Major and trace element, and Sr–Nd isotope constraints on the origin of Paleogene volcanism in South China prior to the South China Sea opening

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Received 6 November 1996; revised 22 May 1997; accepted 22 May 1997

Abstract

Paleogene volcanic rocks crop out in three sedimentary basins, namely, Sanshui, Heyuan and Lienping, in the attenuated continental margin of south China. Lavas from the Sanshui basin which erupted during 64–43 Ma are bimodal, consisting of intraplate tholeiitic basalt and trachyte/rhyolite associations. Similar to Cretaceous A-type granites from the nearby region, the felsic member shows peralkaline nature [$\text{Na}_2\text{O} + \text{K}_2\text{O} \approx 10\text{--}12\%$; $(\text{Na} + \text{K})/\text{Al} \approx 0.98\text{--}1.08$], general enrichment in the incompatible trace elements and significant depletion in Ba, Sr, Eu, P and Ti. Although both types of the Sanshui lavas have rather uniform Nd isotope compositions [$\varepsilon_{\text{Nd}}(T) \approx +6$ to $+4$] that are comparable to Late Cenozoic basalts around the South China Sea, the felsic rocks possess apparently higher initial Sr isotope ratios (I_{Sr} up to ~ 0.713) and form a horizontal array to the right in the Nd vs. Sr isotope plot. Closed system differentiation of mantle-derived magmas in a 'double diffusive' magma chamber is considered for the bimodal volcanism, in which the trachytes and rhyolites represent A-type melts after extensive crystal fractionation in the upper portion of the chamber. Such A-type melts were later contaminated by small amounts (1–3%) of upper crustal materials during ascent. On the other hand, composition of lavas in the other two basins varies from tholeiitic basalt to andesite. Their Sr and Nd isotope ratios [$I_{\text{Sr}} \approx 0.705$ to 0.711 ; $\varepsilon_{\text{Nd}}(T) \approx +1$ to -5] and generally correlative Nb–Ta depletions suggest a distinct magma chamber process involving fractional crystallization concomitant with assimilation of the country rock. We conclude that these Paleogene volcanic activities resulted from the

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lithospheric extension in south China that migrated southwards and eventually led to opening of the South China Sea during ~30–16 Ma. © 1997 Elsevier Science B.V.

Keywords: Paleogene volcanism; Bimodal; South China; Opening of South China Sea

1. Introduction

Much attention has been focused on magmatism in continental extension zones (e.g., Leeman and Fitton, 1989; Wilson and Downes, 1991; Metcalf and Smith, 1995; O'Reilly and Zhang, 1995). During continental extension, different types of intraplate magmas may be generated at various P – T conditions from the convectively upwelling asthenosphere and/or thermally activated lithospheric mantle. Integrated information of magmas thus produced can provide constraints regarding not only the tectonic history of tensional areas but also the chemical characteristics of mantle sources. In the eastern Asian continental margin, extending over 5000 km from Siberia through east China to Indochina, the westward subduction of the Pacific plate and the northward indentation of India are two major tectonic processes commonly considered for the development of Cenozoic extensional basins and associated volcanic eruptions (Zhou and Armstrong, 1982; Tapponnier et al., 1986; Fan and Hooper, 1991). These eastern Asian magmas are composed almost entirely of basaltic rocks (Whitford-Stark, 1987; Fan and Hooper, 1991), distinct from other Cenozoic continental extension provinces, such as the Basin and Range of North America (Draper, 1991) and eastern Australia (Johnson et al., 1989), which often display intensive magmatism of bimodal composition.

In this paper, we report major and trace element and Sr–Nd isotope compositions for Paleogene volcanic rocks from the Sanshui, Heyuan and Lienping basins, three extensional basins in the South China coastal region (Fig. 1A). These volcanics are of

particular interest because (1) they constitute the only on-land magma suite that erupted prior to opening of the South China Sea in the attenuated continental margin, (2) those from the Sanshui basin form the only Paleogene bimodal magmatic province in eastern China (Guangdong, 1988). Therefore the major goals of this paper are (1) to document geochemical and isotopic characteristics of the Paleogene volcanic rocks from South China, (2) to discuss the petrogenesis of the bimodal volcanism and (3) to examine the temporal and spatial geochemical variation of extension-related magmas emplaced in the continental rift zone of south China and its implications for opening of the South China Sea.

2. Geological background

The continental margin of south China has been characterized by an extensional tectonic environment since the Late Mesozoic (Taylor and Hayes, 1983; Ru and Piggot, 1986). The coexistence of Cretaceous magmatism with northeast-trending extensional basins in this region compelled workers to consider that since that time South China has been tectonically similar to the present-day Basin and Range in North America (Gilder et al., 1991; Li, 1997). During the Cenozoic, this extension has caused formation of abundant intraplate magmas via decompression melting of the asthenosphere that ascended after significant thinning of the stretched lithosphere (Tu et al., 1991; Flower et al., 1992; Chung et al., 1994, 1995). Whereas Late Cenozoic basalts are widespread in the coastal areas surrounding the South China Sea, older Paleogene volcanic rocks occur only in the

Fig. 1. (A) Sketch map showing outcrops of Cenozoic extension-related volcanic rocks (black areas) surrounding the South China Sea. Symbols B, C and D mark the three Paleogene extensional basins, Sanshui, Heyuan and Lienping, respectively, in south China. Simplified geologic maps of these basins are shown in (B), (C) and (D), respectively. The geologic units are: (1) sedimentary strata: S = Sinian, LP = Lower Paleozoic, UP = Upper Paleozoic, M = Mesozoic; (2) basin sediments: K₂ = Upper Cretaceous, P = Paleogene, N = Neogene; and (3) Mesozoic magmatic rocks: J₃ = Late Jurassic Porphyries, γ = Yanshanian (140–90 Ma) Granitoids.

Sanshui, Heyuan and Lienping basins whose development might have been essentially controlled by a northeast-trending fault system (Fig. 1).

In the Sanshui basin, which stretches for over 100 km in the north–south direction (Fig. 1B), volcanic activity lasted from the latest Cretaceous to Late Paleogene. The volcanic sequences in several localities are composed of alternating mafic and felsic lavas and reach a total thickness of more than 1000 m (Guangdong, 1988; Yuan et al., 1994). To the northeast, the Heyuan and Lienping basins (Fig. 1; marked with C and D, respectively) are two smaller extensional basins bounded by northeast-trending faults. Volcanic successions there are intercalated with Early Paleogene sediments and consist of basalts to andesites (Guangdong, 1988). The Yanshanian (Jurassic to Cretaceous) granitoids, exposed fringing these three basins (Fig. 1) and widespread in the entire south China margin (cf. Jahn et al., 1990), have been recently envisaged as products from earlier phases of the regional lithospheric extension (Li, 1997).

Opening of the South China Sea is widely believed to have occurred since the Late Oligocene. Its seafloor spreading, based on the magnetic lineations (11 to 5C) identified for the oceanic crust (Taylor and Hayes, 1983) and the Cenozoic geomagnetic polarity time scale (Cande and Kent, 1993), lasted from ~30 to 16 Ma. The key tectonic process responsible for the rifting of the South China continental margin remains controversial. Many workers believe that opening of the South China Sea was simply a manifestation of lithospheric extension (Taylor and Hayes, 1983; Ru and Piggot, 1986; Hayes et al., 1995). Adapting the extrusion tectonics hypothesis (Tapponnier et al., 1982), however, others considered this continental breakup as triggered by the mid-Tertiary movement of Indochina relative to south China along the Ailao Shan–Red River shear zone resulting from the India–Asia collision (Tapponnier et al., 1986; Brias et al., 1993; Leloup et al., 1995). Most recently, Chung et al. (1997a) reported new evidence arguing that the displacement along the Ailao Shan–Red River shear zone began after the onset of seafloor spreading in the South China Sea, in contradiction to that required by the extrusion model. Therefore the simple extension hypothesis is favored for the initiation of the South China Sea

opening. This view will be addressed further in the last section of this paper.

3. Samples and analytical methods

Six mafic and four felsic volcanic rocks from the Sanshui basin and five others from Heyuan and Lienping basins were collected for major and trace element and Sr–Nd isotope determinations. The Sanshui rocks were selected from Zhu et al. (1989), in which twenty five samples have been studied for major element and some of them for Sr and Nd isotope compositions. The ten samples we select cover the whole spectrum of silica contents of the Sanshui volcanics according to the previous study (Zhu et al., 1989). Whereas the Sanshui mafic rocks are porphyritic with augite and plagioclase as major phenocryst phases, the felsic rocks contain abundant sanidine and aegirine-augite characterized by coarser mineral grains (Guangdong, 1988; Zhu et al., 1989). No good quality geochemical data had been reported for volcanic rocks from the other two basins and samples available for this study were restricted because of poor outcrop condition. Thus, apart from with a more detailed description of the Sanshui lavas, only a general picture of rocks from the Heyuan and Lienping basins can be given due to the limited samples analyzed. All the Sanshui samples have been dated by the K–Ar method that yielded an age range of 64–43 Ma for both the mafic and felsic lava suites (Zhu et al., 1989). Volcanic rocks from the other two basins, although yet radiometrically dated, are considered to be also of a similar age on the basis of stratigraphic correlations (Guangdong, 1988).

The powder samples were prepared with standard procedures using a jaw crusher and a corundum mill. Major and some trace elements (Rb, Ba, Nb, Sr, Zr, Y, V, Ga, Cu, Zn, Ni and Cr) were determined by X-ray fluorescence (XRF) method at Macquarie University. Additional trace elements (Th, U, Ta, Hf and the rare earth elements) were determined by instrumental neutron activation analyses (INAA) at National Taiwan University. The results are given in Table 1 and analytical uncertainties are generally better than 5% for the XRF and 5–15% for the

INAA (O'Reilly and Zhang, 1995; Chung et al., 1995). Sr and Nd isotope ratios were measured separately by a VG354[®] mass spectrometer at Chinese Academy of Sciences, Beijing, and by a Finnigan MAT262[®] at Université de Rennes. In both laboratories, chemical procedures described by Jahn et al. (1980) were followed. The results are listed in Table 2, which also include some data published by Zhu et al. (1989). The interlaboratory biases on isotope data are generally within analytical errors, as shown by duplicate analyses.

4. Results

4.1. Major and trace element compositions

In the total alkalis vs. silica plot (Fig. 2), two subgroups composed of basalts and trachytes/rhyolites, respectively, are delineated for volcanic rocks from the Sanshui basin. Such a compositional bimodality is similar to that of Quaternary lavas from the Changbaishan area, Northeast China (Er et al., 1987; Basu et al., 1991), the only Late Cenozoic

Fig. 2. Total alkalis vs. SiO₂ diagram for the Paleogene volcanic rocks from the south China margin. The subdivision for rock types is based on Le Maitre (1989). Fields of Late Cenozoic bimodal magmas in the Changbaishan (CBS) area, northeast China (Basu et al., 1991; M. Zhang, 1995, pers. comm.) and Cretaceous A-type granitic rocks in the Fujian–Jiangsu region, southeast China (Charoy and Raimbault, 1994; Martin et al., 1994) are shown for comparison.

Fig. 3. Chondrite-normalized rare earth element patterns for Paleogene volcanic rocks from the (A) Sanshui basin and (B) Heyuan and Lienping basins.

bimodal magmatic province in eastern China. Although somewhat rich in total alkali contents ($\text{Na}_2\text{O} + \text{K}_2\text{O} \approx 3\text{--}5\%$), the Sanshui mafic rocks are regarded as continental tholeiitic basalts based on their relatively low abundances of the rare earth elements (REE) and moderate enrichment in the light REE ($\text{La}_N \approx 40\text{--}80$) (Fig. 3A). On the other hand, the trachytes and rhyolites are highly differentiated, with SiO₂ ranging from 62 to 70% (Fig. 2). They have significantly elevated REE patterns marked by large negative Eu anomalies (Fig. 3A). These felsic magmas are more alkali-enriched, with $\text{Na}_2\text{O} + \text{K}_2\text{O} \approx 10\text{--}12\%$ (Fig. 2), than Cretaceous A-type granites emplaced in the coastal region of south China (Charoy and Raimbault, 1994; Martin et al., 1994).

The Heyuan and Lienping lavas have a restricted chemical variation from basaltic to andesitic compositions (Fig. 2). These rocks also exhibit light REE-enriched patterns ($\text{La}_N \approx 30\text{--}100$), with the more evolved samples from the Lienping area showing greater enrichment in the light REE (Fig. 3B). In the SiO₂ variation diagram (Fig. 4), they plot between mafic and felsic rocks from the Sanshui basin. Com-

Table 1
Major and trace element data of Paleogene volcanic rocks from Guangdong province, south China

Locality		Sanshui										Heyuan				Lienping			
Sample	KS-2	KS-10	KS-14	KS-15	KS-25	K-41	K-9	K-50	K-51	KS-28	GHY-1	GHY-6	GLP-1	GLP-3	GLS-1				
Age ^a	60.5 Ma	54.3 Ma	56.3 Ma	49.6 Ma	57.5 Ma	56.6 Ma	47.7 Ma	50.9 Ma	51.4 Ma	54.7 Ma									
Major elements (in wt%)																			
SiO ₂	48.33	48.85	48.23	48.52	48.23	52.30	62.60	65.14	64.29	70.04	50.34	52.51	55.76	55.21	62.79				
TiO ₂	1.35	2.84	3.07	2.69	2.77	2.31	0.50	0.42	0.39	0.22	1.57	1.53	0.99	1.05	0.53				
Al ₂ O ₃	16.37	15.29	16.21	17.65	16.17	16.02	14.58	15.69	15.08	13.50	15.47	15.65	16.91	17.48	16.67				
Fe ₂ O ₃ ^b	10.39	13.98	12.65	12.70	12.54	10.60	7.47	5.02	5.96	4.09	12.39	12.30	8.38	8.71	4.64				
MnO	0.11	0.20	0.17	0.13	0.17	0.13	0.21	0.12	0.12	0.09	0.20	0.17	0.15	0.16	0.09				
MgO	6.61	4.57	5.32	4.28	5.13	5.98	0.19	0.25	0.39	0.05	6.87	6.24	4.26	4.28	2.50				
CaO	9.79	9.17	9.91	8.74	9.88	8.83	1.97	1.04	1.25	0.65	8.24	8.76	7.96	7.84	3.19				
Na ₂ O	2.66	3.36	2.89	3.33	3.05	3.40	5.91	5.67	5.50	5.68	2.82	2.78	2.52	2.53	4.91				
K ₂ O	0.45	1.34	0.98	1.00	1.01	0.85	5.12	5.61	5.43	4.77	0.74	0.39	1.61	1.48	1.57				
P ₂ O ₅	0.22	0.69	0.38	0.41	0.36	0.18	0.07	0.05	0.04	0.00	0.22	0.15	0.52	0.56	0.29				
Sum	96.28	100.29	99.81	99.45	99.31	100.60	98.62	99.01	98.45	99.09	98.86	100.48	99.06	99.30	97.18				
Trace elements (in ppm)																			
Rb	7	19	17	15		20	106	161	162	358	14	4	41	52	143				
Ba	155	378	268	245			142	55	53	8	184	149	510	477	353				
Th	1.5	2.7	2.0	1.4	1.9	2.6	10.0	28.1	21.6	58.8	3.4	2.0	3.6	3.4	5.3				
U	0.2	0.5	0.3	0.3	0.6	0.5	2.1	3.5	3.6	9.9	0.5	0.3	0.5	0.6	0.9				
Nb	10	36	25	25		27	106	146	148	299	14	11	11	9	11				
Ta	0.71	2.0	1.5	1.5	1.4	1.5	5.8	8.9	8.0	16.8	0.76	0.52	0.58	0.52	0.67				
Sr	457	395	400	499		384	72	16	20	18	302	240	814	837	626				
Zr	108	207	156	171		167	626	1519	870	1539	113	108	113	101	123				
Hf	2.7	5.2	3.6	4.3	3.7	4.0	13.4	27.1	19.2	35.1	2.8	2.8	2.8	2.8	3.2				
Y	21	35	27	24		21	69	94	81	175	29	26	19	20	13				
V	182	240	325	279		166	bdl	bdl	bdl	2	142	148	159	170	67				
Ga	19	21	24	21		21	32	36	35	39	20	23	20	19	19				
Cu	3	34	34	31		30	bdl	2	2	7	48	58	47	8	1				
Zn	67	127	111	117		105	168	167	180	242	111	105	111	97	83				
Ni	63	37	62	52		1	1	bdl	bdl	bdl	206	139	26	20	13				
Cr	149	68	118	79		65	11	10	5	44	194	199	83	60	34				

La	14.2	24.4	16.6	18.1	16.8	17.3	58.6	69.2	74	166	14.1	11.3	29.4	27.7	30.3
Ce	30.1	52.8	40	36.4	34.6	37.9	119	152	157	321	34.1	25.6	61.9	56.9	55.4
Nd	16.7	27.2	21.8	22.2	22.8	17.9	56.4	66.2	61.3	115	15.3	13.7	30.2	31.5	23.5
Sm	3.91	7.20	5.17	5.17	5.20	5.00	12.1	14.2	13.5	23.2	4.00	3.68	5.74	5.73	4.02
Eu	1.29	1.54	1.83	1.82	1.76	2.50	1.59	0.87	0.73	0.17	1.31	1.28	1.71	1.79	1.28
Tb	0.54	1.09	0.72	0.87	0.92	0.78	2.17	3.00	2.48	5.36	0.74	0.62	0.80	0.80	0.51
Yb	2.27	2.87	2.66	2.38	2.78	1.93	5.20	8.18	7.29	16.4	2.07	2.20	2.37	2.03	1.55
Lu	0.36	0.42	0.31	0.33	0.34	0.3	0.83	1.16	1.02	2.09	0.29	0.32	0.33	0.28	0.21

bdl: below detecting limit.

^a K–Ar age data from Zhu et al. (1989).^b Total iron as Fe₂O₃.

Table 2
Sr and Nd isotopic ratios of Paleogene volcanic rocks from south China

Sample No.	Rock Type	Rb (ppm)	Sr (ppm)	$(^{87}\text{Sr}/^{86}\text{Sr})_{\text{m}}$	$I_{\text{Sr}}(T)$	Sm (ppm)	Nd (ppm)	$(^{143}\text{Nd}/^{144}\text{Nd})_{\text{m}}$	$I_{\text{Nd}}(T)$	$\epsilon_{\text{Nd}}(T)$
Sanshui										
KS-2	basalt			0.706342 ± 36 ^a		3.70 ^a	16.52 ^a	0.512790 ± 8 ^a		
		7	457	0.706287 ± 10 ^c	0.70625			0.512734 ± 5 ^c	0.51268	2.34
KS-10	basalt	19	395	0.704714 ± 23 ^a	0.70461	7.33 ^a	31.03 ^a	0.512865 ± 10 ^a	0.51281	4.80
KS-14	basalt	17	400	0.705061 ± 9 ^a	0.70496	5.40 ^a	21.32 ^a	0.512860 ± 6 ^a	0.51280	4.64
KS-15	basalt			0.705692 ± 12 ^a		5.16 ^a	22.38 ^a	0.512898 ± 12 ^a		
		15	499	0.705408 ± 9 ^c	0.70535			0.512794 ± 5 ^c	0.51275	3.41
KS-25	basalt	20 ^a	348 ^a	0.704584 ± 22 ^a	0.70485	5.63 ^a	22.08 ^a	0.512871 ± 5 ^a	0.51281	4.86
KS-36	basalt	34 ^a	240 ^a	0.705158 ± 15 ^a	0.70511	7.04 ^a	35.76 ^a	0.512932 ± 15 ^a	0.51290	6.14
K-40	basalt	54 ^a	750 ^a	0.703873 ± 12 ^a	0.70373	6.33 ^a	28.41 ^a	0.512936 ± 12 ^a	0.51289	6.18
K-41	b. andesite	20	384	0.704728 ± 17 ^a	0.70461	5.78 ^a	24.35 ^a	0.512878 ± 9 ^a	0.51282	4.82
K-9	trachyte			0.715841 ± 13 ^a		12.01 ^a	55.45 ^a	0.512905 ± 24 ^a		
		106	72	0.715552 ± 8 ^c	0.71266			0.512899 ± 5 ^c	0.51286	5.48
K-50	trachyte	161	16	0.729400 ± 12 ^c	0.70863	14.2	66.2	0.512864 ± 5 ^c	0.51282	4.84
K-51	trachyte	162	20	0.727400 ± 9 ^c	0.71027	13.5	61.3	0.512857 ± 4 ^c	0.51281	4.66
KS-28	rhyolite					22.29 ^a	121.0 ^a	0.512852 ± 10 ^a		
		358	18	0.753526 ± 9 ^c	0.70878			0.512829 ± 4 ^c	0.51279	4.31
Heyuan (assumed age ≈ 54 Ma)										
GHY-1	basalt	14	302	0.704761 ± 22 ^b	0.70466	4.0	15.3	0.512679 ± 24 ^b	0.51262	1.05
GHY-6	b. andesite	4	240	0.705150 ± 22 ^b						
				0.705098 ± 10 ^c	0.70506	3.7	13.7	0.512638 ± 5 ^c	0.51258	0.21
Lienping (assumed age ≈ 54 Ma)										
GLP-1	b. andesite	41	814	0.708114 ± 39 ^b	0.70800	5.7	30.2	0.512375 ± 24 ^b	0.51233	−4.58
GLP-3	b. andesite	52	837	0.707499 ± 16 ^b	0.70736	5.7	31.5	0.512480 ± 9 ^b	0.51244	−2.50
GLS-1	andesite	143	626	0.711410 ± 30 ^b	0.71090	4.0	23.5	0.512357 ± 18 ^b	0.51232	−4.84

All Sr and Nd isotope ratios given, with two standard errors, relative to $^{87}\text{Sr}/^{86}\text{Sr} = 0.71020$ for the NBS 987 Sr standard and $^{143}\text{Nd}/^{144}\text{Nd} = 0.511860$ for the La Jolla Nd standard. $I_{\text{Sr}}(T)$ and $I_{\text{Nd}}(T)$ represent initial Sr and Nd isotopic compositions, respectively.

^a Data from Zhu et al. (1989). Sm–Nd concentrations determined by the isotopic dilution method.

^b Analyses at Institute of Geology, Chinese Academy of Sciences, Beijing.

^c Analyses at Institut de Géologie, Université de Rennes 1.

pared with one of the Sanshui trachyte samples (K-9) which has the same silica content, however, the Lienping andesite (GLS-1) shows much lower contents in potassium and the incompatible trace elements but higher Sr (Fig. 4). This may argue against a petrogenetic link between the magmas of these two areas.

The geochemical distinction between lavas from the Sanshui and other two basins is clearly shown by the primitive-mantle-normalized diagram (Fig. 5). In the former, almost all rocks studied (except one sample KS-2) display mild enrichments in Nb–Ta relative to La (i.e., Nb/La > 1), a rule that exists

even for the highly differentiated felsic member. On the other hand, whereas lavas from the Heyuan basin reveal a relatively flat pattern (Nb/La $\approx$ 1), those from the Lienping area have a significant Nb–Ta negative anomaly (Nb/La < 1) that seem to increase concomitantly with increasing silica contents. The Lienping rocks furthermore show depletions in Zr, Hf and Ti (Fig. 5B). We note that the Sanshui basalts exhibit an incompatible trace element pattern that is similar to oceanic island basalts (e.g., Sun and McDonough, 1989), and extension-related Late Cenozoic intraplate tholeiitic basalts in South China (Tu et al., 1991; Chung et al., 1994). Additionally, the

Fig. 4. Oxides and trace elements vs. SiO₂ variation diagrams for the Paleogene volcanics in south China. Symbols as in Fig. 2.

trachytes/rhyolites also display an overall enriched pattern except in Ba, Sr, P, Eu and Ti, a feature similar to that of Cretaceous A-type granites from the coast of southeast China (Charoy and Raimbault, 1994; Martin et al., 1994). Along with their high $(\text{Na} + \text{K})/\text{Al}$ ratios from 0.98 to 1.08, these peralkaline felsic lavas from the Sanshui basin plot in the field of within-plate granites in the discrimination diagram (Fig. 6A). Their incompatible element abundances fall in the same range of A-type granites worldwide (Whalen et al., 1987; Eby, 1992), but higher than A-type granites from south China (Fig. 6B).

4.2. Sr and Nd isotope ratios

Excluding an exceptional sample (KS-2) which shows a lower Nd isotope ratio owing to significant

crustal contamination in the petrogenesis (see discussion below), the Sanshui bimodal volcanic rocks have rather uniform $\varepsilon_{\text{Nd}}(T)$ values from +6 to +4 (Fig. 7). This is consistent with the range of most Late Cenozoic intraplate basalts from South China (Tu et al., 1991; Chung et al., 1995) and close to that of seamount basalts in the South China Sea (Tu et al., 1992). However, Sr isotope data for the felsic lavas are unusual, with I_{Sr} up to 0.7127 and plotting to the right of the mantle array in the $\varepsilon_{\text{Nd}}(T)$ vs. I_{Sr} diagram (Fig. 7). This horizontal displacement is unlikely to be caused by shift of the Rb/Sr ratios, e.g., decrease in the Rb and/or increase in the Sr abundances owing to secondary alteration processes, because the samples studied are fresh and do not show unusual K/Rb and other trace element ratios. The $\varepsilon_{\text{Nd}}(T)$ values of the Sanshui felsic rocks are

Fig. 5. Primitive-mantle-normalized diagram for the Paleogene volcanic rocks from (A) Sanshui and (B) Heyuan and Lienping basins. The normalizing values are from Sun and McDonough (1989). SiO_2 data for the samples are also shown in parentheses.

Fig. 6. Plots of the Sanshui felsic lavas in (A) the Rb vs. (Nb + Y) discrimination diagram of Pearce et al. (1984), and (B) the (Zr + Nb + Ce + Y) vs. (Ga/Al) * 10000 diagram of Whalen et al. (1987). Fields for A-type granites worldwide are from Whalen et al. (1987) and Eby (1992); for those in south China from Charoy and Raimbault (1994) and Martin et al. (1994).

remarkably higher than those of the Cretaceous A-type granites in the southeast China continental margin, whose $\varepsilon_{\text{Nd}}(T)$ values are around -2 to -7 (Jahn et al., 1990; Martin et al., 1994).

The 'initial' Nd and Sr isotope ratios for volcanic rocks from the Heyuan and Lienping areas were calculated at 54 Ma, a mean age inferred from the Sanshui lavas (Zhu et al., 1989). They show more heterogeneous isotope compositions (Fig. 7), with $\varepsilon_{\text{Nd}}(T) \approx +1$ to -5 and $I_{\text{Sr}} \approx 0.705$ to 0.711 (Table 2). Additionally, the decrease of Nd and increase of Sr isotope ratios for these volcanic rocks correlate generally with the increase of their silica and incompatible trace element abundances. Consequently lavas from the Lienping basin which have more evolved chemical compositions than those of the Heyuan basin display lower $\varepsilon_{\text{Nd}}(T)$ and higher I_{Sr} values. In the $\varepsilon_{\text{Nd}}(T)$ vs. I_{Sr} plot (Fig. 7), these Heyuan and

Lienping volcanics form a distinct array from that of the Sanshui bimodal magmas. This isotopic distinction is also present in the $\varepsilon_{\text{Nd}}(T)$ vs. $1/\text{Nd}$ and I_{Sr} vs. $1/\text{Sr}$ diagrams, in which the Lienping samples plot toward an upper crustal component (Fig. 8).

5. Petrogenesis of the Paleogene volcanism

5.1. The Sanshui bimodal volcanism

The extension-induced Late Cenozoic intraplate basalts in the south China margin are widely considered to have originated from the upper mantle sources with negligible crustal contamination (Tu et al., 1991; Flower et al., 1992; Chung et al., 1994, 1995). With Sr and Nd isotope compositions resembling those of the Late Cenozoic basalts (Fig. 7), the Sanshui mafic lavas, though older than these, could have been derived from similar petrogenetic processes. This is supported by the incompatible trace element characteristics of the Sanshui basalts, which exhibit smooth mantle-normalized patterns (Fig. 5A) similar to those of Late Cenozoic tholeiitic basalts from the Hainan island (Flower et al., 1992), the Fujian–Taiwan region (Chung et al., 1994, 1995) and postspreading seamounts in the South China Sea (Tu et al., 1992). By analogy, it may therefore be concluded that no significant upper crustal materials were involved in the generation of Sanshui basaltic magmas. The exception observed is sample KS-2 which was formed during the early stage of the Sanshui volcanism at ~ 60 Ma (Table 1). This sample has the lowest alkalinity (Fig. 2) and REE abundances (Fig. 3A), and shows features of crustal contamination such as higher Sr and lower Nd isotope ratios (Fig. 7).

There is growing evidence indicating that many high-silica, A-type magmas result from extensive crystal fractionation, without crustal assimilation, from mantle-derived parental melts (Turner et al., 1992). The uniform $\varepsilon_{\text{Nd}}(T)$ values and comparable ranges of most incompatible trace element ratios (e.g., Th/U, Nb/Th, Sm/Nd and Zr/Y; Fig. 5A) between mafic and felsic lavas from the Sanshui basin do support the idea that the latter can be differentiated from the former by appropriate magma chamber processes. This genetic relation is clearly illustrated by the 'fractional crystallization' trend in

the $\epsilon_{\text{Nd}}(T)$ vs. MgO and Nb/La plots (Fig. 9). Apparent depletions of Ba, Sr, P, Eu and Ti observed in the Sanshui felsic rocks indicate that phases including plagioclase, apatite and iron–titanium oxides were involved in the differentiation process. At a late stage, as revealed by the potassium depletion in the syenite sample KS-28 which may represent the most evolved melt fraction, a potash-feldspar (e.g., sanidine) became the controlling phase over plagioclase in the magma chamber. The overall elemental features of the Sanshui felsic lavas do not favor involvement of volatile phases in the melt differentiation, because the addition of volatiles can exclusively fractionate certain trace element ratios (e.g., Nb/Ta and Zr/Hf) as often observed in the late stage of A-type magmatism (Whalen et al., 1987; Eby, 1992; Charoy and Raimbault, 1994).

Any petrogenetic models for the Sanshui volcanism must furthermore explain two phenomena, i.e., a compositional gap between the mafic and felsic lavas and the apparent horizontal Sr isotope shift in the isotope plots for the felsic rocks. Here we adopt the 'double diffusive' magma chamber model (e.g., Campbell and Turner, 1987), which has been applied successfully to silicic magma generation in the Kenya rift (Macdonald, 1987) and the Taupo Volcano, New Zealand (McCulloch et al., 1994). In this model, a double diffusive interface, through which heat can be transported efficiently with little mass transfer, exists between the upper and lower portions of the magma chamber (Fig. 10). How such an interface was formed is highly hypothetical. In contrary to Campbell and Turner (1987) who proposed melting of country rocks above the roof to produce lighter melts pond-

Fig. 7. Plots of Initial Sr isotope ratios vs. $\epsilon_{\text{Nd}}(T)$ values for Paleogene volcanics in south China showing probable petrogenetic processes of mixing or upper crustal contamination. Fields for Late Cenozoic intraplate basalts from South China (Tu et al., 1991; Chung et al., 1994; Lan et al., 1995) and seamount basalts in the South China Sea (Tu et al., 1992) are shown for comparison. DMM marks isotope range of the east Taiwan ophiolite (Jahn, 1986; Chung and Sun, 1992), representing the depleted (asthenospheric) upper mantle source in the south China region. The endmembers used for mixing calculations are: (1) tholeiitic basalt: $(^{87}\text{Sr}/^{86}\text{Sr})_i = 0.704$, $\epsilon_{\text{Nd}}(T) = +5$, $[\text{Sr}] = 600$ ppm, $[\text{Nd}] = 15$ ppm; (2) A-type trachytic melt: $(^{87}\text{Sr}/^{86}\text{Sr})_i = 0.704$, $\epsilon_{\text{Nd}} = +5$, $[\text{Sr}] = 20$ ppm, $[\text{Nd}] = 80$ ppm; and (3) upper continental crust: $(^{87}\text{Sr}/^{86}\text{Sr})_i = 0.730$, $\epsilon_{\text{Nd}} = -10$, $[\text{Sr}] = 400$ ppm, $[\text{Nd}] = 30$ ppm. The crustal endmember is based on elemental and isotopic data of the country rock (Li, 1988; Cheng and Chung, unpubl. data). The two mixing curves represent mixes of (1) and (3) for curve 1 and of (2) and (3) for curve 2. Ticks mark degrees of involvement of the upper crust component in mixing. Fields for the Cretaceous mafic rocks (Li and McCulloch, 1997; Lapierre et al., 1997; Lee et al., unpubl. data) and A-type granites from south China (Martin et al., 1994) are also shown. See text for discussion.

Fig. 8. (A) $\epsilon_{Nd}(T)$ vs. $1/Nd$ and (B) $(^{87}Sr/^{86}Sr)_i$ vs. $1/Sr$ diagrams of the Paleogene volcanic rocks from South China. Symbols as in Fig. 2.

ing at the top in the chamber, we follow the model of Macdonald (1987) suggesting that the interface results from buoyancy-driven separation of magmas during the periods of eruptive quiescence. The lower portion of the chamber consists dominantly of mantle-derived basaltic magma and is characterized by turbulent convection and crystal fractionation. Whereas the gabbroic cumulates sink to the bottom, lighter residual liquids rise by boundary-layer migration along the side-wall toward the upper portion (cf. Macdonald, 1987) where they undergo subsequent differentiation to form melts of trachyte/rhyolite composition.

Accordingly, we summarize a scenario for the Sanshui volcanism (Fig. 10). First of all, a chilled margin should have formed at the margin of the magma chamber. This was followed by crystal accumulation on the floor and then the upper levels, a process that could not only further prevent crustal contamination but also account for initiation of the double diffusive interlayer. Closed-system differentiation in the upper and lower portions of the magma chamber led to generation of the bimodal melts with tholeiitic basalt and A-type granite like trachytic

Fig. 9. Plots of (A) $\epsilon_{Nd}(T)$ vs. MgO and (B) Nb/La for the Paleogene volcanics in south China. Symbols as in Fig. 2. Note that two different trends, FC (fractional crystallization) and AFC (assimilation with fractional crystallization), are delineated by rocks from the Sanshui and Heyuan–Lienping basins, respectively.

Fig. 10. Schematic cartoon showing magma chamber processes for the generation of Sanshui bimodal volcanism.

compositions, respectively. Later, the A-type melts were subjected to a small amount ($\sim 1\text{--}3\%$) of upper crustal contamination which caused the significant Sr isotope shift without changing Nd isotope ratios (Fig. 7). This process might have taken place as the A-type melts were erupting en route to the surface, although the possibility of assimilation of overlying country rocks in the upper portion of the chamber before eruption can not be ruled out because so far no felsic xenoliths have been found in the Sanshui volcanic rocks. At a critical condition, perhaps controlled by the volatile content or Fe-enrichment (Turner et al., 1983), the bimodal magmas were ejected from the magma chamber.

5.2. The Heyuan and Lienping volcanism

Volcanics from the Heyuan and Lienping areas underwent different petrogenetic processes. As shown in the $\varepsilon_{\text{Nd}}(T)$ vs. MgO and Nb/La plots (Fig. 9), we apply the AFC (i.e., assimilation and fractional crystallization) model described by Taylor (1980) and DePaolo (1981) to interpret the geochemical and isotopic features observed in these volcanic rocks. It is suggested that in the magma chambers of the Heyuan and Lienping basins the AFC process occurred to dominate the melt compositions. When compared with that of the Sanshui basin, assimilation of the country rocks had played a more important role than fractional crystallization in the open-system magma chambers of Heyuan and Lienping basins, thereby causing a significant variation in the radiogenic isotope ratios [$\varepsilon_{\text{Nd}}(T) \approx +1$ to -5 ; $I_{\text{Si}} \approx 0.705$ to 0.711] within a rather restricted silica range ($\text{SiO}_2 \approx 50\text{--}63\%$) for lavas. A simple two component mixing calculation (Fig. 7), for example, shows that quite large amounts of upper crustal materials (up to $\sim 40\%$) might have been involved in the generation of andesitic rocks emplaced in the Lienping basin.

6. Tectonic implications

6.1. Extension-induced magmatism in south China

As pointed out earlier, the south China continental margin might have been an extensional tectonic set-

ting since Late Mesozoic time. A compressive regime related to subduction of the Kula or paleo-Pacific ocean plate has been considered prevailing until the Late Cretaceous when bimodal volcanic rocks and associated A-type granites were emplaced in the coastal region of southeast China (Charvet et al., 1994; Martin et al., 1994). This subduction-related interpretation rests simply upon the calc-alkaline geochemical character dominant in the Cretaceous igneous rocks in south China (Jahn, 1974; Huang et al., 1986; Jahn et al., 1990; Charvet et al., 1994; Martin et al., 1994; Lan et al., 1996). On the contrary, based on a compilation of geochemical and chronologic data, Li (1997) strengthened the viewpoint argued by Gilder et al. (1991) that the Cretaceous magmatism in south China took place in an extensional environment analogous to the Basin and Range of North America. Li (1997) further suggested that the south China lithospheric extension may have commenced at the early Cretaceous. This is supported by a recent $^{40}\text{Ar}/^{39}\text{Ar}$ dating study on the Mesozoic basaltic rocks from southern Hunan Province, ~ 300 km north of the Sanshui basin on the coastline of south China, where intraplate alkali basalts occurred as early as ~ 175 Ma (Chung et al., 1997b).

The Basin and Range province of North America has been the locus of an Andean type convergent margin until the latest Cretaceous or Early Paleocene (cf. Armstrong and Ward, 1991). Subsequent lithospheric extension, began at ~ 40 Ma, caused two principal episodes of intraplate magmatism with different geochemical characteristics. Whilst magmas formed in the early stage (40–5 Ma) have heterogeneous compositions marked by the calc-alkaline signature as that commonly observed in subduction zone lavas, those of the later stage (since ~ 5 Ma) dominantly show geochemical affinities to oceanic island basalts (OIB) (Leeman and Harry, 1993; Leeman and Harry (1993); Hawkesworth et al., 1995; Hooper et al., 1995). postulated a binary source model, in which the older magmas were derived from melting of the enriched lithospheric mantle that had been metasomatized previously by Mesozoic subduction zone processes and the younger ones originated from melting of the ascended asthenospheric mantle after significant lithospheric thinning. This diachronous transition in magma sources de-

depends on initial variations in the lithospheric thickness and rates of the lithospheric attenuation.

A similar scenario may be applicable to the south China continental margin on the other side of the North Pacific. The Cretaceous and Cenozoic magmatism around the Taiwan Strait (Fig. 1) may serve as a comparable example. Whereas abundant Miocene basalts resulting from the lithospheric thinning and asthenospheric upwelling have OIB-type elemental and isotopic characteristics (Chung et al., 1994, 1995; Lan et al., 1995), the Cretaceous to Eocene magmas erupted during earlier stages of continental extension in south China are heterogeneous in composition and overwhelmingly show calc-alkaline features coupled with higher Sr and lower Nd isotope ratios (Charvet et al., 1994; Lee, 1994; Lapierre et al., 1997; Chung et al., unpubl. data). This chemical variation with time suggests a dramatic change in the magma sources. Two distinct source regions involved, similar to those proposed by Leeman and Harry (1993), could be the subduction-modified lithospheric mantle in the earlier stages and the ascended asthenospheric mantle during Miocene time after significant extension had occurred in the Taiwan Strait (Chung et al., 1994).

6.2. Opening of the South China Sea

The extension-induced magmatism can provide information regarding the mechanism responsible for opening of the South China Sea. Along with the dominant calc-alkaline rock suites, Mesozoic to Paleogene mantle-derived magmas with OIB-type geochemical features form a southward younging trend in South China. These are, from the coast to inland, Paleogene (64–43 Ma) basalts in the Sanshui basin discussed here, Cretaceous (140–90 Ma) mafic dikes in northern Guangdong (Li and McCulloch, 1997) and mid-Jurassic (~175 Ma) alkali basalts in southern Hunan (Chung et al., 1997b). The latter might have been associated with development of the Gan–Hang rift, the northernmost extension zone in south China which was initiated since the Jurassic (Gilder et al., 1991). This younging trend implies a progressive southward migration of lithospheric extension in south China, which consequently led to continental breakup in the southern margin of south China and opening of the South China Sea in Oligocene time.

Seafloor spreading of the South China Sea lasted between ~30 and 16 Ma, and stopped because the North Palawan block, a rifted fragment from south China, collided with the west Philippines (Lee and Lawver, 1994).

Since Tapponnier et al. (1982) proposed the continental extrusion hypothesis as a result of the collision of India with Asia, it became very popular to interpret the opening of the South China Sea as a response to the mid-Tertiary Indochina escaping along the Ailao Shan–Red River shear zone (e.g., Tapponnier et al., 1986; Brias et al., 1993; Leloup et al., 1995). A major support for this model comes from radiometric age data from the intrusive bodies along the shear zone, which suggest a duration of the shear movement from ~35 to 17 Ma nearly coeval with the time span of the South China Sea spreading (Schärer et al., 1990, 1994; and Leloup et al., 1995 for a comprehensive review). Most recently, however, Chung et al. (1997a) re-evaluated the age constraints and demonstrated that the Ailao Shan–Red River shear zone might have been active only from ~27 to 22 Ma. This clearly indicates that the strike-slip displacement of the Ailao Shan–Red River shear zone was initiated after the seafloor spreading in the South China Sea, contradicting the requirement of the extrusion-induced model. It may therefore be concluded that opening of the South China Sea was mainly a consequence of the lithospheric extension in south China which might have commenced in Jurassic time and migrated southwards to eventually breakup the continent at its southern margin. * *

Acknowledgements

We thank Xianhua Li for providing preprints and stimulating discussion on the Mesozoic history of south China. Appreciations are extended to J. Cornichet, J. Macé, O. Henin and J.B. Zhang for help with isotopic analysis, to S.-s. Sun for numerous suggestions, and to U. Knittel and L.M. Larsen for constructive journal reviews. This study was benefited by supports from Australia, China, France and Taiwan at different stages, and completed through a grant by the National Science Council, Taiwan, ROC (NSC 84-2111-M-002-004 GM). This is contribution No. 87 from the Key Centre for Geochemical Evolu-

tion and Metallogeny of Continents, Macquarie University.

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