fig. 4b. Masuda and Aoki (1978) recognized that the Quarternary tholeiites along the volcanic front and those of the Izu-Marianas show differences in the REE patterns. Their data suggest that the mantle wedge of the intra-oceanic arc (A-type arc of Nohda, 1984). Nevertheless, a depleted source is required for the mantle of the back-arc side to explain the depleted isotopic signature of the volcanics from the back-arc side.

We propose a two-layered structure of the mantle wedge of NE Japan to explain the obtained Nd and Sr isotopic signature, as shown in Fig. 5c. The SCL is thicker beneath the volcanic front and gradually thins towards the back-arc side. The mechanism of magma generation for the post-opening stage is similar to that of the pre-opening stage. Namely, during upwelling of the partial molten mantle diapir within the higher-temprature zone (>1400°C), chemical reaction with the overlying mantle determines the Nd and Sr isotopes of the magma. The magmas of the back-arc side require a higher involvement of the MORB source to match their depleted isotopic signatures of Nd and Sr. The trench side basalts show an unchanged and undeplete isotopic signature of Nd and Sr through 22Ma, which implies that the ratio of the SCL to the MORB source concerning the magma generation was kept constant and higher than those for the back-arc side of the post opening. In addition, a linear temporal variation of Nd and Sr isotopes is a result of an identical Nd/Sr ratio between two end components in the mixing process (DePaolo and Wasserburg, 1979).

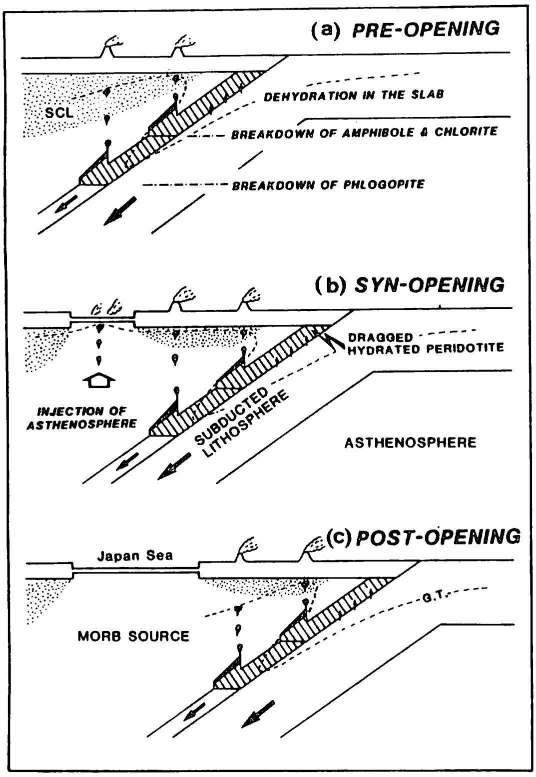

Fig. 5. A sketch for the magma genesis in the Neogene NE Japan arc. The subducted lithosphere can supply H_2O to the mantle wedge only beneath the fore-arc region. The slab-derived H_2O reacts with mantle wedge materials to form hydrated peridotite, which is dragged downwards on the slab. H_2O released through the breakdown of hydrous phases in the dragged hydrated perdotite causes partial melting in the mantle wedge beneath the volcanic arc. The subcontinental lithosphere (SCL ; dotted area) becomes thinner beneath the back-arc side of the NE Japan arc through the injection of asthenosphere with composition similar to the depleted MORB source during the back-arc spreading. G.T. represents an isotherm of 1000° (Tastumi, 1986).

It is well recognized that incompatible elements of lavas from NE Japan behave in a similar manner to K_2O which increases with increasing distance from the trench (Fujitani and Masuda, 1981 ; Gill, 1981 ; Sankuyama and Nesbitt, 1986). This geochemical feature is attributed to a decrease in degree of partial melting of a homogeneous source in the same direction (Sakuyama and Nesbitt, 1986). this is not in conflict with our present model of the two-layered mantle, because the high abundance of incompatible elements of the lavas from the back-arc side is explained by the small degree of partial melting of the source, predominantly MORB source, to match with the depleted isotopic signature. The flat pattern of REE abundances found for the basalts from the trench side is possibly caused by a higher degree of partial melting of the mantle which involves a higher volume of SCL to have the undepleted isotopic composition of Nd and Sr.

Opening of the Japan Sea ; asthenospheric injection

During the pre-opening stage, the volcanics had a more enriched isotopic signature of Nd and Sr with increasing distance from the trench, which was caused by a higher involvement of the SCL for magma generation in the region of the back-arc side than those in the trench side. With decreasing age, Nd and Sr isotopes of the lavas from the back-arc side shift to the depleted side, which implies a change in the volume ratio between SCL and MORB source. This structual transition - the thinning of SCL and complementary growth of the depleted MORB source in the mantle wedge of the back-arc side - took place along with the opening of the Japan Sea. We believe that the asthenosphere was injected into the mantle wedge of the back-arc side and caused growth of the depleted mantle (MORB source). Moreover, the asthenospheric injection caused the opening of the Japan Sea. Due to injection of the asthenosphere, SCL was subjected to the thinning process. The thinning of SCL gave tensional stress to the overlying continental lithosphere, that finally rifted. Subsequent migration of continental fragments as the Japanese islands is traced by paleomagnetic data. The idea of asthenosphric injection is supported by eastward asthenospheric flow which explains the distribution of the back-arc basins in the western Pacific (Boström, 1981), and may be related with migration of the hot region of Miyashiro (1986).

Models explaining processes during back-arc opening are discussed by Taylor and Karner (1983). Diapirism and the return flow within the enriched SCL could not supply the depleted magmas and fail to explain the linear trend of Nd and Sr isotopes observed in the volcanics from the back-arc side of NE Japan. It is probable that induced flow is insufficient to initiate back-arc spreading where the overlying lithosphere is continental (Toksöz and Bird, 1977). Trench retreat seems to be present in every subduction zone, but cannot explain the spacial distribution of back-arc basins in the western Pacific. Moreover, trench retreating necessarily involves a volume deficit beneath the region of the back-arc side and requires injection of the asthenosphere.

The mantle wedge beneath the present volcanic front was not under the influence of the asthenospheric injection. It shows an unchanged and undepleted Nd and Sr isotopic signature through the period from 22Ma, which is correlated with the observation that the intermediate Q and V layers are observed in the mantle wedge between the volcanic front and the aseismic front (Matsuzawa et al., 1986). Thus, the asthenospheric injection seems to match the isotopic trend of Nd and Sr found in the volcanic rocks and the opening of the Japan Sea from paleomagnetic evidence.

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