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Petrologic perspectives on tectonic evolution of a nascent basin (Okinawa Trough) behind Ryukyu Arc: A review

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Abstract

Okinawa Trough is a back-arc, initial marginal sea basin, located behind the Ryukyu Arc–Trench System. The formation and evolution of the Okinawa Trough is intimately related to the subduction process of the Philippine Sea Plate beneath the Eurasian Plate since the late Miocene. The tectonic evolution of the trough is similar to other active back-arcs, such as the Mariana Trough and southern Lau Basin, all of which are experiencing the initial rifting and subsequent spreading process. This study reviews all petrologic and geochemical data of mafic volcanic lavas from the Okinawa Trough, Ryukyu Arc, and Philippine Sea Plate, combined with geophysical data to indicate the relationship between the subduction sources (input) and arc or back-arc magmas (output) in the Philippine Sea Plate–Ryukyu Arc–Okinawa Trough system (PROS). The results obtained showed that several components were variably involved in the petrogenesis of the Okinawa Trough lavas: sub-continental lithospheric mantle underlying the Eurasian Plate, Indian mid-oceanic ridge basalt (MORB)-type mantle, and Pacific MORB-type mantle. The addition of shallow aqueous fluids and deep hydrous melts from subducted components with the characteristics of Indian MORB-type mantle into the mantle source of lavas variably modifies the primitive mantle wedge beneath the Ryukyu and sub-continental lithospheric mantle (SCLM) beneath the Okinawa Trough. In the northeastern end of the trough and arc, instead of Indian MORB-type mantle, Pacific MORB-type mantle dominates the magma source. Along the strike of the Ryukyu Arc and Okinawa Trough, the systematic variations in trace element ratios and isotopic compositions reflect the first-order effect of variable subduction input on the magma source. In general, petrologic data, combined with geophysical data, imply that the Okinawa Trough is experiencing the “seafloor spreading” process in the southwest segment, “rift propagation” process in the middle segment, and “crustal extension” process in the northeast segment, and a nascent ocean basin occurs in the southwest segment.

Key words: nascent ocean basin, spreading, tectonic evolution, petrology, geochemistry, Okinawa Trough

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1 Introduction

Similar to the Mariana Trough and Lau Basin, Okinawa Trough is in the evolutionary phase from stretching or rifting to spreading (e.g., Bibee et al., 1980; Yamazaki et al., 1993; Hawkins, 1995; Fryer, 1996). Volcanic rock, as a probe of the deep mantle process, undoubtedly provides the direct constraint on the geodynamic setting of this tectonic evolutionary phase. Investigations on the Okinawa Trough commenced since the 1970s or earlier (Lee et al., 1980; Letouzey and Kimura, 1985; Qin et al., 1987; Li, 2008), and acquired a large amount of geological and geophysical data. However, the main important findings on the Okinawa Trough have been achieved on the basis of geophysical data, and geological (especially petrologic) studies of the trough have mainly focused on hydrothermal vents and the vicinity. Most seriously, regional petrologic and geological comparative studies of different segments (possibly reflecting different evolutionary phases) in the whole trough, coupled with geophysical data, are scarce, which hinders us to comprehensively understand magmatic processes in the Okinawa Trough and then to decipher its concealed geodynamic information. This paper reviewed updated petrologic and geochemical data of the Okinawa Trough (e.g., Qin et al., 1987; Ishizuka et al., 1990; Honma et al., 1991; Chen et al., 1993; Zhai and Gan, 1995; Li et al., 1997a, b; Shinjo, 1998; Shinjo et al., 1999; Meng et al., 1999; Shinjo and Kato, 2000; Wu, 2000; Ma et al., 2004; Han et al., 2005, 2008; Huang et al., 2006a, b; Zeng et al., 2010) and discussed its petrogenesis from a regional perspective. Then, combined with geophysical data of the trough and petrologic and geochemical data from its adjacent areas (e.g., Ryukyu Arc, Philippine Sea Plate, southeastern China), this study attempted to discuss the response of magmatic activities on different evolutionary phases (e.g., crustal stretching, rifting, and spreading) occurring in the trough. Therefore, it may be helpful to comprehensively understand petrogenesis and geodynamic setting in different tectonic units in the relatively young Ryukyu supra-subduction zone (SSZ).

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2 Geological background and magmatic activities of the Okinawa Trough

2.1 *Overview*

The Okinawa Trough lies between the Ryukyu Volcanic Arc (RVA) and East China Sea (ECS) shelf. It is a band-shaped graben with a generally NNE orientation (Fig. 1), with a length of 1 200 km, width of 100–150 km, and area of about 19.2 km^2. The Okinawa Trough is an active, nascent back-arc basin behind the Ryukyu Arc–Trench System. Most scientists agree that the most recent extension commenced about 2 Ma ago (Kimura, 1985; Li et al., 1997a; Sibuet et al., 1998; Shinjo and Kato, 2000; Li, 2001), although the timing of earlier rifting is still debated.

As a whole, the trough shows the following geological characteristics: thin crustal thickness, gravity anomaly, and high heat flow values (Li, 2001). The crustal thickness of the axial zone is about 13–24 km, and gradually increases from the southwest part to northeast part (Wang et al., 1998; Han et al., 2007). Moreover, in contrast to the ECS shelf of the west side and the RVA of the east side, the trough has extreme crustal thinning, and the basement is gradually transforming from continental crust (e.g., southeast part north of the Tokara Fault) to continental to oceanic transition type (e.g., the part between the Tokara Fault and Kerama Fault) and then to oceanic crust (e.g., southwest part west of Kerama Fault) (Wang et al., 1998; Han et al., 2007). Note that linear magnetic anomalies have been identified in the axial zone (Liang et al., 2001). This, combined with the occurrence of tholeiite in this segment (Li et al., 1997a; Shinjo et al., 1999), at least suggests that the ongoing seafloor spreading process may take place in the southern part of the Okinawa Trough,

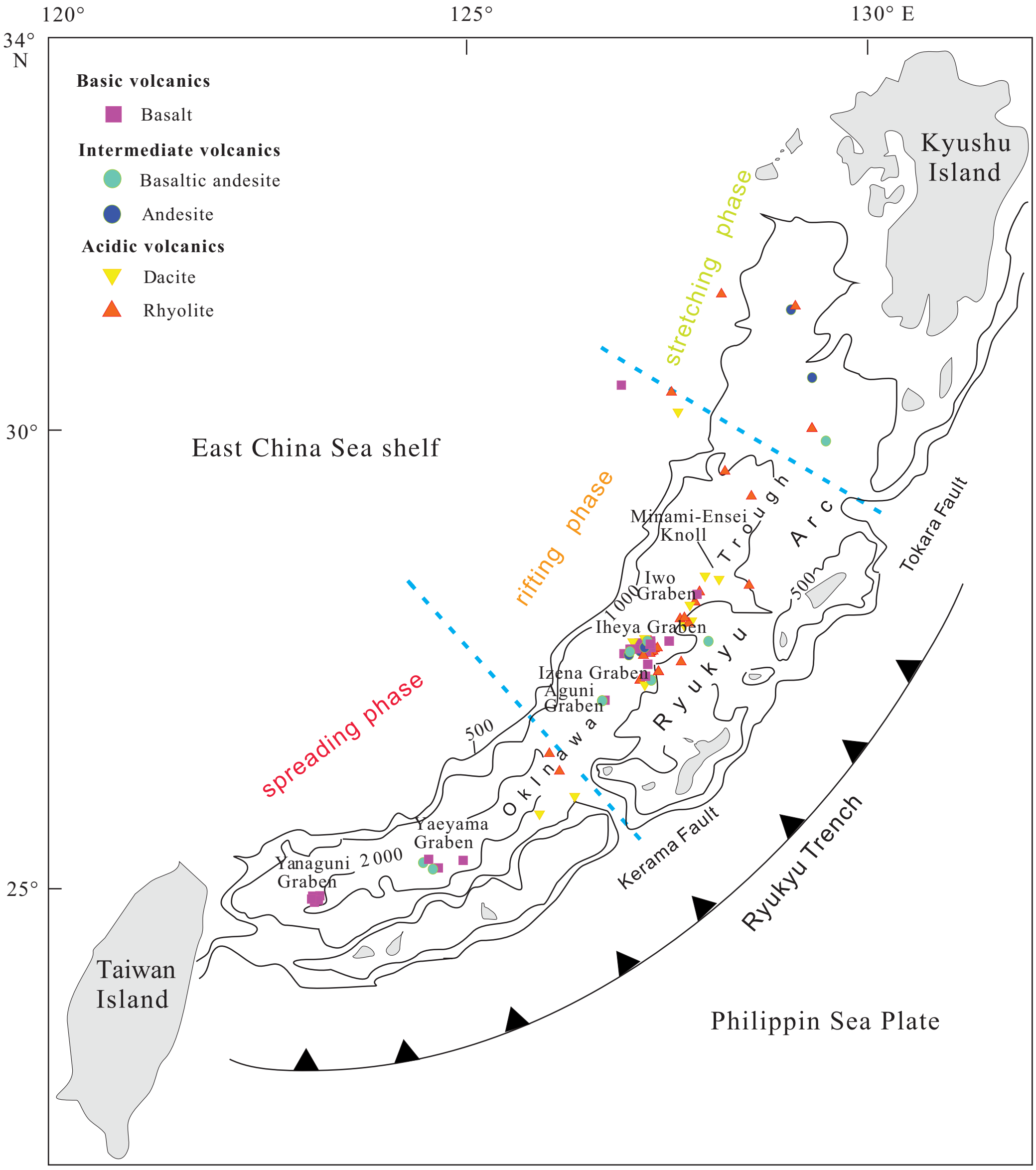

Fig.1. Sampling locations of volcanic rocks from Okinawa Trough. Inferred tectonic evolutionary phases of different segments in Okinawa Trough based on geological and geophysical data are also shown.

with new oceanic crust forming simultaneously. In addition, the tectonic evolution of the southwest part of the trough is obviously affected by the arc-continent collision at Taiwan Island (Miki et al., 1990; Wang et al., 1999).

For the convenience of considering and describing the morphological and tectonic characteristics of the trough, this paper divided the trough into three segments: the southwest segment (SWS), middle segment (MDS), and northeast segment (NES) (Fig. 1). The borders between the SWS and MDS and between the MDS and NES are the Kerama Fault (Gap) and Tokara Fault (Strait), respectively. The SWS, MDS, and NES correspond to the initial spreading phase, propagating rift phase, and crustal stretching phase, respectively. However, the tectonic division and its evolutionary phases mentioned above are crude delineations, and keep in mind that in fact the features of magmatic-tectonic activity gradually transform from NES to MDS to SWS, which may reflect differences in geodynamic setting. The surface manifestation of extensional tectonics is many grabens that have developed in the trough, such as Yanaguni and Yaeyama Grabens in the SWS, and Aguni, Izena, Iheya, and Io Grabens in the MDS, which are accompanied by extensive hydrothermal activities and vents (Wu, 2000). Although there is no obvious graben tectonics, extensive tectonic activity also occurs in the NES (Wang et al., 1998).

2.2 *Magmatism in the Okinawa Trough*

As mentioned above, the Okinawa Trough is a part of the Ryukyu Trench–Arc–Back-arc Basin System; the tectonic-magmatic thermal events therein are predominantly controlled by the subduction process of the Philippine Sea Plate beneath the Eurasian Plate. The rock sample locations are provided in Fig. 1. Rock types include basalt and more differentiated rocks, such as basaltic andesite, andesite dacite, and rhyolite. Rock samples from the SWS, mainly collected from Yanaguni and Yaeyama Grabens, are basaltic rocks (Li et al., 1997b; Shinjo et al., 1999; Ma et al., 2004) with small amounts of andesite and rhyolitic rocks (Li et al., 1997a; Huang et al., 2006a, b). The phenocryst mineral assemblage reflects that these basalts are of characteristic back-arc basin basalt (BABB) and mid-oceanic ridge basalt (MORB) (Li et al., 1997b; Shinjo et al., 1999). Rock samples collected from some graben areas (e.g., Yanaguni, Izena, Aguni, Iheya, and Io Grabens, and Minami–Ensei Knoll) in the MDS segment (Zhai and Gan, 1995; Shinjo et al., 1999; Shinjo and Kato, 2000; Wu, 2000; Huang et al., 2006a, b) (Fig. 1) were mainly basaltic rocks and rhyolitic rocks, and intermediate rocks were very scarce. The petrographic characteristics of basaltic rocks from this segment are similar to those from Yaeyama Graben in the SWS (Zhai and Gan, 1995; Shinjo et al., 1999; Wu, 2000). Rhyolitic rocks have aphyric glassy texture (Shinjo and Kato, 2000; Huang et al., 2006a). Rock samples of NES are mainly rhyolitic rocks (Huang et al., 2006). In addition, Huang et al. (2006a) reported that they dredged basaltic andesite from the HF-5 site. In the ECS shelf, northwest side of the NES of Okinawa Trough, Zeng et al. (2010) reported that they obtained some basaltic rocks with K-Ar ages of 3.65–3.86 Ma.

Volcanic activities in the Okinawa Trough commenced around 4 Ma, and continue to the present (Huang et al., 2006b). The volcanism in the trough can be divided into the following two periods: 3–4 Ma and < 1.6 Ma. In addition to small-scale volcanism occurring at about 4 Ma, the main volcanic activities mainly commenced around 1.6 Ma, which reflects that the timing for initial rifting in the Okinawa Trough was obviously later than for subduction initiation of the Philippine Sea Plate (about 8 Ma; Hall, 2002) and formation of the Ryukyu Volcanic Arc.

3 Geochemistry of volcanic rocks in the Okinawa Trough

Geochemical compositions of volcanic rocks from the trough are presented in Figs 2, 3, 4, and 5.

3.1 *SWS volcanic rocks*

Basaltic rocks from this segment were all sub-alkaline series (Fig. 2). All rock samples were enriched in Pb and large ion lithophile elements (LILE) and/or strongly incompatible elements, such as Rb, Ba, Th, and U (Fig. 3a). In addition, the andesite sample was the only sample with a negative anomaly in Eu (not shown), reflecting that fractional crystallization (e.g., plagioclase) plays a significant role in petrogenesis of rocks from the SWS.

The $^{87}Sr/^{86}Sr$ ratio of tholeiite from Yanaguni Graben was 0.704 33 (Li et al., 1997b), which was higher than those of normal MORB (0.702 5) and high U/Pb ratio (HIMU) (0.702 9) and lower than ocean island basalt (OIB) (0.705–0.706) (Sun and McDonough, 1989). For basalt and basaltic andesite samples from Yaeyama Graben, they had relatively limited ranges in Sr-Nd isotopic compositions: 0.703 69–0.704 62 for $^{87}Sr/^{86}Sr$ and 0.512 81–0.512 90 for $^{143}Nd/^{144}Nd$ (Shinjo et al., 1999). In plot of εSr versus εNd, all samples are plotted into the field close to DMM (depleted MORB mantle) (Fig. 4a).

3.2 *MDS volcanic rocks*

All samples of basaltic rocks belonged to the sub-alkaline series (Fig. 2). Basaltic rocks from MDS were comparable to those from SWS, and had somewhat higher Al_2O_3 and lower FeO and TiO_2 relative to those from SWS (not shown). All rhyolitic rocks were also in the sub-alkaline series. In addition, a few intermediate rocks (e.g., andesite) were also sub-alkaline series rocks. Similar to SWS rocks, the MDS lavas also had well-defined liquid lines of descent (LLD) in SiO_2 versus other major oxide diagrams (not shown). However, at given SiO_2 content, other major oxide contents of MDS lavas were obviously higher than those of SWS lavas (not shown). All types of rocks from the MDS showed consistent variation trends in trace element composi-

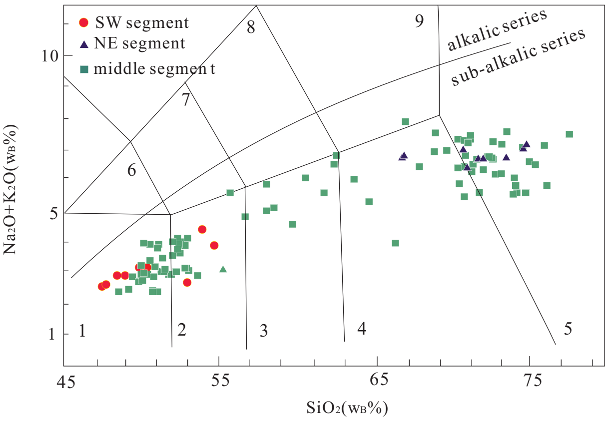

Fig.2. SiO_2 versus Na_2O+K_2O plot for volcanic rocks from the Okinawa Trough for each segment: southwest (SW), northeast (NE), and middle.

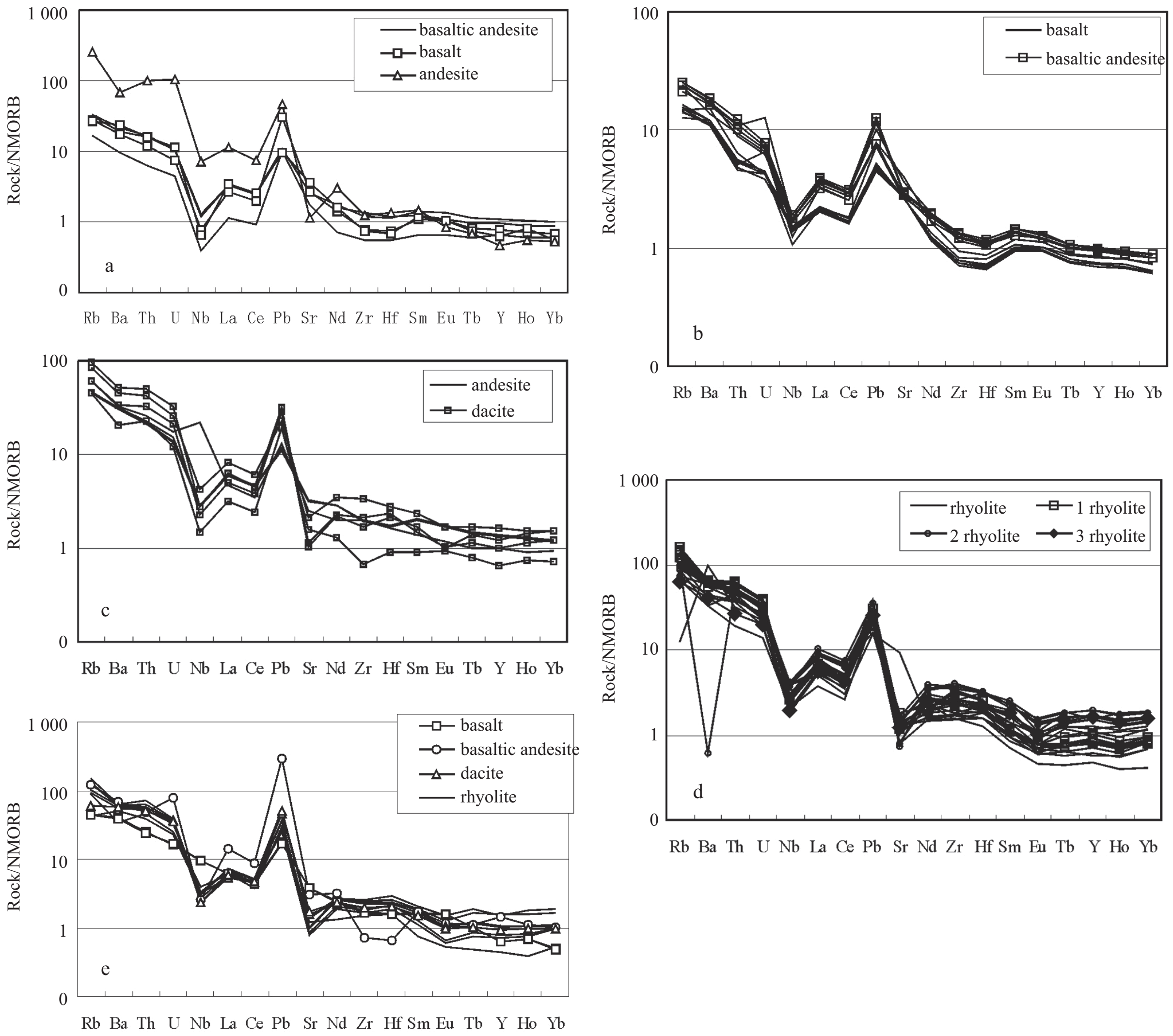

Fig.3. Spider diagrams showing primitive mantle-normalized trace element abundances in volcanic rocks from the Okinawa Trough. Trace element abundances of the primitive mantle and normal mid-oceanic ridge basalts are from Sun and McDonough (1989). a. Southwest segment, b. middle segment-basaltic rocks, c. middle segment-intermediate rocks, d. middle segment-acidic rocks, and e. northeast segment.

tions (Figs 3b, c and d), which were comparable to those from the SWS (Fig. 3a). Yet, there were some differences among different rock types. For example, basaltic rocks showed negative anomalies in Zr and Hf (similar to Nb), while intermediate and acidic rocks did not. From basaltic rocks to andesite to rhyolitic rocks, the concentrations of strongly incompatible elements (e.g., Sr) gradually increased: there was no anomaly in Sr for basaltic rocks, a negative anomaly in Sr for intermediate rocks, and an even greater negative anomaly in Sr for rhyolitic rocks (Figs 3b, c and d).

Basaltic rocks from this segment showed greater variations in Sr-Nd compositions than those from SWS: 0.703 89–0.706 62 for ^{87}Sr/^{86}Sr ratio and 0.512 53–0.512 88 for ^{143}Nd/^{144}Nd ratio. They had slightly higher ^{87}Sr/^{86}Sr for a given ^{143}Nd/^{144}Nd ratio than SWS lavas in general (Fig. 4b). The only exception was Sample CH-7, which showed extraordinary enrichment (^{87}Sr/^{86}Sr = 0.706 62 and ^{143}Nd/^{144}Nd = 0.512 53) (Meng et al., 1999). Two andesite samples showed similar Sr-Nd isotopic compositions to basaltic rock in the same segment (Fig. 4b), except for Sample CH-1 (^{87}Sr/^{86}Sr = 0.708 77 and ^{143}Nd/^{144}Nd = 0.512 41), which may have been affected by crustal contamination (Meng et al., 1999). Acidic rocks have limited ranges in ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd ratios as 0.704 02–0.705 70 and 0.512 63–0.512 90, respectively, and overlapped with basaltic rocks in Fig. 4b except for a few samples. Note that Sample CH-6 was not shown, for which the Sr-Nd isotopic compositions (^{87}Sr/^{86}Sr = 0.720 30 and ^{143}Nd/^{144}Nd = 0.512 03) were similar to those of average continental crust (Goldstein, 1988).

3.3 *NES volcanic rocks*

All rock samples from this segment belonged to the sub-alkaline series (Fig. 2). If the basaltic rock samples from Zeng et al. (2010), collected from the ECS shelf on the northwest side of the NES of the Okinawa Trough, can be regarded as relatively primitive magma of rhyolitic rocks of the NES, the lavas of NES also have well-defined liquid lines of descent in SiO_2 versus

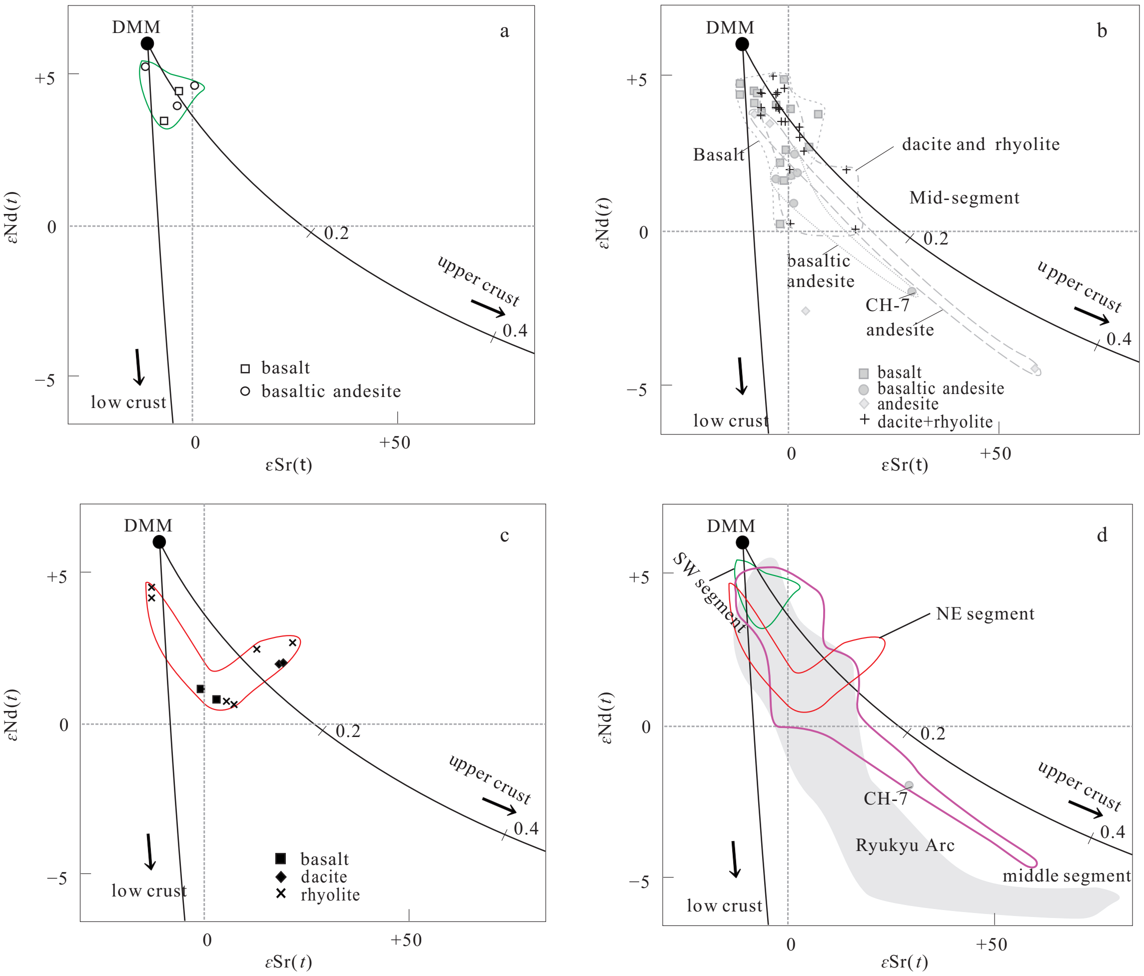

Fig.4. Plot of εSr(*t*) versus εNd(*t*) for volcanic rocks from Okinawa Trough. Data for Sr and Nd of upper crust, lower crust, and depleted MORB mantle (DMM) are from Faure (1986). Data for mean Sr-Nd isotope compositions of Cenozoic lavas from SE China are from Zou et al. (2000). Measured values of $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ for volcanic rocks were assumed to be approximate initial ratios due to the very young ages (< 1 Ma). Data for Ryukyu Arc lavas are from the PetDB database (http://www.petdb.org/). a. Southwest segment, b. middle segment, c. northeast segment, and d. comparison with Ryukyu volcanics.

other major oxide diagrams, similar to those of the SWS and MDS (not shown). All of the rock samples from the MDS, including basaltic andesite and rhyolitic rocks, showed consistent variation trends in trace element compositions (Fig. 3e), which were comparable to those from the SWS (Fig. 3a). Yet, there were some differences among different rock types. For example, the basaltic andesite sample showed the most obvious positive anomaly in Pb and negative anomalies in Nb, Zr, Hf, and Sr, whereas rhyolitic rocks showed negative anomalies in Nb and Sr and no obvious anomalies in Zr and Hf (Fig. 3a).

The $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios of rhyolitic rocks from the NES were 0.704 29–0.706 03 and 0.512 67–0.512 87, respectively (Huang et al., 2006a). Note that $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios of the two samples from the ECS shelf northwest side of the NES were 0.704 42–0.704 71 and 0.512 67–0.512 68, respectively (Zeng et al., 2010), which more closely resemble the value of bulk Earth relative to rhyolites in the same segment (Fig. 4c).

4 Petrogenesis of volcanic rocks in the Okinawa Trough

Some petrogenetic models have been proposed to interpret the magmatic process experienced by volcanic rocks from the trough (e.g., Ishizuka et al., 1990; Honma et al., 1991; Li et al., 1997a; Shinjo et al., 1999; Shinjo and Kato, 2000; Huang et al., 2006a). By compiling data, this study reconsidered the proposed petrogenesis models.

4.1 *Nature of the mantle source beneath the Okinawa Trough*

Previous studies on Cenozoic basalts from SE China and the ECS shelf suggest that two mantle end members exist: a depleted one and an enriched one, considered to be a sub-continental lithospheric mantle (Zou et al., 2000; Zeng et al., 2010). In contrast to intraplate setting of SE China and the ECS shelf, the Okinawa Trough has definitely been strongly affected by subducted components, including the Indian Ocean-type MORB of the Philippine Sea Plate (Hickey-Vargas, 1991, 1998; Hickey-Vargas et al., 1995; Savov et al., 2006; Hickey-Vargas et al., 2008), and oceanic island basalt-like materials on an aseismic ridge (e.g., Gagua Ridge) and submarine plateau (e.g., Amami-Daito igneous province) (Hickey-Vargas, 2005). Therefore, due to modification by subducted components, the mantle source of

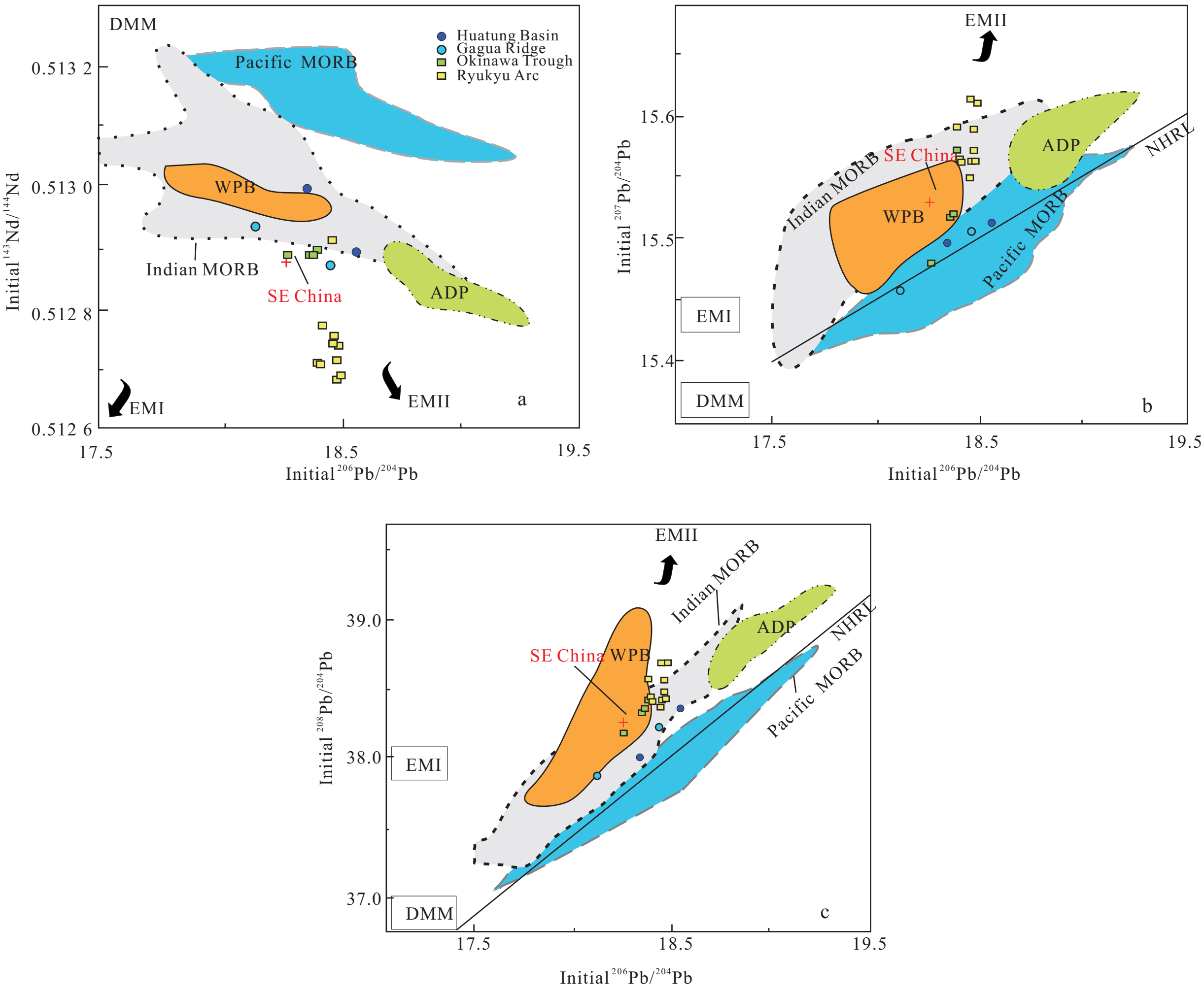

Fig.5. Plots of ^{143}Nd/^{144}Nd (a), ^{207}Pb/^{204}Pb (b), and ^{208}Pb/^{204}Pb (c) versus ^{206}Pb/^{204}Pb. Data sources for the Pb isotope of lavas from the Ryukyu Arc and Okinawa Trough are from Hoang and Uto (2006). Data for Huatung Basin, Amami–Daito Plateau, including DSDP Site 446, and other dredged locations (e.g., Geodynamics Project of Japan from 1974–1976), and DSDP and ODP sites (291, 294, and 1201D) in the Philippine Ocean Basin are from Hickey-Vargas (1991, 1998, 2005), Hickey-Vargas et al. (1995, 2008), and Savov et al. (2006). The approximate fields for DMM, HIMU, EMI, and EMII are from Zindler and Hart (1986); the field for OIB is from Staudigel et al. (1984); and NHRL is northern hemisphere reference line (Hart, 1984). The field for the Dupal anomaly is from Hamelin and Allègre (1985) and Castillo (1988). SE China data are from Zou et al. (2000).

the Okinawa Trough lavas is very complex. In plots of *ε*Sr versus *ε*Nd (Fig. 4), ^{206}Pb/^{204}Pb versus ^{143}Nd/^{144}Nd, ^{206}Pb/^{204}Pb versus ^{207}Pb/^{204}Pb, and ^{206}Pb/^{204}Pb versus ^{208}Pb/^{204}Pb (Fig. 5), basaltic rocks from the Okinawa Trough are close to DMM and extend to enriched mantle types I and II (EMI and EMII), reflecting that its mantle source is a mixture between DMM and several enriched mantle end members. Geophysical data show that there is no active mantle plume within and around the Okinawa Trough (Zhao et al., 2011). This, combined with the fact that the Okinawa Trough was caused by the strong extension of continental crust behind the Ryukyu, suggests that enriched geochemical characteristics in the basaltic rocks of the Okinawa Trough may originate from the upper and lower continental crust and/or sub-continental lithospheric mantle (SCLM) metasomatized by subducted fluids released from the subducted Philippine Sea slab. Based on the above analysis, the mantle sources of the Okinawa Trough may include a mixed mantle source indicated by Cenozoic basalts from SE China and the ECS shelf (Zou et al., 2000; Zeng et al., 2010), and Indian Ocean-type mantle and OIB-like materials entrained by the subducted Philippine Sea slab (Hickey-Vargas, 1991, 1998, 2005). In addition, the effect of the Pacific Ocean-type mantle on the Okinawa Trough lavas is limited to the northeast end of the NES (Hoang and Uto, 2006).

Similar to Cenozoic basalts from SE China, basaltic rocks in the SWS were plotted within the field between DMM and EMII, but more closely to DMM (Fig. 4a), reflecting that the main mantle source of the SWS is the DMM (possibly Indian Ocean-type mantle), and slightly affected by EMII end member. The enriched mantle end members may not be pre-existing SCLM, but possibly upper continental materials (in the form of pelagic sediments). The latter were added to the mantle source beneath the SWS by subduction recycling.

The plotted field of basaltic lavas from the MDS was similar to that of Ryukyu Arc (Fig. 4b). However, except for a few samples that possibly reflect crustal contamination (e.g., basaltic rock samples CH-1, CH-6, and CH-7 reported by Meng et al. (1999), for which the $^{87}Sr/^{86}Sr$ ratio was high relative to other samples from the same segment), the plotted fields of most other basaltic, intermediate, and acidic rocks were similar (Fig. 4b), reflecting that they may share a common mantle source. The sources for volcanic rocks in the MDS may include DMM, enriched mantle type I (EMI), and enriched mantle type II (EMII) (Figs 4d, 5a and b). Of them, DMM is Indian Ocean-type mantle contaminated by extremely small amounts of Pacific Ocean-type mantle (Fig. 5b), EMI is SCLM beneath the Eurasian Plate metasomatized by aqueous fluids released from the subducted slab, and EMII is the pelagic sediments overlying the oceanic crust of the Philippine Sea Plate being subducted.

The mantle source of NES lavas is the mixture between DMM and EMII (Fig. 4c), and is close to prevalent mantle (PREMA) (Huang et al., 2006b). Of them, the DMM end member (especially for the northeast end of the NES) may be Pacific MORB-type mantle (Hoang and Uto, 2006), reflecting that the Indian Ocean type mantle dominant in the SWS and MDS was gradually replaced by Pacific MORB-type mantle northeastwards. The Amami–Daito igneous province that is being subducted beneath Ryukyu Arc on the southeast side of the NES (Yan and Shi, 2011 and references therein) may be the main source of EMII, as indicated by NES lavas.

4.2 *Fractional crystallization-dominated magmatic process*

4.2.1 *Crustal contamination*

Average Ce/Pb ratios of basaltic rocks from the SWS and MDS were 6.23 (5.86–6.49) and 7.64 (6.17–9.23), respectively, which were obviously higher than those of bulk continental crust (BCC) and upper continental crust (UCC), which were 2.10 and 5.08 according to Taylor and McLennan (1985) and Rudnick and Fountain (1995), respectively, and higher than that of island arc basalt (IAB), which was 2.31 according to Niu and O'Hara (2003). Likewise, average Nb/U ratios of basaltic rocks from the SWS and MDS were 11.80 (4.29–23.79) and 13.65 (4.67–34.65), respectively, which were obviously higher than those of BCC (8.93) and UCC (8.59), and higher than that of IAB (4.25), according to the same respective studies. Data for Ce/Pb ratios of basaltic rocks from the Okinawa Trough were plotted to a triangular field encircled by three linkage lines among NMORB, IAB, and OIB (Fig. 6a), and far from UCC and BCC. In the plot of Nb versus Nb/U, data for basaltic rocks from the Okinawa Trough were plotted between NMORB and IAB (Fig. 6b), and Nb abundances of basaltic rocks from the Okinawa Trough were less than those of UCC and BCC, but close to those of NMORB and IAB. As a whole, these two trace element plots therefore showed that basaltic rocks in the Okinawa Trough underwent slight and/or no crustal contamination. Sr and Nd isotopic compositions provided by Meng et al. (1999) also demonstrated that few samples were affected by crustal contamination.

4.2.2 *Fractional crystallization*

All rock samples from the SWS showed similar trace element characteristics (Fig. 3a), reflecting that they originated from a common source. Negative anomalies in Eu and Sr in andesites implied that parent magmas represented by basaltic rocks experienced plagioclase crystallization during their ascent to the surface from the source.

Lavas from the MDS with characteristics of slight enrichment from light rare earth elements (LREE) were comparable to those from other back-arc basins at earlier rifting phases, such as the Mariana Trough, Guaymas Basin, and Sumisu Rift worldwide (Shinjo et al., 1999), reflecting that the MDS is still in the rifting phase. Similar to the SWS, parent basaltic magma in this segment also experienced assimilation and fractional crystallization (AFC) processes (Shinjo and Kato, 2000). Based on compiled data, however, we suggested that fractional crystallization was the dominant factor for magmatic evolution in this segment (see Section 3.2).

Although basic rocks have been collected from the west side of the NES in the ECS shelf (Zeng et al., 2010), there was no basaltic rock reported from the NES until recently. Trace element characteristics (Fig. 3e) showed there were no obvious differences in element abundances among several types of rocks. The distributional patterns of rhyolitic rocks were similar to those

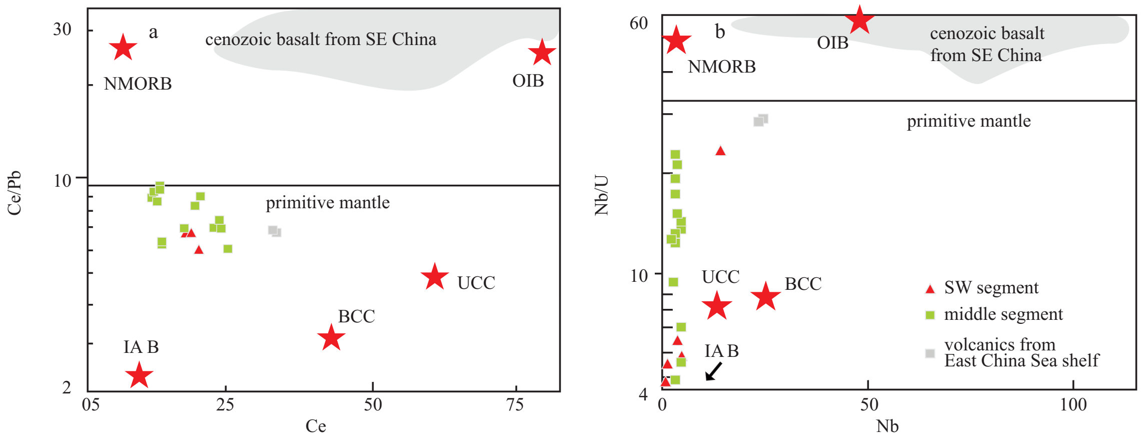

Fig.6. Plots for Ce/Pb versus Ce and Nb/U versus Nb. Data for Cenozoic basalts in Southeast China and the East China Sea shelf are from Zou et al. (2000) and Zeng et al. (2010). Data for primitive mantle and normal mid-oceanic ridge basalt (NMORB) are from Sun and McDonough (1989); oceanic island basalt (OIB) and island arc basalt (IAB) are from Niu and O'Hara (2003); upper continental crust (UCC) are from Taylor and McLennan (1985); bulk continental crust (BCC) are from Rudnick and Fountain (1995); and global subducted sediment (GLOSS) and Ryukyu sediment (RS) are from Plank and Langmuir (1998).

of intermediate rocks (Fig. 3e), reflecting that both may come from a common source. During the ascent of the parent magma to the surface, it underwent obvious fractional crystallization (Huang et al., 2006a). For example, the degree of negative anomalies in Eu and Sr gradually increased from intermediate rocks to rhyolitic rocks.

In general, parent magmas in all three of these segments experienced fractional crystallization, but the extent was different among the SWS, MDS, and NES. From the SWS to MDS to NES, the degree of fractional crystallization gradually increased. Although the crust was thin, it was still thicker in the NES than in the SWS and MDS, meaning the parent magma was strongly fractionally crystallized to highly differentiated rhyolitic rocks, such as dacites and rhyolites. In summary, the magmas may have experienced fractional crystallization-dominated processes during ascent to the surface.

4.3 *Effects of subducted fluids*

From offshore east of Taiwan arcward to the west side of the Kyushu–Palau Ridge (KPR), the Huatung Basin, Gagua Ridge, West Philippine oceanic crust, and the complex Amami–Daito Plateau are distributed in sequence. Therefore, in the Ryukyu SSZ setting, the complexity of the subduction input directly resulted in the variability of volcanic output represented by Ryukyu Arc and Okinawa Trough lavas.

It can be seen in Fig. 7a that, in comparison with the Ryukyu Arc lavas that were obviously affected by subducted sediment components, the Okinawa Trough lavas were mainly affected by the addition of fluids released from the subducted slab, and the extent of effects from slab fluids on SWS lavas was greater than on MDS lavas. The plotted areas for the Okinawa Trough lavas lie between fields of Ryukyu Arc lavas and Indian Ocean-type mantle represented by Philippine Sea Plate basement samples from Huatung Basin (Hickey-Vargas et al., 2008), Deep Sea Drilling Project (DSDP) Site 191 (Hickey-Vargas, 1998), and Ocean Drilling Program (ODP) Site 1201D (Savov et al., 2006). Except for a few samples from the MDS that possibly underwent subducted slab melts, $(La/Sm)_N$ ratios of most lavas from the Okinawa Trough including the SWS and MDS were less than those of many types of sediments (Fig. 7b), such as GLOSS ($(La/Sm)_N$ = 3.21), sediments being subducted along Nankai Trough ($(La/Sm)_N$ = 3.99), and sediments subducted beneath Ryukyu Arc ($(La/Sm)_N$ = 2.4) (Plank and Langmuir, 1998). In general, the $(La/Sm)_N$ ratios of lavas from the Okinawa Trough lavas including the SWS and NES were less than those of Ryukyu Arc lavas, and similar to or slightly higher than those of the Amami Plateau ($(La/Sm)_N$ = 1.42; Hickey-Vargas, 2005), Huatung Basin ($(La/Sm)_N$ = 1.58; Hickey-Vargas et al., 2008) and DSDP Site 291 ($(La/Sm)_N$ = 1.2; Hickey-Vargas, 1998). The evidence shown above suggested that the effects of subduction components on the Okinawa Trough lavas were not from partial melts from sediments, which consisted of pelagic oozes and volcaniclastics, but mainly aqueous fluids released from altered oceanic crust (AOC). Under the given $(La/Sm)_N$ ratios, Ba/Nb ratios for SWS lavas were lower than those for MDS lavas. The plotted trend of Ba/Nb ratios points to the field of aqueous liquid (Fig. 7a), reflecting that the extent of the effects of aqueous fluids on SWS lavas was higher than that on MDS lavas. In Fig. 7b, the plotted field of the Okinawa Trough lavas lies between Ryukyu Arc volcanic rocks and Indian Ocean-type MORB, and was far from GLOSS, sediments subducted along Nankai Trough, and sediments subducted beneath Ryukyu Arc (Plank and Langmuir, 1998). In general, the field of the Okinawa Trough lavas lies below the Ryukyu Arc lavas and is close to and slightly higher than the Amami Plateau, Huatung Basin, and DSDP Site 291 (Hickey-Vargas, 1998, 2005; Hickey-Vargas et al., 2008). Under the given $(La/Sm)_N$ ratios, Nb/Yb ratios for SWS lavas were lower than those for MDS lavas and the plotted trend of Nb/Yb ratios points to the field of aqueous liquid (Fig. 7b), reflecting that the extent of the effects of aqueous fluids on SWS lavas were higher than on MDS lavas.

5 Implications for tectonic evolution of the Okinawa Trough

5.1 *Three tectonic evolution phases existing in the Okinawa Trough*

(1) NES: crustal stretching phase (Fig. 8a)

Geophyscial data show that the continental crust has

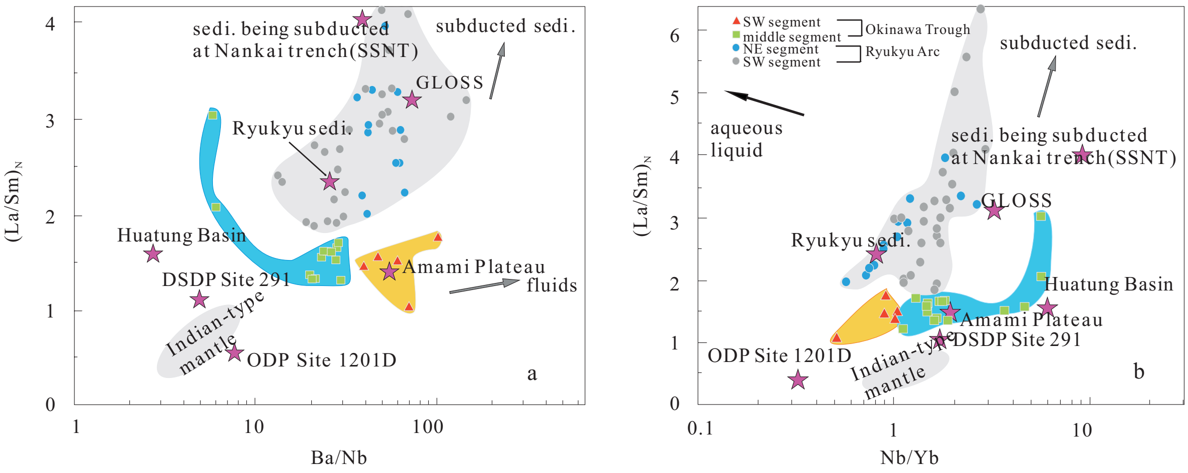

Fig.7. Plots of $(La/Sm)_N$ versus Ba/Nb (a) and $(La/Sm)_N$ versus Nb/Yb (b), indicating the various effects of subducted components (sediments and/or fluids released from altered oceanic crust). The data sources are the same as Figs 4–6. Part of the rock samples from Ryukyu Arc (with $(La/Sm)_N$ ratios higher than 5.5) were not plotted in Fig. 6a, but they definitely suffered more serious effects from subducted sediment due to the anomalously high $(La/Sm)_N$ ratios. Sedi. means sediments.

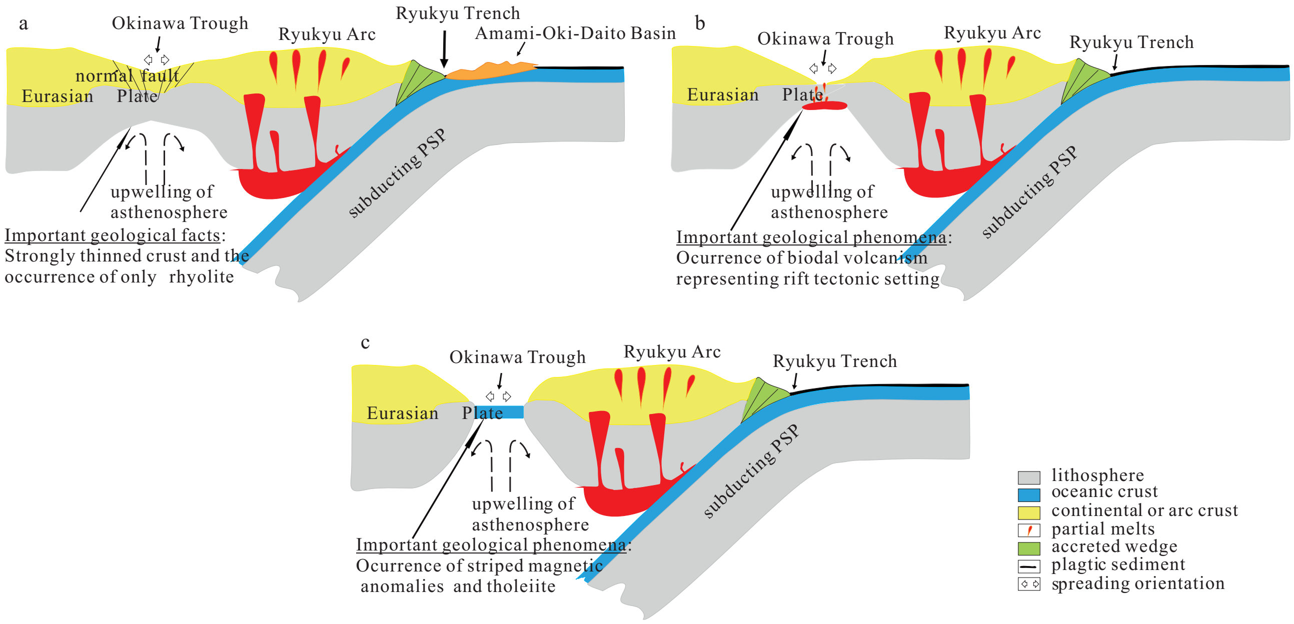

Fig.8. Schematic cartoon demonstrating the three phases of tectonic evolution of the Okinawa Trough. a. Stage 1—northeast segment, b. Stage 2—middle segment, and c. Stage 3—southwest segment. PSP represents Philippine Sea Plate.

thinned to a certain extent (Wang et al., 1998; Han et al., 2007). The subduction of the Philippine Sea Plate, including Amami Plateau, caused an extensional setting at the back-arc site of this segment behind Ryukyu Arc. The upwelling of the asthenospheric mantle resulting from tectonic extension not only provided enough heat for the anatexes of its overlying lithosphere and lower continental crust, but some contributions of material. Parent magma produced by partial melting of the lithosphere and lower continental crust then experienced fractional crystallization through its thick crust during ascent to the surface, thereby differentiating into dacite and rhyolites, as in our current samples. Therefore, the segment is in the stage of crustal stretching.

(2) MDS: rifting phase (Fig. 8b)

Previous studies have shown that bimodal volcanism generally occurs in continental extension and thinned setting of the zone when transitioning from continental crust to oceanic crust and/or continental rifts (Foder and Verrer, 1984; Garland et al., 1995). In this geodynamic setting, rhyolite and basalt share a common parent mantle-derived magma. Rhyolite is the product of fractional crystallization of basaltic magma accompanied by the addition of limited and/or no continental materials (Bacon and Druit, 1988). In addition to few rhyolitic rocks (tuff) possibly migrating from nearby Ryukyu Arc, geochemical data show that most of the rhyolitic rocks in the MDS evolved in situ from basaltic rocks mainly by fractional crystallization. This reflects that volcanic activities in the MDS are characterized by bimodal volcanism and the tectonic setting of the MDS is a continental rift or rifted continent. Moreover, geophysical data show that the continent crust of the MDS has been thinning to an extreme extent, much more so than that of the NES (Liang et al., 2001), and many graben tectonics have occurred, such as Aguni, Izena, Iheya, and Io Grabens (Wu, 2000). Therefore, petrologic and geophysical data mentioned above implies that the MDS is in the rifting phase.

(3) SWS: initial seafloor spreading phase (Fig. 8c)

The subduction of the Philippine Sea Plate beneath the Eurasian Plate since about 8 Ma caused a greater extensional setting at the SWS relative to the NES and MDS. Geophysical data suggests that some obvious magnetic anomaly stripes and crust have thinned up to 13 km (Liang et al., 2001). In addition, the lithologies of dredged rock are olivine tholeiite (e.g., Li et al., 1997b). This evidence, combined with geochemical data, implies that oceanic crust was possibly produced by a seafloor spreading process similar to the mid-oceanic ridge and other mature back-arc basins such as the Mariana Trough and Lau Basin (Fig. 8c). As Fig. 8c shows, the subduction of the Philippine Sea Plate changed the normal mantle convection beneath the segment, and induced passive upwelling of asthenospheric mantle. Due to underplating of the asthenospheric mantle, the lithosphere and/or the lowest part of the continental crust partially melted to the parent basaltic magma. Then the parent magma rapidly ascended, finally erupting onto the surface to form oceanic crust. It should be noted that the back-arc opening in the southern segment of the Okinawa Trough caused tectonic clockwise rotation of about 19° of the southern part of the Ryukyu Arc during the past 10 Ma (Miki et al., 1990). In general, the Okinawa Trough is experiencing rift propagation and subsequent seafloor spreading, similar to the tectonic evolution of the Mariana Trough and Lau Basin (Fryer, 1996).

5.2 *What causes this tectonic evolution scenario?*

In those back-arc sites for which the distances to the trench and/or volcanic arc are identical, why does the back-arc rifting not take place simultaneously and subsequently develop into seafloor spreading? This is a very complex question, which possibly includes some issues such as the relative motion orientations between several large plates around the arc–trench–back-arc systems, subduction vectors, subduction rates, and subducted components (normal oceanic crust versus aseimic ridges or seafloor plateau) (e.g., Vogt, 1973; Cloos, 1993; Tetreault and Buiter, 2012).

In the present study, we suggested that the differences of subducted components may be the first-order factor causing the differential back-arc spreading process. Previous studies have shown that seamount or plateau subduction plays an important role in the dynamic regime of the supra-subduction zone (e.g., Vogt, 1973; Miller et al., 2006; Gerya et al., 2009; Tetreault and Buiter, 2012) and global distribution of heterogeneous mantle geochemistry and dynamic geochemical cycles in solid earth (Staudigel et al., 2010; Ulrich et al., 2012). The positive buoyancy of seamounts or plateaus inhibits their subduction to the mantle when they move close to the subduction zone accompanying normal oceanic crust. Relative to normal oceanic crust, slower subduction of seamounts or plateaus causes more locally weak mantle convection of the back-arc site directly behind the subduction of seamounts or plateaus, thereby resulting in no adequate extension. In comparison with the case for seamount subduction, the subduction rate of normal oceanic crust is obviously higher under the same subduction system, first rifting at back-arc sites where oceanic crust subducts, then subsequently spreading. The motion directions of mantle flows beneath back-arc areas are not single. While the sub-arc site flows towards the back-arc site (perpendicular to the volcanic arc), lateral flows (parallel to the volcanic arc) also take place. For example, mantle materials flow towards the back-arc site of seamount subduction, which may cause the latter to rift and subsequently the seafloor to spread, thereby resulting in rift propagation. For the NES of the Okinawa Trough in the present study, due to the Amami–Daito Plateau (ADP) west of the Kyushu–Palau Ridge that inhibits its subduction along the Ryukyu Arc beneath the Eurasian Plate, the rifting of back-arc sites on the subduction orientation of ADP take place much more slowly relative to the MDS and especially for the SWS. While spreading occurs in the SWS, the northeastward mantle flows from the SWS, causing rift propagation to the MDS and then to the NES, as expected.

6 Summary and conclusions

(1) The mantle sources beneath the Okinawa Trough include continental lithospheric mantle underlying the Eurasian Plate, Indian Ocean-type mantle, and Pacific Ocean-type mantle (mainly occurring in the northeast end of the NES), which are variably affected by subducted components (mainly aqueous fluids). From the SWS to MDS to NES, the effects on lava chemistry from subduction components gradually decrease.

(2) The olivine tholeiites that occur in the SWS are low-K and medium-K calc-alkaline series, which provide direct geological evidence for the occurrence of oceanic crust in the SWS. Trace element and isotopic data show that parent magma did not undergo assimilation during its ascent to the surface. A few differentiated rocks, such as rhyolites, are the products of fractional crystallization of basaltic rocks.

(3) Basic rocks, accompanied by acidic rocks, occur in many grabens in the MDS, reflecting that bimodal volcanism widely took place in the segment. Geochemical data suggest both basaltic and rhyolitic rocks share a common mantle source, and rhyolitic rocks are products of fractional crystallization of basaltic rocks.

(4) Only intermediate and acidic rocks, such as basaltic andesite, andesite, dacite, and rhyolitic tuff, occur in the NES. Sr-Nd isotopic compositions of all types of rocks in the segment show that their sources were close to the PREMA end member. During the ascent of the parent magma, they experienced AFC processes.

(5) In general, petrologic data, combined with geophysical data, show that the Okinawa Trough is experiencing processes of seafloor spreading to rift propagation to crustal extension, and a nascent ocean basin occurs in the southwest segment.

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Refereneces

Bacon C R, Druit T H. 1988. Compositional evolution of the zoned calc-alkaline magma chamber of Mount Magma, Crater Lake Oregon. Contributions to Mineralogy and Petrology, 98: 224–256

Bibee L D, Shor Jr G G, Lu R S. 1980. Inter-arc spreading in the Mariana Trough. Marine Geology, 35: 183–197

Castillo P. 1988. The Dupal anomaly as a trace of the upwelling lower mantle. Nature, 336: 667–670

Chen Lirong, Zhai Shikui, Shen Shunxi. 1993. Isotopic characteristics and ages of pumices from the Okinawa Trough. Science in China (Series B) (in Chinese), 23(3): 324–329

Cloos M. 1993. Lithospheric buoyancy and collisional orogenesis—subduction of oceanic plateaus, continental margins, island arcs, spreading ridges, and seamounts. Geological Society of America Bulletin, 105: 715–737

Faure G. 1986. Principle of Isotope Geology. 2nd edition. New York: John Wiley and Sons, 589

Foder R V, Verrer S K. 1984. Rift-zone magmatism: petrology of basaltic rocks transitional from CFB to MORB, southeastern Brazil margin. Contributions to Mineralogy and Petrology, 88: 307–321

Fryer P. 1996. Evolution of the Mariana Convergent Plate Margin System. Reviews of Geophysics, 34: 89–125

Goldstein S L. 1988. Decoupled evolution of Nd and Sr isotopes in the continental crust and mantle. Nature, 336: 733–738

Garland F, Hawkesworth C J, Mantovani M S. 1995. Description and petrogenesis of the paraná rhyolites, southern Brazil. Journal of Petrology, 36: 1193–1227

Gerya T V, Fossati D, Canetini C, et al. 2009. Dynamic effects of aseismic ridge subduction: numerical modeling. European Journal of Mineralogy, 21: 649–661

Hamelin B, Allègre C J. 1985. Large scale regional units in the depleted upper mantle revealed by an isotopic study of the south-west Indian ridge. Nature, 315: 196–198

Hall R. 2002. Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions, model and animations. Journal of Asian Earth Sciences, 20(4): 353–431

Han Bo, Zhang Xunhua, Pei Jianxin, et al. 2007. Characteristics of crust-mantle in East China sea and adjacent regions. Progress in Geophysics (in Chinese), 22(2): 376–382

Han Zongzhu, Yu Hang, Zhao Guangtao, et al. 2005. Petrology and geochemistry of the basalt from the middle part of Okinawa. Marine Sciences (in Chinese), 29(6): 17–21

Han Zongzhu, Li Chao, Lai Zhiqing. 2008. Geochemical features and origin of the pumice from middle and south Okinawa Trough. Transactions of Oceanology and Limnology (in Chinese), 39(3): 61–66

Hart S R. 1984. A large-scale isotope anomaly in the southern hemisphere mantle. Nature, 309: 753–757

Hawkins J W. 1995. Evolution of the Lau Basin-Insights from ODP Leg 135. In: Taylor B, Natland J, eds. Active Margins and Marginal Basins of the Western Pacific. Geophysical Monograph 88, American Geophysical Union, 125–173

Hickey-Vargas R. 1991. Isotope characteristics of submarine lavas from the Philippine Sea: implications for the origin of arc and basin magmas of the Philippine tectonic plate. Earth and Planetary Science Letters, 107: 290–304

Hickey-Vargas R. 1998. Origin of the Indian Ocean-type isotopic signature in basalts from Philippine Sea plate spreading centers: an assessment of local versus large-scale processes. Journal of Geophysical Research, 103: 20963–20979

Hickey-Vargas R. 2005. Basalt and tonalite from the Amami Plateau, northern West Philippine Basin: New Early Cretaceous ages and geochemical results, and their petrologic and tectonic implications. Island Arc, 14: 653–665

Hickey-Vargas R, Hergt J M, Spadea P. 1995. The Indian Ocean-type isotopic signature in western Pacific marginal basins: origin and significance. In: Taylor B, Natland J, eds. Active Margins and Marginal Basins of the Western Pacific. Geophysical Monograph 88, American Geophysical Union, 88: 175–197

Hickey-Vargas R, Bizimis M, Deschamps A. 2008. Onset of the Indian Ocean isotopic signature in the Philippine Sea Plate: Hf and Pb isotope evidence from Early Cretaceous terranes. Earth and Planetary Science Letters, 268: 255–267

Hoang N, Uto K. 2006. Upper mantle isotopic components beneath the Ryukyu arc system: Evidence for 'back-arc' entrapment of Pacific MORB mantle. Earth and Planetary Science Letters, 249: 229–240

Honma H, Kusakabe M, Kagami H, et al. 1991. Major and trace element chemistry and D/H, $^{18}O/^{16}O$, $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios of rocks from the spreading center of the Okinawa Trough. Geochemical Journal, 25(2): 121–136

Huang Peng, Li Anchun, Jiang Hengyi. 2006a. Geochemical features and their geological implications of volcanic rocks from the northern and middle Okinawa Trough. Acta Petrologica Sinica (in Chinese), 22(6): 1703–1712

Huang Peng, Li Anchun, Hu Ningjing, et al. 2006b. Sr-Nd isotopic characteristics and U-series ages of volcanics from the Okinawa Trough. Science in China (Series D) (in Chinese), 36(4): 351–358

Ishizuka H, Kawanobe Y, Sakai H. 1990. Petrology and geochemistry of volcanic rocks dredged from the Okinawa Trough,an active backarc basin. Geochemical Journal, 24: 75–92

Kimura M. 1985. Back-arc rifting in the Okinawa Trough. Marine and Petroleum Geology, 2: 222–239

Lee C S, Shor G G, Bibee L D, et al. 1980. Okinawa Trough: Origin of a back-arc basin. Marine Geology, 35: 219–241

Letouzey J, Kimura M. 1985. Okinawa trough genesis: structure and evolution of a back arc basin developed in a continent. Marine and Petroleum Geology, 2: 111–130

Li Jiabiao. 2008. Regional Geology in East China Sea. Beijing: Ocean Press

Li Naisheng. 2001. On Tectonic problems of the Okinawa trough. Chinese Journal of Oceanology and Limnology, 19(3): 255–364

Li Weiran, Yang Zuosheng, Wang Yongjie, et al. 1997a. The petrochemical features of the volcanic rocks in Okinawa Trough and their geological significance. Acta Petrologica Sinica (in Chinese), 13(4): 1703–1712

Li W, Yang Zuosheng, Zhang Baomin, et al. 1997b. Study on the olivine tholeiite of the southern Okinawa Trough. Oceanologica et Limnologica Sinica (in Chinese), 28: 665–672

Liang Ruicai, Wu Jinlong, Liu Baohua, et al. 2001. Linear magnetic anomalies and tectonic development for the middle Okinawa Trough. Acta Oceanologica Sinica (in Chinese), 23(2): 69–78

Ma Weilin, Wang Xianlan, Ji Xianglong, et al. 2004. Areal difference of middle and southern basalts from the Okinawa Trough and its genesis study. Acta Geologica Sinica (in Chinese), 78(6): 758–769

Meng Xianwei, Du Dewen, Wu Jinlong, et al. 1999. Sr-Nd isotopic geochemistry and its geological significances of volcanic rock series from the middle part of Okinawa Trough. Science in China (Series D) (in Chinese), 29(4): 367–371

Miki M, Matsuda T, Otofuji Y. 1990. Opening mode of the Okinawa Trough: paleomagnetic evidence from the South Ryukyu Arc. Tectonophysics, 175: 335–347

Miller M S, Kennett B L, Toy V G. 2006. Spatial and temporal evolution of the subducting Pacific plate structure along the western Pacific margin. Journal of Geophysical Research, 111: B02401, doi: 10.1029/2005JB003705

Niu Y L, O'Hara M J. 2003. Origin of ocean island basalts: A new perspective from petrology, geochemistry, and mineral physics considerations. Journal of Geophysical Research, 108(B4): 2209, doi: 10.1029/2002JB002048

Plank T, Langmuir C H. 1998. The chemical composition of subducting sediment and its consequences for the crust and mantle. Chemical Geology, 145: 325–394

Qin Yunshan, Zhai Shikui, Mao Xueying. 1987. Trace element features and its geological significances of pumices from the Okinawa Trough. Oceanologica et Limnologica Sinica (in Chinese), 18(4): 313–319

Rudnick R L, Fountain D M. 1995. Nature and composition of the continental crust: A lower crustal perspective. Reviews of Geophysics, 33: 267–309

Savov I, Hickey-Vargas R, D'Antonio M, et al. 2006. Petrology and geochemistry of West Philippine Basin Basalts and Early Palau– Kyushu Arc Volcanic Clasts from ODP Leg 195, Site 1201D: Implications for the early history of the Izu–Bonin–Mariana Arc. Journal of Petrology, 47: 277–299

Shinjo R.1998. Petrochemistry and tectonic significance of the emerged late Cenozoic basalts behind the Okinawa Trough Ryukyu arc system. Journal of Volcanology and Geothermal Research, 80: 39–53

Shinjo R, Chung S L, Kato Y, et al. 1999. Geochemical and Sr—Nd isotopic characteristics of volcanic rocks from the Okinawa Trough and Ryukyu Arc: Implications for the evolution of a young intracontinental back arc basin. Journal of Geophysical Research, 104(B5): 10591–10608

Shinjo R, Kato Y. 2000. Geochemical constraints on the origin of bimodal magmatism at the Okinawa Trough, an incipient back-arc basin. Lithos, 54: 117–137

Sibuet J C, Deffontaines B, Hsu S K, et al. 1998. Okinawa Trough backarc basin: early tectonic and magmatic evolution. Journal of Geophysical Research, 103: 30245–30267

Staudigel P, Zindler A, Hart S R, et al. 1984. The isotope systematics of a juvenile intra-plate volcano: Pb, Nd and Sr isotope ratios of basalts from loihi Seamount, Hawaii. Earth and Planetary Science Letters, 69: 13–29

Staudigel H, Koopers A P, Plank T A, et al. 2010. Seamounts in the subduction factory. Oceanography, 23(1): 176–181

Sun S S, McDonough W F. 1989. Chemical and isotopic systematics of ocean basalt: Implications for mantle composition and processes. Geological Society London Special Publications, 42: 323–345

Taylor S R, McLennan S M. 1985. The Continental Crust: Its Composition and Evolution. Oxford: Blackwell

Tetreault J L, Buiter S J H. 2012. Geodynamic models of terrane accretion: Testing the fate of island arcs, oceanic plateaus, and continental fragments in subduction zones. Journal of Geophysical Research, 117: B08403, doi:10.1029/2012JB009316

Ulrich M, Hémond C, Nonnotte P, et al. 2012. OIB/seamount recycling as a possible process for E-MORB genesis. Geochem Geophys Geosyst, 13: Q0AC19, doi: 10.1029/2012GC004078

Vogt P R. 1973. Subduction and aseismic ridges. Nature, 241: 189–191

Wang K L, Chung S L, Chen C H, et al. 1999. Post-collisional magmatism around northern Taiwan and its relation with opening of the Okinawa Trough. Tectonophysics, 308: 363–376

Wang Shugong, Liang Ruicai, Wang Yong, et al. 1998. Gravity and magnetic characteristics of the north part of the Okinawa Trough and geological interpretation. Marine Geology & Quaternary Geology (in Chinese), 18(4): 19–27

Wu Shiying. 2000. Hydrothermal Sulfide Resources in Global Seafloor (in Chinese). Beijing: China Ocean Press, 21–25, 41–43

Yamazaki T, Murakami F, Saito E. 1993. Mode of seafloor spreading in the northern Mariana Trough. Tectonophysics, 221: 207–222

Yan Quanshu, Shi Xuefa. 2011. Geological comparative studies of Japan Arc System and Kyushu-Palau Arc. Acta Oceanologica Sinica, 30(4): 107–121

Zeng Zhigang, Yu Shaoxiong, Wang Xiaoyuan, et al. 2010. Geochemical and isotopic characteristics of volcanic rocks from the northern East China Sea shelf margin and the Okinawa Trough. Acta Oceanologica Sinica, 29(4): 48–61

Zou H B, Zindler A, Xu X S, et al. 2000. Major, trace element, and Nd, Sr and Pb isotope studies of Cenozoic basalts in SE China: mantle sources, regional variations, and tectonic significance. Chemical Geology, 171: 33–47

Zhai Shikui, Gan Xiaoqun. 1995. Study of basalt from the hydrothermal field of the Okinawa trough. Oceanologica et Limnologica Sinica (in Chinese), 26(2): 115–123

Zhao D, Yu S, Ohtani E. 2011. East Asia: Seismotectonics, magmatism and mantle dynamics. Journal of Asian Earth Sciences, 40: 689–709

Zindler A, Hart S. 1986. Chemical geodynamics. Annual Review of Earth and Planetary Sciences, 14: 493–571