

Geochronological and geochemical constraint on the Cenozoic extension of Cathaysian lithosphere and tectonic evolution of the border sea basins in East Asia

Zhu Bing-Quan*, Wang Hui-Fen, Chen Yu-Wei, Chang Xian-Yang, Hu Yao-Guo, Xie Jin

Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Wushan, Guangzhou, 510640, China

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Abstract

Geochronological and geochemical evidence indicates that continuous volcanism occurred from 92–38 Ma in Maoming and Sanshui basins in Guangdong. However, the source regions changed sharply from the lower crust to the upper mantle at 56 ± 2 Ma. That change might have been related to the time when India began to collide with Tibet (at ca. 55 Ma). The first stage of opening of border sea basins to East Asia also occurred ca. 56 Ma. A set of pull-apart basins in the Cathaysian block as well as the proto-South China Sea, Celebes Sea and West Philippine Sea were formed during Eocene (53–34 Ma). Indochina was extruded through left-lateral slip along the Red River fault between 35–17 Ma, which interrupted the NE directed shear extension in East Asia. No basaltic magmatism related to extension erupted during this interval. Significant extension of the lithosphere occurred along a NE strike in the Cathaysian block, East Sea and Japan Sea since 17 Ma, which also changed the movement direction of the Indochina block from left-lateral to right-lateral slip. The South China Sea possibly opened again during this stage. Isotopic geochemical features of the mantle beneath the border seas are distinct from those of the Pacific Plate and resemble those of the Indian Ocean domain.

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1. Introduction

The basins of the Philippine Sea, South China Sea, Sulu Sea, Celebes Sea, Japan Sea, Bohai Gulf, East China Sea and Yellow Sea constitute the border seas of Eastern Asia (Fig. 1). Extension of these sea basins is related to backarc opening (Hawkins et al., 1990; Stern et al., 1990; Honza, 1991), and to extrusion of the Indochina block (Tapponnier et al., 1986; Briais et al., 1993). Many authors also link the opening of the South China Sea in its early stages to lithospheric extension of the Cathaysian block in South China (Fig. 1) (Ru and Piggot, 1986; Hayes et al., 1995; Chung et al., 1997). Although there was limited extension of the Cathaysian block indicated by mafic dike intrusions since the Late Jurassic (Li et al., 1997), the generation of pull-apart basins associated with volcanism on a large scale was mainly during the Late Cretaceous and Tertiary. The Beibuwan, Maoming-Liedong, Sanshui, Heyuan and

Lieping-Nanxiong basins are typical pull-apart basins in the Guangdong area (Fig. 2). Our published age data have indicated that Cenozoic volcanism in the Cathaysian block can be clearly divided into two stages; before 40 and after 17 Ma, and there was almost no volcanism between 40–17 Ma (Zhu et al., 1988; Zhu and Wang, 1989a,b; Wang et al., 1989). The idea of two-stage evolution of the border seas of East Asia has been supported by geochronological and paleo-magnetic data (Ru and Piggot, 1986; Lee and Lawver, 1994; Hickey-Vargas, 1998). According to published results, the proto-South China Sea, Celebes Sea and West Philippine Sea opened in the Early Tertiary (65–34 Ma), and the northeastern part of the South China Sea, East Philippine Sea and Japan Sea originated during the Late Tertiary. The Pb, Sr and Nd isotopic features of basalts from these border seas are distinct from those of Pacific basalts, and comparable to those from the Indian Ocean-Tethyan basalts (Hickey-Vargas, 1998; Tu et al., 1992). Based on published and present data, we further discuss the relationships between the sea floor spreading in the marginal

* Corresponding author. Tel.: +86-020-85290579.
E-mail address: bqzhu@gig.ac.cn (Z. Bing-Quan).

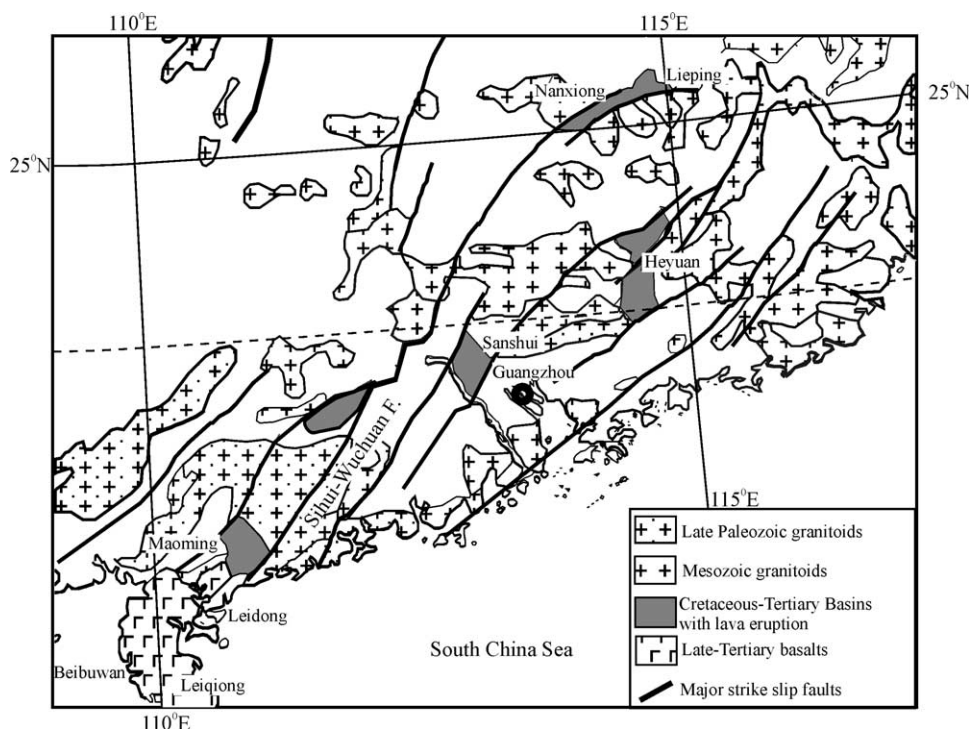


Fig. 2. A sketch geologic map showing the distribution of Phanerozoic magmatic rocks and Cretaceous–Tertiary basins in the Guangdong area.

on the published and present data, the lava eruption ages in the Sanshui basin are in the range of 38–64 Ma, during which time andesite-rhyolite eruptions were in an early stage (64–56 Ma), and basalt-trachyte eruptions were in a later stage (38–56 Ma). The published and new Nd isotopic data from the Sanshui basin (Table 1) (Zhu and Wang, 1989a; Chung et al., 1997a,b) indicate that $\epsilon_{\text{Nd}}(t)$ values increase gradually from +3.2 at 56 Ma to +6.4 at 38 Ma in spite of lithologic variation. Thus, the magmatic source was mainly in the upper mantle, and mantle components in the magma gradually increased as the eruption ages became younger. The andesite with an age of 56 Ma (88–4) shows a slight negative $\epsilon_{\text{Nd}}(t)$ value (−0.5), indicating that the magmatic source in the Sanshui basin changed at that time. The eruption period of volcanic rocks composed of andesite/rhyolite in the Maoming basin is 56–92 Ma (Table 2), which is concordant with that of granitic magmatism in the Late Yenshanian period in this area (57.9–92.3 Ma) (Yu and Chen, 1990). The composition of this suite of volcanic rocks shows adakitic features (Wang et al., 2001a,b) (SiO_2 :59–73%, Al_2O_3 :16–17%, $\text{MgO} < 2.2\%$, $\text{Na}_2\text{O}/\text{K}_2\text{O} \geq 1$) (Table 3), indicating a source in a subducted slab or lower crust. Nd isotopic compositions (Table 1) are in a range of 0.5120–0.5122, and yield negative $\epsilon_{\text{Nd}}(t)$ values (−6.7 to −11.5). However, $\epsilon_{\text{Nd}}(t)$ for the sample with an age of 56 Ma (88–44) suddenly increases to a slightly positive value (0.5). A Late Cretaceous granite on the border of Sanshui basin yields $\epsilon_{\text{Nd}}(t)$ of −9.7 (Chen and Jahn, 1998), which is comparable to that of the Maoming lava. Nd isotopic features indicate that a preferable source for the volcanic rocks in the Maoming basin is in the lower

crust. Chung et al. (1997a,b) have reported some negative $\epsilon_{\text{Nd}}(t)$ values for andesites from the Lieping and Heyuan basins (0 to −4.8). The age of these andesites inferred from dating of the Sanshui lava and stratigraphic comparison (Zhu and Wang, 1989a; Chung et al., 1997a,b) is about 56 ± 2 Ma. The lava sources in these basins show a transition between Sanshui and Maoming. An age- t vs. $\epsilon_{\text{Nd}}(t)$ plot is given in Fig. 3. The $\epsilon_{\text{Nd}}(t)$ variation curve with time (t) in Fig. 3 shows that the sources of volcanism changed abruptly at 56 ± 2 Ma. This turning point age of volcanic sources signaled the beginning of lithospheric extension and mantle upwelling on a large scale. The Sr isotopic compositions also show regular variation in these basins (Table 1). Basalts and andesites in these basins usually have $^{87}\text{Rb}/^{86}\text{Sr}$ ratios lower than 0.4, which yields age revisions for initial $^{87}\text{Sr}/^{86}\text{Sr}$ that are lower than 0.0004. Since $^{87}\text{Rb}/^{86}\text{Sr}$ ratios for trachytes are extremely high (10–400), they cannot yield correct initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Zhu, 1998). Thus, only Sr isotopes from basalts and andesites can be used for tracing source regions. The basalts from the Sanshui basin have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios ranging from 0.7038 to 0.7064. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for andesites in the Maoming basin vary from 0.7106 to 0.7136. Andesites and basalts from the Heyuan and Lieping basins also show a transition in Sr isotopic compositions (0.7047–0.7114). A correlation diagram of Nd–Sr isotopes shows variation in the source regions of volcanism from the Maoming basin (data lying in the area of S type granites with crustal genesis) to the Sanshui basin (data close to the mantle source region in Cathaysia) (Zhu, 1998)(Fig. 4). The Pb isotopic compositions in the Sanshui basin show that $^{207}\text{Pb}/^{204}\text{Pb} = 15.44$ –15.54 for samples

Table 1

Data of Nd–Sr isotopes and ages for volcanic rocks from the Cretaceous-Tertiary basins in Guangdong area

Sample No	Rock type	Age (Ma)	$^{143}\text{Nd}/^{144}\text{Nd}$	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$\epsilon_{\text{Nd}}(\text{t})$	$^{87}\text{Sr}/^{86}\text{Sr}$
<i>Sanshui basin</i>								
88–13	Basalt	$37.98 \pm 0.66^{\text{P}}$	$0.512952 \pm 7^{\text{P}}$	4.72	19.20	0.1487	6.40	$0.703782 \pm 12^{\text{P}}$
84KS-36	Basalt	$43.1 \pm 1.3^{\text{a}}$	$0.512916 \pm 15^{\text{a}}$	7.04	35.76	0.1190	5.89	$0.705182 \pm 15^{\text{a}}$
81K-40	Basalt	$47.57 \pm 0.73^{\text{a}}$	$0.512920 \pm 12^{\text{a}}$	6.33	28.41	0.1347	5.92	$0.703897 \pm 12^{\text{a}}$
81K-9	Trachyte	$47.71 \pm 0.80^{\text{a}}$	$0.512899 \pm 5^{\text{b}}$	12.01	55.45	0.1310	5.53	$0.715865 \pm 13^{\text{a}}$
81K-49	Trachyte	$48.84 \pm 0.31^{\text{a}}$	$0.512896 \pm 5^{\text{a}}$	20.90	121.8	0.1037	5.65	$0.793800 \pm 80^{\text{a}}$
84KS-15	Basalt	$49.6 \pm 1.1^{\text{a}}$	$0.512882 \pm 12^{\text{a}}$	5.16	22.38	0.1394	5.16	$0.705716 \pm 12^{\text{a}}$
81K-50	Trachyte	$50.92 \pm 0.84^{\text{a}}$	$0.512864 \pm 5^{\text{b}}$	14.2	66.2	0.1297	4.88	$0.729400 \pm 12^{\text{b}}$
81K-51	Trachyte	$51.38 \pm 0.93^{\text{a}}$	$0.512857 \pm 5^{\text{b}}$	13.5	61.3	0.1331	4.73	$0.727400 \pm 9^{\text{a}}$
84KS-10	Basalt	$54.3 \pm 1.4^{\text{a}}$	$0.512849 \pm 10^{\text{a}}$	7.33	31.03	0.1428	4.53	$0.704738 \pm 23^{\text{a}}$
84KS-28	Trachyte	$54.73 \pm 0.42^{\text{a}}$	$0.512836 \pm 10^{\text{a}}$	22.29	121.0	0.1114	4.50	$0.76764 \pm 20^{\text{a}}$
84KS-14	Basalt	$56.3 \pm 1.5^{\text{a}}$	$0.512844 \pm 6^{\text{a}}$	5.40	21.32	0.1531	4.37	$0.705085 \pm 9^{\text{a}}$
81K-41	Basalt	$56.6 \pm 1.1^{\text{a}}$	$0.512862 \pm 9^{\text{a}}$	5.78	24.35	0.1435	4.79	$0.704752 \pm 17^{\text{a}}$
84KS-25	Basalt	$57.5 \pm 2.2^{\text{a}}$	$0.512855 \pm 5^{\text{a}}$	5.63	22.08	0.1542	4.58	$0.704608 \pm 22^{\text{a}}$
84KS-2	Basalt	$58.4 \pm 2.6^{\text{a}}$	$0.512774 \pm 8^{\text{a}}$	3.70	16.52	0.1354	3.15	$0.706366 \pm 36^{\text{a}}$
88-4	Dacite	$55.80 \pm 0.89^{\text{P}}$	$0.512582 \pm 10^{\text{P}}$	4.541	22.32	0.1227	−0.53	$0.704932 \pm 15^{\text{P}}$
<i>Maoming basin</i>								
88–44	Andesite	$56.06 \pm 0.90^{\text{P}}$	$0.512622 \pm 10^{\text{P}}$	7.91	53.23	0.08779	0.51	$0.711976 \pm 7^{\text{P}}$
88–20	Andesite	$56.11 \pm 0.90^{\text{P}}$	$0.512110 \pm 8^{\text{P}}$	7.63	52.23	0.08616	−9.47	$0.713601 \pm 16^{\text{P}}$
88–19	Basalt	$62.2 \pm 1.0^{\text{P}}$	$0.512005 \pm 13^{\text{P}}$	6.26	39.58	0.09561	−11.5	$0.711784 \pm 5^{\text{P}}$
88–28	Andesite	$66.5 \pm 1.0^{\text{P}}$	$0.512214 \pm 5^{\text{P}}$	9.22	54.91	0.09058	−7.33	$0.710622 \pm 18^{\text{P}}$
88–22	Andesite	$68.82 \pm 1.1^{\text{P}}$	$0.512066 \pm 13^{\text{P}}$	9.05	59.89	0.09880	−10.3	$0.712593 \pm 11^{\text{P}}$
88–25	Andesite	$74.0 \pm 1.1^{\text{P}}$	$0.512174 \pm 5^{\text{P}}$	8.13	50.10	0.08264	−7.94	$0.710646 \pm 19^{\text{P}}$
88–32	Andesite	$81.0 \pm 1.3^{\text{P}}$	$0.512236 \pm 10^{\text{P}}$	5.89	41.66	0.06879	−6.48	$0.712950 \pm 10^{\text{P}}$
<i>Lieping basin</i>								
GLP-1	Andesite	$\approx 56 \pm 2$	$0.512375 \pm 24^{\text{b}}$	5.7	30.2	0.1141	−4.50	$0.708114 \pm 39^{\text{b}}$
GLP-3	Andesite	$\approx 56 \pm 2$	$0.512480 \pm 9^{\text{b}}$	5.7	31.5	0.1094	−2.42	$0.707499 \pm 15^{\text{b}}$
GLS-1	Andesite	$\approx 56 \pm 2$	$0.512357 \pm 18^{\text{b}}$	4.0	23.5	0.1029	−4.77	$0.711410 \pm 30^{\text{b}}$
<i>Heyuan basin</i>								
GHY-1	Basalt	$\approx 56 \pm 2$	$0.512679 \pm 24^{\text{b}}$	4.0	15.3	0.1581	1.12	$0.704761 \pm 22^{\text{b}}$
GHY-6	Andesite	$\approx 56 \pm 2$	$0.512638 \pm 5^{\text{b}}$	3.7	13.7	0.1633	0.28	$0.705150 \pm 22^{\text{b}}$
<i>Leiqiong basin</i>								
81-H-15	Tholeiite	$16.77 \pm .47^{\text{c}}$	$0.512957 \pm 22^{\text{c}}$	4.12	13.29	0.1874	6.2	$0.703780 \pm 18^{\text{c}}$
81-H-13	Tholeiite	$11.68 \pm .75^{\text{c}}$	$0.513039 \pm 9^{\text{c}}$	4.37	13.63	0.1936	7.9	$0.703471 \pm 33^{\text{c}}$
81-K-11	Tholeiite	$6.12 \pm .25^{\text{c}}$	$0.512943 \pm 5^{\text{c}}$	5.53	17.71	0.1887	6.1	$0.703418 \pm 9^{\text{c}}$
81-K-38	Alkaline basalt	$5.62 \pm .76^{\text{c}}$	$0.512914 \pm 7^{\text{c}}$	5.91	26.48	0.1349	5.6	$0.706635 \pm 17^{\text{c}}$
81-H-1	Alkaline basalt	$4.05 \pm .33^{\text{c}}$	$0.512892 \pm 5^{\text{c}}$	9.59	44.69	0.1297	5.1	$0.703722 \pm 11^{\text{c}}$

The isotopic ratio and dilution measurements of concentrations for Nd, Sr and Pb were done with VG-354 mass spectrometer. Chemical procedures are described by Zhu et al. (2001). The $^{143}\text{Nd}/^{144}\text{Nd}$ ratios are double normalized to $^{145}\text{Nd}/^{144}\text{Nd} = 0.348440$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.721906$ and La Jolla Standard yield a mean value of 0.511861 ± 10 during sample analyses. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.11940$ and the measured mean value of $^{87}\text{Sr}/^{86}\text{Sr}$ for the standard SRM-987 is 0.710263 ± 10 . P, Data published in this paper.

^a Data from Zhu et al.(1989).

^b Data from Chung et al.(1997a,b).

^c Data from Zhu and Wang (1989b).

with ages younger than 56 Ma, and $^{207}\text{Pb}/^{204}\text{Pb} = 15.57–15.59$ for samples with ages older than 56 Ma (Table 4). The former corresponds to the $^{207}\text{Pb}/^{204}\text{Pb}$ range of the Cathaysian mantle and the latter to the $^{207}\text{Pb}/^{204}\text{Pb}$ range of the Cathaysian orogenic belt or lower crust of Gondwana type (Zhu, 1998). Although, adakitic volcanism can thin lithospheric thickness, we prefer that the abrupt extension event indicated in magma source change originated from a variation of the tectonic framework.

Changes in eruption style from andesitic to basaltic lava at 56 ± 2 Ma were also identified in other basins in East

China, such as the Bohai-huanghua Basin (56.3 Ma), the Yellow Sea-Subei basin (55.9 Ma) (Wang et al., 1989) and the western basin of Taiwan (53.5 ± 2.7 Ma) (Lan et al., 1996) (Fig. 1).

3. Geochronological constraints on the border sea evolution of East Asia

$^{40}\text{Ar}/^{39}\text{Ar}$ and K–Ar age data for basalts from areas near the Philippine Trench and the Oki-Daito ridge (a remnant arc)

Table 2
Data of K–Ar ages for volcanic rocks from Maoming and Sanshui basins

Sample No	Location	Rock type	K%	Radiogenic ^{40}Ar (10^{-10} mole/gSTP)	Radiogenic $^{40}\text{Ar}\%$	Age (Ma)
<i>Maoming basin</i>						
88–19	Shitanchang, Huazhou	Grey andesite	$2.50 \pm .03$	2.743	68.58	62.2 ± 1.0
88–20	Shitanchang, Huazhou	Grey andesite	$4.14 \pm .06$	4.092	93.01	$56.11 \pm .90$
88–44	Xiangshan, Huazhou	Grey andesite	$4.36 \pm .06$	4.306	91.86	$56.06 \pm .90$
88–22	Nansheng, Huazhou	Reddish andsite	$4.64 \pm .06$	5.645	94.77	68.8 ± 1.1
88–23	Nansheng, Huazhou	Grey andesite	$4.52 \pm .06$	7.417	96.80	92.2 ± 1.4
88–24	Nansheng, Huazhou	Grey andesite	$5.02 \pm .07$	7.284	96.64	81.8 ± 1.3
88–32–1	Shigu, Huazhou	Grey andesite	$4.73 \pm .07$	6.799	95.62	81.0 ± 1.3
88–38	Jiurangqiao, Huazhou	Grey andesite	$4.10 \pm .06$	5.658	92.67	77.9 ± 1.2
88–28	Shidong, Maoming	Basaltic-andesite	$3.24 \pm .05$	3.806	91.35	66.5 ± 1.0
88–25	Fuziling, Maoming	Basaltic-andesite	$3.43 \pm .05$	4.496	93.03	74.0 ± 1.1
88–27	Fuziling, Maoming	Basaltic-andesite	$3.08 \pm .05$	3.108	88.73	$57.18 \pm .85$
<i>Sanshui basin</i>						
88–13	Dafu, Fushan	Massive basalt	$1.31 \pm .02$	0.8721	74.21	$37.98 \pm .66$
88–4	Northern side of the San-Fu high way	decite	$3.97 \pm .06$	3.902	70.11	$55.80 \pm .89$

Isotopic dilution measurements of argon were done with VG Micromass 1200 mass spectrometer. The BB-6 K–Ar internal standard of yang volcanic rocks (0.441 ± 0.013 Ma) (Jäger et al., 1985) is used for checking sample analyses, which the age results are in a range of 0.435–0.458 Ma.

indicate that the earliest opening along the Central basin ridge in the West Philippine Sea is at 54–57 Ma (Ozima et al., 1980; Hilde and Lee, 1984; Hickey-Vargas, 1998). The initiation of West Philippine Sea opening is consistent with that of extension of the Cathaysian lithosphere on a large scale. Although isotopic ages for the basalts related to the opening of the proto-South China Sea have not been obtained, the close relationship between extension of the Cathaysian lithosphere and South China Sea imply that the earliest opening time was at about 56 Ma. Based on an opening model involving two stages as proposed by Ru and Piggot (1986), the first stage of extension along a NE striking ridge in the southwestern basin of South China Sea was at about 55 Ma. Lee and Lawver (1994) estimated that the NW–SE opening of the South China Sea and Celebes

Sea occurred during 45–65 Ma according to a tectonic evolution model of the major blocks surrounding the South China Sea. Drilling has shown that the Celebes basin was generated about 43 Ma ago (Shyu et al., 1991). Based on geophysical evidence, Yumul (1995) proposed that the Zambales ophiolite melange of Paleocene-Eocene age (~ 56.5 Ma) in the Philippines represents a subducted margin basin related to extension in the southwestern basin of the South China Sea. As the Philippine Sea Plate was positioned south of the equator before 50 Ma and has undergone anti-clockwise rotation of about 90° , the Central basin ridge with NW strike at present in the West Philippine Sea was also restored in a NE direction (Hall et al., 1995). There has been no significant change in the configuration of East Asia, South China Sea and Celebes Sea since 50 Ma

Table 3
Major element data of Andesite-Rhyolite in Maoming basin and in comparison with andesites in Sanshui basin

No:	Andesite-Rhyolite in Maoming basin								Andesite in Sanshui basin				
	88–19	88–20	88–22	88–25	88–28	88–32	88–33	88–44	K-49	K-50	K-51	KS-9	KS-28
SiO ₂	62.58	76.04	73.96	64.03	59.96	75.16	73.27	71.69	65.45	65.37	63.56	61.52	68.31
TiO ₂	0.60	0.06	0.05	0.52	1.02	0.30	0.31	0.16	0.14	0.14	0.12	0.64	0.78
Al ₂ O ₃	16.53	13.52	13.74	17.17	17.60	13.74	12.45	15.24	14.38	14.43	16.15	14.54	14.20
Fe ₂ O ₃	3.37	0.70	0.65	2.50	3.40	0.90	1.25	0.87	2.47	2.50	3.23	1.07	1.29
FeO	2.33	0.20	0.35	1.20	2.20	0.30	0.65	0.95	3.61	3.58	2.34	4.97	2.66
MnO	0.10	0.01	0.04	0.06	0.16	0.03	0.01	0.04	0.11	0.12	0.12	0.23	0.11
MgO	2.20	0.20	0.30	1.70	1.40	0.001	0.001	0.30	0.34	0.32	0.55	0.36	0.20
CaO	4.40	0.80	1.60	4.50	3.80	1.10	1.20	1.30	0.95	1.02	0.73	3.17	2.26
Na ₂ O	3.27	3.14	3.01	3.21	3.73	2.10	1.82	2.62	5.96	6.15	6.10	5.71	5.16
K ₂ O	2.57	4.24	4.69	3.07	3.60	5.92	5.26	4.92	5.05	5.15	5.37	4.96	4.02
H ₂ O + CO ₂	1.80	0.92	1.54	1.80	2.75	0.36	3.53	1.80	0.72	0.69	0.72	2.46	1.06
P ₂ O ₅	0.17	0.12	0.001	0.17	0.23	0.001	0.002	0.001	0.06	0.05	0.07	0.30	0.01
Total	99.92	99.95	99.93	99.93	99.85	99.91	99.75	99.89	99.24	99.52	99.06	99.93	100.06

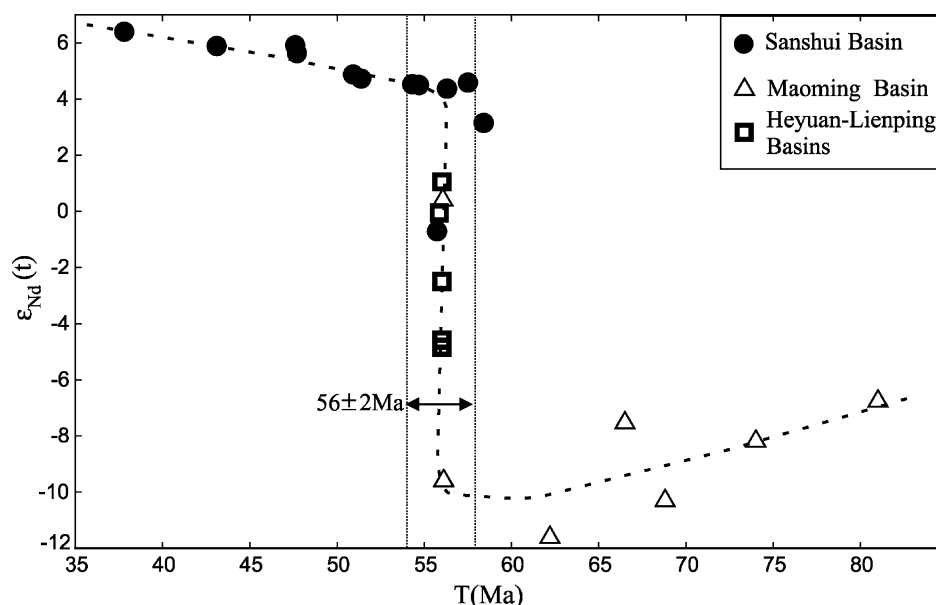


Fig. 3. An age- t vs. $\epsilon_{\text{Nd}}(t)$ plot for volcanic rocks from the Maoming, Heyuan, Lienping and Sanshui basins in Guangdong. Data from Zhu and Wang (1989a); Chung et al. (1997a,b) and Table 2. 56 ± 2 Ma mark a great transition period for magma sources.

(Hall et al., 1995; Lee and Lawver, 1994). Therefore, there existed a series of NW–SE extensional basins during the Early Eocene, which included the proto-South China Sea, Celebes Sea, Daito Sea and West Philippine Sea from north to south (Fig. 5). The NE striking extensional ridges in these basins is consistent with the shearing strike of tectonic lines and pull-apart basins in the Cathaysian block. Therefore, we propose that the Early Eocene opening of the border sea basins in East Asia is closely associated with lithosphere extension along the NE striking tectonic lines.

Based on the interpretation of magnetic lineations, many authors have shown that the Late Tertiary opening of the South China Sea along the ridges with E–W strike was

during 32–17 Ma (Tapponnier et al., 1986; Briais et al., 1993). However, geochronological evidence indicates that there was an interruption in volcanism between 37–17 Ma in Cathaysia (Fig. 6) and occurred significant extensional activities in East China and the border sea areas since 17 Ma.

3.1. Age distribution of Cenozoic basalts in the Cathaysian block

The large scale basaltic lava eruptions during the Late Tertiary in the Cathaysian block mostly occurred after 17 ± 1 Ma, such as Leiqiong in Guangdong,

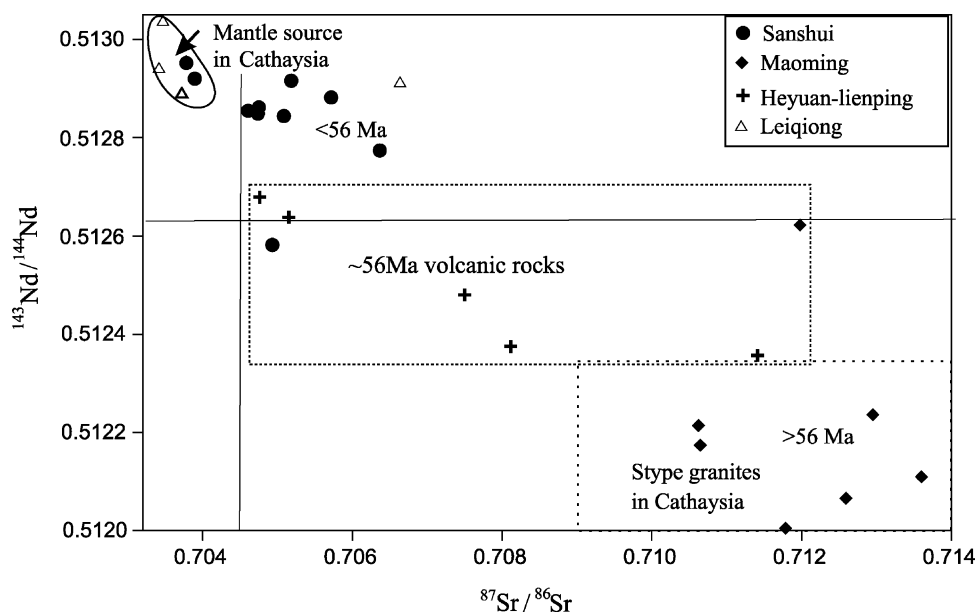


Fig. 4. A Nd–Sr correlation diagram for volcanic rocks from the Maoming Heyuan, Lienping and Sanshui basins in Guangdong.

Table 4
Pb–Sr isotopic ratios of basalts from the South China Sea

No:	Location	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{87}\text{Sr}/^{86}\text{Sr}$	
S-17	Basalt from north part of South China Sea	18.406	15.587	38.507	0.70497 ± 2	p
S-18	Basalt from north part of South China Sea	18.223	15.583	38.237	0.70381 ± 1	p
	Basalt from north part of South China Sea	18.600–18.704	15.609–15.632	37.61–38.85	0.70318–0.70319	Tu et al., 1992
S-9-2	Tholeiite from middle part of South China Sea	17.759	15.557	37.542	0.70421 ± 1	P
S-10-2	Alkaline basalt from middle part of South China Sea	18.585	15.616	38.744	0.70457 ± 2	P
	Basalts from middle part of South China Sea	18.667–19.029	15.535–15.600	38.68–39.10	0.70380–0.70391	Tu et al., 1992
E-1	Basaltic glass in south part of South China Sea	18.507	15.601	38.518		P
	Basalts in south part of South China Sea	18.411–18.601	15.537–15.606	38.49–38.63	0.70343–0.70445	Tu et al., 1992
	Xisha basalt	18.660	15.535	38.605	0.70291 ± 1	P
	Basalts from Palawan	17.886	15.449	37.65	0.70375	Tu et al., 1992
	Basalts from Philippine Sea	17.75–19.45	15.42–15.61	37.45–39.03	0.7026–0.7044	Hickey-Vargas, 1998
	Sediments from South China Sea	18.249–19.163	15.524–15.691	37.889–38.845		Chen and Gui, 1998
	Mean values of Granites in Cathaysia	18.546 ± 0.012	15.679 ± 0.006	38.679 ± 0.026		Zhu, 1998

The precision (2σ) for Pb isotope determination is lower than 0.015‰/AMU. The mean measured value in recent years for the standard SRM-981 is $^{206}\text{Pb}/^{204}\text{Pb} = 16.934 \pm 0.007$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.486 \pm 0.012$, and $^{208}\text{Pb}/^{204}\text{Pb} = 36.673 \pm 0.033$, respectively, which are in good agreement with the recalibrated values of double spike determination: 16.9322, 15.4855, and 36.6856, respectively (Todi et al., 1993). Chemical procedures are described by Zhu et al. (2001). P, This paper.

Xinchang-Shengxian in Zhejiang, Longhai in the eastern Fujian and Mingxi in the western Fujian (Figs. 1 and 6). The basalt eruptions that occurred in Vietnam, Taiwan, the Okinawa trough and the Izu-Bonin arc also have this age range (Zhu et al., 1988; Wang et al., 1989; Zhu and Wang, 1989; Lan et al., 1996; Zhu et al., 1997; Lee et al., 1998; Ishizuka et al., 2000). A few age data of about 25 Ma in the northern Fujian are for small volcanic necks composed of ultramafic rocks with glass. The extensional event in Taiwan from 32–37 Ma only involved mafic dike intrusions. Therefore, extension of the Cathaysian lithosphere only occurred since 17 Ma, and having almost ceased spreading between 37–17 Ma.

3.2. Transition age of slip direction of Indochina block

Geochronological data indicate that the movement of the Indochina block changed from left-lateral extrusion during 35–17 Ma to right-lateral slip after 17 Ma (Zhang and Schärer, 1999; Wang and Burchfiel, 1997; Wang et al., 2001a,b). Although many authors interpreted the opening of the South China Sea as a response to the left-lateral extrusion of the Indochina block, the SE striking motion of the Indochina block during 35–17 Ma should block seafloor spreading along the NE striking ridge during the Early Tertiary. Conversely, the right-lateral slip of the Indochina block since 17 Ma could be a result of

lithospheric extension along a NW–SE strike on a large scale in East Asia. Chung et al. (1997a,b) noted that left-lateral strike-slip displacement of the Ailaoshan-Red River shear zone was initiated after seafloor spreading in the South China Sea and concluded that the opening of the South China Sea was mainly a consequence of lithospheric extension in Cathaysia.

3.3. Subduction ages along the margin of the South China Sea

Subduction of the South China Sea basin towards a SE direction along the Luzon Arc occurred during 12–3 Ma, and originated from extension in Cathaysia, Taiwan Strait and the northern part of the South China Sea (Lan et al., 1996). The collision of the North Palawan block with Kalimantan occurred at about 17 Ma. Drilling in the Cagayan ridge indicates that the volcanic arc, formed by southward subduction of the South China Sea basin, was still active during 17.5–15 Ma (Spadea et al., 1996). The volcanic arc activity in the Sulu Archipelago recorded the southward subduction of the Sulu basin along the Sulu trench with ages ranging from Middle Miocene to Pliocene (14–1.5 Ma). The lava with REE features of MORB in the northern side of South China Sea, Leiqiong Basin, yields an age of 12–17 Ma (Table 1) (Zhu and Wang, 1989b), which is similar to the Palawan ophiolites in

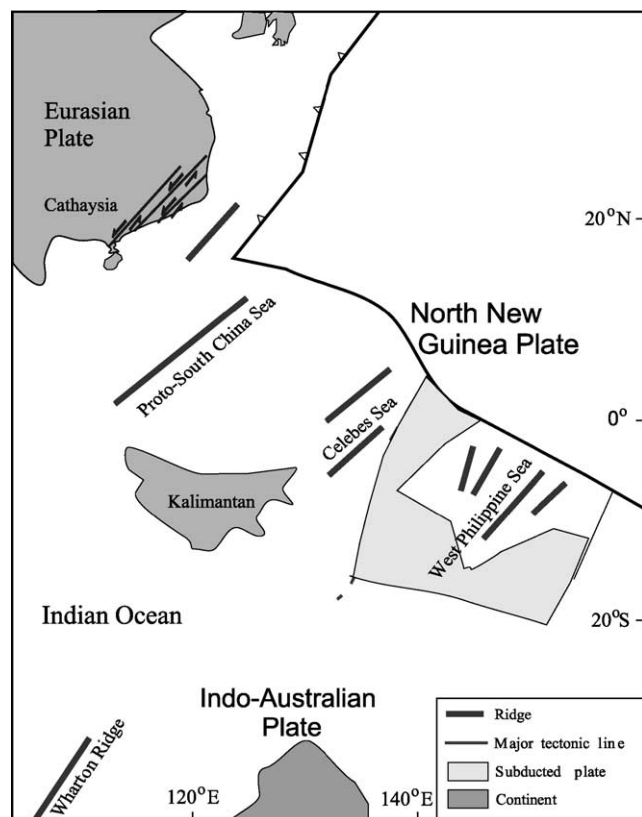


Fig. 5. A sketch map for restoration of the border sea basins and the extensional ridges with NE strike in East Asia and adjacent areas at 56 ± 2 Ma (after Hall et al., 1995; Hickey-Vargas, 1998; Lee and Lawver, 1994).

the south side of the South China Sea. Lead isotopic and paleomagnetic comparisons indicate that the North Palawan block was initially a part of Cathaysia. The extrusion of Indochina towards the SE direction had ceased during this stage, thus was not a force that caused subduction in the Luzon Arc, Palawan Trench and Sulu Trench.

The continental collision in the Tibet Plateau induced extrusion of the Indochina block towards the SE since 55 Ma. The extrusion displacements of the Indochina block along the Red River fault probably stopped the SE–NW extension in East Asia, thus there was no basaltic lava

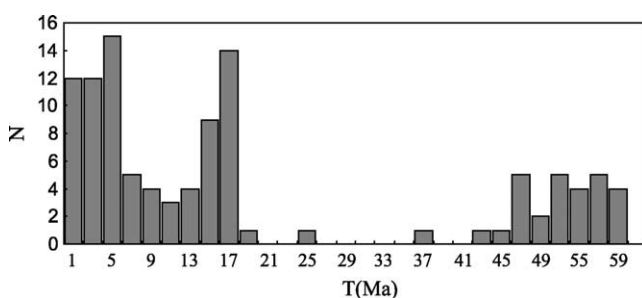


Fig. 6. A histogram of the age distribution of Cenozoic basaltic lavas in the Cathaysian block, including Leiqiong in Guangdong, Xinchang-Shengxian in Zhejiang, Longhai in the eastern Fujian and Mingxi in the western Fujian. Data from Zhu et al. (1988, 1997); Zhu and Wang (1989a,b); Wang et al. (1989); Zhu (1998) and Table 1.

eruption between 35–17 Ma. However, seafloor spreading of the East Philippine Sea plate in the Parece Vela basin and the Shikoku basin was during 30–17 Ma (Mrozowski and Hayes, 1979; Shih, 1980). The position of the Philippine Sea Plate during that time implies that the spreading ridge paralleling the Palau-Kyushu arc in these basins was SE striking, in agreement with extrusion of the Indochina block. In order to define temporal and spatial correlation between extrusion displacements of the Indochina block and extensions in East Asia, a detail geochronological and geochemical study of seafloor basalts in the South China Sea is warranted.

4. Isotopic features of basalts and geochemical boundaries in the border sea basins of East Asia

Comprehensive isotopic studies for oceanic basalts indicate that the DUPAL anomaly represents an isotopic signature of mantle beneath the Indian and Tethyan Oceans, which constitute a distinct geochemical province. Its geochemical boundaries have been well established in several districts (Klein et al., 1988; Pyle et al., 1992, 1995; Mahoney et al., 1998). Abundant Pb, Sr and Nd isotopic data for Cenozoic MORB and OIB and Mesozoic residual MORB from the Philippine Sea, South China Sea, Celebes Sea and Sulu Sea has been obtained (Mukasa et al., 1987; Hickey-Vargas, 1991, 1998; Tu et al., 1992; Pearce et al., 1992; McDermott et al., 1993; Hickey-Vargas et al., 1995; Spadea et al., 1996; Castillo and Punongbayan, 1996; Knittel et al., 1997; DeBari et al., 1999). Sr isotopic systematics are easily disturbed by seawater alteration because of the high strontium concentration and long residence time in sea water. Hence, Pb and Nd isotopes are reliable tracers for oceanic basalts. However, Pb isotopes are more sensitive for revealing lateral mantle heterogeneity than are Nd isotopes. Thus, $^{208}\text{Pb}/^{204}\text{Pb}$ – $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ – $^{206}\text{Pb}/^{204}\text{Pb}$ and ϵ_{Nd} – $^{206}\text{Pb}/^{204}\text{Pb}$ plots (Fig. 7) are employed to identify the mantle domain beneath the border seas. Isotopic evidence indicates that the geochemical features of the upper mantle beneath the Philippine Sea, South China Sea, Celebes Sea and Sulu Sea are clearly distinguished from that of the Pacific Plate, and consistent with that of the Indian Ocean (DUPAL anomaly) (Fig. 7). Samples from the forearc basement of the Izu-Bonin Arc (ODP Leg 125) and southeastern Pacific basin to the east of the Mariana Arc plot just below the North Hemisphere Reference Line (NHRL) proposed by Hart (1984) and lie in the area of Pacific MORB (Fig. 7a and b) (Meijer, 1976; Johnson, 1985; Woodhead and Fraser, 1985; Woodhead, 1989; Volpe et al., 1990; Stern et al., 1991; Pearce et al., 1992; Van Der Laan et al., 1992; Gribble et al., 1996, 1998; Janney and Castillo, 1997; Elliott et al., 1997; Taylor and Nesbitt, 1998; DeBari et al., 1999; Elburg and Foden, 1999). The lead isotopic compositions of basalts from both sides of the Izu–Bonin–Mariana Arc can be

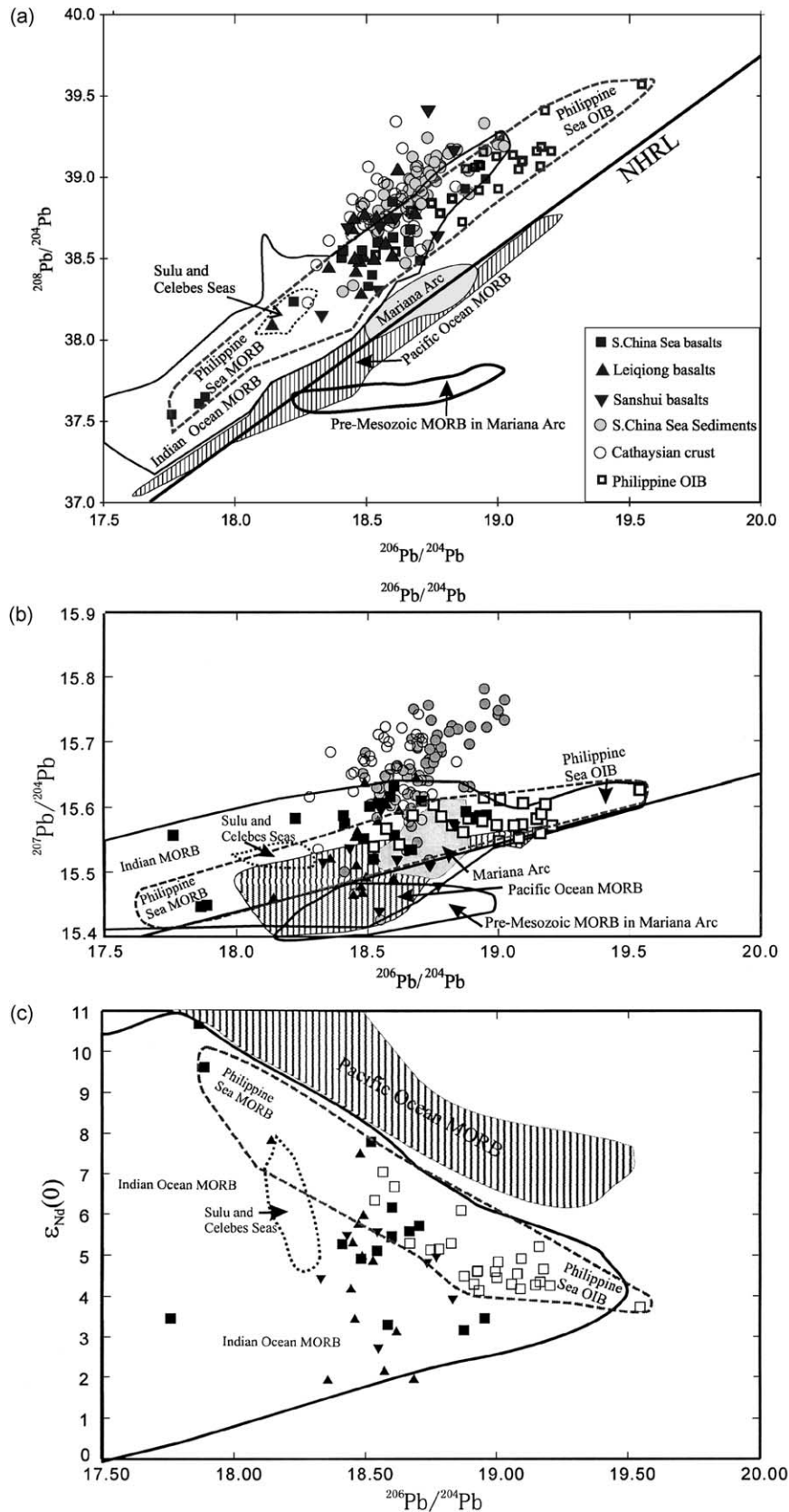


Fig. 7. $^{206}\text{Pb}/^{204}\text{Pb}$ – $^{208}\text{Pb}/^{204}\text{Pb}$ (7a), $^{206}\text{Pb}/^{204}\text{Pb}$ – $^{207}\text{Pb}/^{204}\text{Pb}$ (7b) and $\epsilon_{\text{Nd}}(0)$ – $^{206}\text{Pb}/^{204}\text{Pb}$ (7c) diagrams for Cenozoic basalts from the South China Sea, Leiqiong and Sanshui basins, as well as sediments from the South China Sea and granitic rocks from the Cathaysian block. Data from Tu et al. (1992); Zhu and Wang (1989a,b) and Table 4. The areas of lead isotopic variation for basalts from the Philippine Sea Plate, Mariana Arc, Indian Ocean and Pacific Ocean are according to Hickey-Vargas et al. (1995); Hickey-Vargas (1991,1998); DeBari et al. (1999).

apparently divided by NHRL. Hickey-Vargas et al. (1995) have pointed out that asthenosphere of Indian Ocean affinity extends into all East Asian marginal basins and upper mantle. Contamination by the surrounding subduction or Western Pacific mantle plumes did not produce the DUPAL signature observed in the Philippine Sea magmas. A contour line map of Pb isotope $\Delta 8/4$ values ($= [^{208}\text{Pb}/^{204}\text{Pb} - (15.627 + 1.209 \times ^{206}\text{Pb}/^{204}\text{Pb})] \times 100$, defined by Hart, 1984) for rocks and ores derived from mantle is given in Fig. 8. The border sea areas show a $\Delta 8/4$ range of 15–80, in agreement with that of the Indian Ocean. There is an isotopic steep zone with $\Delta 8/4$ values varying from 10–40 at the Izu–Bonin–Mariana Arc. Thus, we suggest that the Izu–Bonin–Mariana arcs can be regarded as a geochemical boundary ($\Delta 8/4 \approx 15$) between the Pacific ($\Delta 8/4 < 15$) and Philippine Sea ($\Delta 8/4 = 15–65$) Plates since Mesozoic time.

The lead isotopic discordance with $\Delta 8/4$ values varying from 15–90 also occurs between the outer- and inter-zones of the Japan Arc (Sasaki and Sato, 1982; Zhu, 1994; Zhu et al., 1996), which delineate a geochemical boundary ($\Delta 8/4 \approx 80$) between the Eurasian and Philippine Sea Plates (Figs. 1 and 8). Paleontological and paleomagnetic evidence indicates that the outer-zone of the Japan Arc is a part of Gondwana. This geochemical boundary could connect with that occurring between the Cathaysian and Yangtze blocks established by the authors (Zhu et al., 1996) (Fig. 1 and 8). There is a sea mountain chain on the northern margin of the East Sea basin near 32°N, which seems to link the Cathaysian–Yangtze boundary with the outer- and inter-zone boundary (Fig. 8). There is a triple junction between the outer- and inter-zone boundary and the Izu–Bonin–Mariana Arc boundary at the bend in the Japan Arc. These

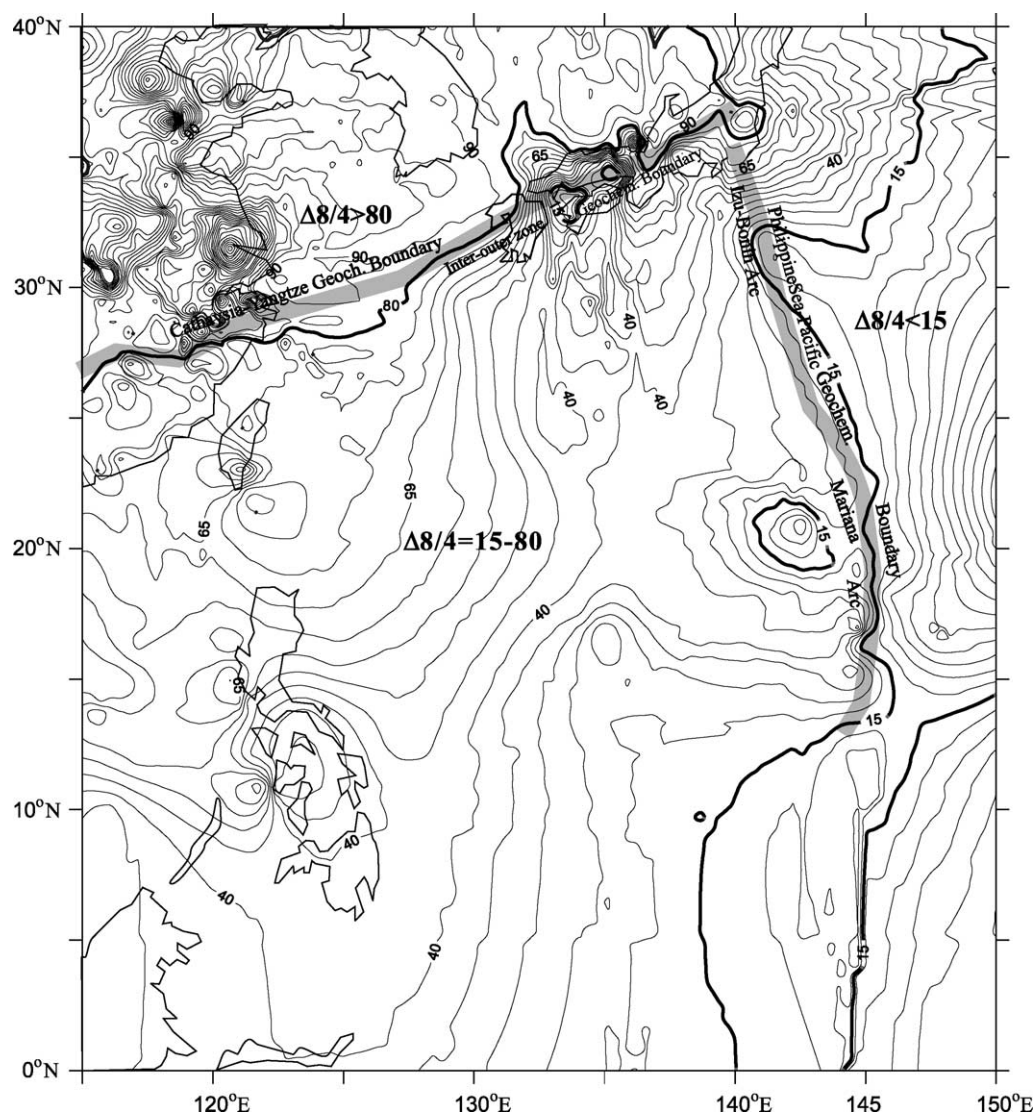


Fig. 8. A contour line map of Pb isotope $\Delta 8/4$ values (defined by Hart, 1984) for mantle derived rocks and ores in the border sea area, East Asia. Data from Meijer, 1976; Sasaki and Sato, 1982; Johnson, 1985; Woodhead and Fraser, 1985; Mukasa, 1987; Woodhead, 1989; Zhu and Wang, 1989a,b; Volpe et al., 1990; Stern et al., 1991; Hickey-Vargas, 1991, 1998; Tu et al., 1992; Pearce et al., 1992; Van Der Laan et al., 1992; McDermott et al., 1993; Hickey-Vargas et al., 1995; Spadea et al., 1996; Castillo and Punongbayan, 1996; Gribble et al., 1996, 1998; Knittel et al., 1997; Janney and Castillo, 1997; Castillo, 1997; Zhu et al., 1997; Zhu, 1998; Taylor and Nesbitt, 1998; DeBari et al., 1999; and this paper.

geochemical boundaries represent the northeastern margin of the Philippine Sea plate or Gondwana-derived continental blocks. The Pb isotopic data for basalts from the South China Sea published by Tu et al. (1992) and authors in this paper (Table 4) yield variable ranges of $^{206}\text{Pb}/^{204}\text{Pb}$ –17.56–19.03, $^{207}\text{Pb}/^{204}\text{Pb}$ –15.46–15.63 and $^{208}\text{Pb}/^{204}\text{Pb}$ –37.54–39.10 (18/4–33–65), which are consistent with those of the Philippine Sea Plate (Figs. 7 and 8). The ranges of lead isotopic compositions for sediments from seafloor of the South China Sea (Chen and Gui, 1998) and granitic rocks from the Cathaysian block (Table 4) (Zhu, 1998) overlap those of sediments from the Pacific Ocean and Indian Ocean (Ben Othman et al., 1989). They have evidently higher $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ ratios and a smaller $^{206}\text{Pb}/^{204}\text{Pb}$ range than those of MORB and OIB from the border seas in East Asia (Fig. 7). Therefore, local upper crustal components represented by sediments and granitic rocks could not constitute a recycling end member originating from subduction for the upper mantle beneath the border seas in East Asia. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for the basalts from the border seas lie within the range 0.7026–0.7049 (Table 4), which is also comparable with that of the Indian Ocean (0.7026–0.7035) and evidently, differ from that of the Pacific Ocean (<0.7026) (Klein et al., 1988). The isotopic variations of basalts from the border seas in East Asia contain inherent features of the mantle beneath the Indian-Tethyan Ocean. The Asian Continent was developed from accretion of Gondwana-derived continental blocks (Metcalfe, 1996), which was also associated with northward migration of the Indian Ocean-type asthenospheric mantle (Davies and Richards, 1992; Hickey-Vargas, 1991, 1998; Chung et al., 1995; Flower et al., 1998). Based on seismic S-wave tomography, Cai et al. (2002) revealed a gigantic low-velocity anomaly zone and defined a mega-rift system between East Asia and the Western Pacific. Thus, we regard that the mantle evolution in East Asia was related to Indian Ocean extension and Gondwana dispersion.

5. Discussion and conclusion

Collision between the Eurasian and Indian Plates and extension of the Indian Ocean Plate are mutually influenced and complemented one other. Although many authors have considered, from a global tectonic framework, that the Cathaysian lithosphere extension and border sea opening are related to collision of the Eurasian-Indian Plates, their causality and time-spatial relationship is debated. Geochronological and geochemical constraints indicate that the lithospheric extension of the border sea basins in East Asia and Cathaysian block has occurred on a large scale since 56 Ma. The collision between the Eurasian and Indian Plates also began at 56.5 Ma. Indian Ocean spreading and Gondwana dispersion were inhibited in the northwest due to continental collision along the Yalu Zangpo suture zone. Since resistance in the east of

Indian Ocean was relatively low, a set of NE striking pull-apart basins in Cathaysia, as well as the proto-South China Sea, Celebes Sea and West Philippine Sea formed in the areas of East Asia and the eastern Indian Ocean during this period. Based on age and Paleomagnetic data, these rifting and sea basins aligned from north to south for a distance of 3000–4000 km as shown in Fig. 5. Continental collision in the Tibet Plateau caused extrusion of Indochina block towards the SE. This extrusion displacement probably stopped the SE–NW extension in East Asia during 35–17 Ma. Therefore, there was no basaltic lava eruption. Since 17 Ma, strong shear extension of lithosphere along a NE strike appeared in Cathaysia, Okinawa and Japan Sea, which synchronized with the change of the strike slip direction of the Indochina block from left- to right-lateral.

Since geochemical features of the mantle beneath the border seas indicate strong isotopic signatures of the DUPAL anomaly, we conclude that the mantle of intermediate depths beneath the border seas in East Asia resemble that which underlies the Neo Tethyan or Indian Ocean domain.

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