Extremely high-Na adakite-like magmas derived from alkali-rich basaltic underplate: The Late Cretaceous Zhantang andesites in the Huichang Basin, SE China

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The Zhantang andesites, which erupted in the Late Cretaceous Huichang Basin of SE China interior, were associated with the Late Mesozoic lithospheric extension and basaltic underplating. They are high-Na (6.59–8.46 wt% Na₂O), high-Al trondhjemitic rocks with high Sr and Ba, low Y and HREE, and high Sr/Y and La/Yb ratios, similar to modern adakites. However, they are much higher in Na₂O but lower in CaO than adakites. Their $\epsilon\text{Nd}(T)$ values of –2.3 to –3.8 and initial ⁸⁷Sr/⁸⁶Sr ratios of 0.707 to 0.708 are also significantly different from those of adakites with MORB-like isotopic compositions. These chemical and isotopic features, along with the tectonic setting, suggest that they were not produced by partial melting of subducting slab.

The Zhantang adakite-like magmas may be derived from underplated basaltic lower crust, but require a compositionally peculiar basaltic protolith to account for their extremely high-Na and low-Ca feature. They are compositionally comparable to the experimentally produced partial melts of alkali-rich basalt. We therefore interpret them as the products of melting of an alkali-rich basaltic rock.

INTRODUCTION

Like Archean high-Al tonalite-trondhjemitic-granodiorite (TTG), modern adakitic rocks are high-Al (>15% Al₂O₃ at the 70% SiO₂ level), sodic, intermediate to felsic igneous rocks (Defant and Drummond, 1990; Atherton and Petford 1993). The origin of adakitic (or TTG-like) magmas has been the subject of much discussion (e.g., Drummond and Defant, 1990; Defant and Drummond, 1990; Atherton and Petford 1993; Drummond *et al.*, 1996; Martin, 1999; Defant *et al.*, 2002). These rocks have distinctive geochemical features such as high Sr, low Y and HREE contents and high Sr/Y and La/Yb ratios, suggesting that they are derived from a basaltic source at pressures high enough to stabilize garnet ± amphibole (e.g., Kay, 1978; Martin, 1986;

Drummond and Defant, 1990; Atherton and Petford 1993). Experimental partial melting data have shown that adakitic melts can be produced by high pressure (≥10 kbar) partial melting of basaltic rocks, leaving a residual assemblage of garnet + clinopyroxene ± amphibole ± plagioclase (e.g., Rapp and Watson, 1995). Petrogenetic models proposed for the generation of adakitic magmas mainly invoke partial melting of subducting oceanic lithosphere (Drummond and Defant, 1990; Defant and Drummond, 1990; Kay *et al.*, 1993), partial melting of basaltic lower crust (Atherton and Petford 1993; Muir *et al.*, 1995; Zhang, Q. *et al.*, 2001), and fractionation and contamination of mantle-derived basaltic magmas with garnet-bearing lower continental crust (e.g., Feeley and Hacker, 1995).

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Fig. 1. Distribution of the Late Mesozoic igneous rocks in SE China (after Zhou and Li, 2000). The square area that contains Huichang Basin is the range of Fig. 2.

Huichang Basin, Southeastern (SE) China, are extremely high-Na (up to 8.46 wt% Na_2O), and high-Al trondhjemitic rocks. They have trace element geochemical feature similar to adakite, but much higher Na_2O content than adakite. The extremely high-Na signature probably implies a particular aspect for generating these magmas. In this paper, we present detailed data on the major element, trace element and Sr-Nd isotopes of the Zhantang andesites. These data were used in conjunction with the associated geological setting to

constrain their petrogenesis. Compositional comparisons of these rocks with adakite and experimental high-pressure partial melts of basalts were also made to characterize their source composition. The extremely high-Na Zhantang andesites provide an example of atypical adakite magmas. We will argue that this atypical feature is most likely source-related, and that a Na-rich or alkaline basaltic protolith is necessary for the generation of these magmas.

Fig. 2. Distribution of the volcanic rocks in the Huichang Basin. The amplified part is the sketch of the Zhintang andesites and basalts.

GEOLOGICAL SETTING

Tectonic setting for the Late Mesozoic magmatism in SE China

SE China is geologically characterized by extensive Late Mesozoic (Jurassic and Cretaceous) magmatism (Fig. 1). The Late Mesozoic igneous rocks are dominated by felsic rocks, with minor mafic and intermediate rocks. Their ages range from 180 to 79 Ma (Li, 2000; Zhou and Li, 2000). In general, the Jurassic (180–140 Ma) igneous rocks scatter in the inland, while the Cretaceous (140–79 Ma) igneous rocks occur mainly in the coastal area, but some of them also occur in the inland area.

It is commonly accepted that the magmatism in the coastal area was related to subduction of the paleo-Pacific plate underneath SE China (e.g., Jahn *et al.*, 1976; Charvet *et al.*, 1994; Lapierre *et al.*, 1997; Zhou and Li, 2000). The ocean-continent paleo-suture is located along the Yuli high-pressure, lower-temperature metamorphic belt in

Taiwan, where blue schist and ophiolite complexes were found in the Tananao Basement Complex (Biq, 1971; Jahn *et al.*, 1986). The subduction-related compressive regime was believed to be dominant until the end of Early Cretaceous when A-type granites in the coastal area were intruded around 92–101 Ma (e.g., Martin *et al.*, 1994; Qiu *et al.*, 1999).

The tectonic setting for the magmatism in the inland area is predominantly extensional, which is completely different from that in the coastal area. Gilder *et al.* (1991) proposed that a system of NE-trending grabens, similar to those of the Basin and Range Province in the western United States, formed in SE China during Mesozoic. The A-type granitic and intraplate basaltic magmatisms from Jurassic to Cretaceous in the inland support a dominant lithospheric extension during that period (Li and McCulloch, 1998; Li, 2000). A series of Cretaceous sedimentary basins also occur inboard of the coastal area (Fig. 1). These basins, developing on the Proterozoic base-

Fig. 3. Isodepth contour line (km) of Moho (a) and T_{DM} isoline (Ga) of the Late Mesozoic granitoids (b) in SE China (from Li and Zhou, 2001).

ment and Paleozoic folded strata, were interpreted as intraplate rift basins (Li, 2000).

Regional geology and field relationships of ZhanTang andesites and basalts

The Eastern Nanling Range, with the Huichang Basin and the ZhanTang andesites and basalts in its eastern section, is situated inboard of the Cretaceous arc magmatism of the coastal area (Figs. 1 and 2). This region with a crustal thickness over 36 km (Fig. 3a) is one of the most conspicuous sites of intraplate magmatism in SE China. A-type granites, calc-alkaline, alkaline and shoshonitic basalts and mafic dykes, with ages ranging from 180 Ma to 85 Ma (Li and McCulloch, 1998; Chen *et al.*, 1998; Zhang *et al.*, 1999; Li *et al.*, 2002), are extensively distributed and coeval with the calc-alkaline granitoids or dacitic-rhyolitic lavas. Some of the basalts and mafic dykes have high TiO_2 contents and high Nb/La ratio, together with the A-type granites suggesting an intraplate extensional environment (Li and McCulloch, 1998; Chen *et al.*, 1999).

The Eastern Nanling Range is also one of the

most striking regions of Nd isotopic anomaly for the Late Mesozoic granitoids in SE China (Fig. 3b). The granitoids in this region have low T_{DM} (Nd depleted-mantle model age) relative to most of the granitoids elsewhere in SE China. Underplating and addition of mantle-derived magmas to the recycling materials were advocated to explain the origin of these granitoids (Zhou and Li, 2000).

The Huichang Basin occurs along the NNE-striking Shicheng-Xinwu Fault (Fig. 1), and is composed of the Ganzhou Formation, a 2400 m thick basal sequence of Late Cretaceous sandstones and mudstones intercalated with volcanic rocks. There are three localities of volcanic rocks within the Huichang Basin. They all occur along the eastern margin of the basin (Fig. 2) and were probably related to the revitalization of the Shicheng-Xinwu Fault during Late Cretaceous (Gannan Geological Team, 1995). The ZhanTang andesites and basalts crop out from ZhanTang town to Dongbei village; the shoshonitic basalts occur to the north of Xiewu in the northern segment of the basin (Zhang, B. T. *et al.*, 2001); while the

rhyolites lie to the east of Junmenling in the southern segment of the basin (Zhou *et al.*, 1998).

The Zhantang andesites, with an average dimension of about 6 km long and 300 m wide, occur subparallel to the strike of the Late Cretaceous sedimentary rocks (Fig. 2). Locally, comfortable contacts between the andesites and sedimentary rocks can be observed, suggesting that the eruption of the andesite magmas took place in the Late Cretaceous. The associated basalts crop out to the north of the andesites and were dated at 84.6 Ma (Rb-Sr whole rocks isochron age; Zhou *et al.*, 1998). Gannan Geological Team (1995) and Zhou *et al.* (1998) ascribed the andesites and basalts to the Late Cretaceous Maodian Group and considered them to be the products of a same tectonic event.

In summary, the Late Cretaceous Huichang Basin and the Zhantang andesitic and basaltic magmas hosted therein clearly occurred in an intracontinental setting, that is, inboard of the Early Cretaceous arc magmatism in the coastal area. They were not associated temporally and spatially with subduction, but directly associated with the Late Mesozoic lithospheric extension, intraplate magmatism and underplating in the Eastern Nanling Range of the inland area.

PETROGRAPHY

Based on microscope observation and electron microprobe analysis, the petrography of the Zhantang andesites and basalts is described as follows:

The Zhantang andesites are porphyritic, with 20–30% (volume proportion) of phenocrysts. The phenocrysts consist of about 70% of plagioclase and 30% of hornblende. The plagioclase ranges in length from 1 to 3 mm, is predominantly euhedral, has weak normal zoning, and has a compositional range from inner zones of An_{12} to sodic rims of An_7 . The hornblende is also euhedral and ranges in length from 1 to 5 mm. Most of the amphibole crystals have been oxidized, but still preserve the shapes of amphibole. The groundmass mainly consists of albite, magnetite and K-feld-

spar. The albite is dominant and is of nearly pure Ab composition ($An < 2$). The albite laths in the groundmass are subparallel-arranged and flow-aligned, suggesting magmatic crystallization. Magnetite and K-feldspar are minor and generally comprise <10 modal %, where they occur as interstitial phases. Trace amounts of apatite and zircon are also observed in many samples.

The basalts associated with the andesites are also porphyritic, containing about 10% of olivine (Fo_{72-75}) phenocrysts, which have partially been iddingsitized in some samples. The groundmass is primarily composed of plagioclase (An_{60-70}), clinopyroxene (augite), orthopyroxene (En_{73-77}) and magnetite. The plagioclase laths in the groundmass are unoriented, with pyroxene and magnetite filled between them. Trace amount of K-feldspar was also observed as an interstitial phase in the groundmass.

GEOCHEMISTRY

Analytical procedures

Major elements were analyzed by wet chemical methods at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. SiO_2 , Al_2O_3 , Na_2O , K_2O and MnO were determined by atomic absorption (Price, 1972). MgO , CaO and FeO were determined volumetrically, and TiO_2 and P_2O_5 colorimetrically. Analytical uncertainties for these major-element oxides except MnO , TiO_2 and P_2O_5 are less than 5%. Trace elements (Rb, Cs, Sr, Ba, Ga, U, Th, Y, Zr, Hf, Ta, Nb, Sc, V, Cr, Co, Ni, and rare earth elements) were determined using inductively-coupled plasma mass spectrometry (ICP-MS) at the Guiyang Institute of Geochemistry, Chinese Academy of Sciences. One hundred milligrams of sample were digested with 1 ml of HF and 0.5 ml of HNO_3 in screw top PTFE-lined stainless steel bombs at 190°C for 12 h. Insoluble residues were dissolved using 8 ml of 40% HNO_3 (v/v) heated to 110°C for 3 h. Analytical technique was similar to that described in detail by Qi *et al.* (2000). The accuracy and precision of these trace elements and rare earth elements were monitored by re-

peated analysis of the GSR-1 granite standard and are within 3% relative standard deviation (RSD).

Sr and Nd isotopic compositions and Rb, Sr, Sm and Nd concentrations were determined using mass spectrometry on a VG354 instrument at the Institute of Geology and Geophysics, Chinese Academy of Sciences. The analytical procedures are similar to those described by Huang and Wu (1990). Overall blank contributions are about 0.2–0.5 ng for Rb and Sr, and about 50 pg for Nd and Sm. The Rb, Sr, Sm and Nd concentrations exhibit good agreement with those analyzed using ICP-MS, typically within 10%. Measured $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7129$, respectively. The reported $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were further adjusted, respectively, to $^{87}\text{Sr}/^{86}\text{Sr} = 0.71025$ for the SRM987 (MST) Sr standard and $^{143}\text{Nd}/^{144}\text{Nd} = 0.511860$ for the LaJolla Nd standard.

Major and trace element compositions of the andesites

The Zhantang andesites range in the SiO_2 content from 59.98 to 64.63 wt% (Table 1) and are metaluminous to weakly peraluminous, with aluminium saturation index (ASI) mostly between 0.90 and 1.10. All of the samples are characterized by high Na_2O (6.59–8.46 wt%), alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O} = 9.33$ –11.29 wt%, with $\text{Na}/\text{K} = 2.96$ –6.05) and Al_2O_3 (16.37–18.67 wt%), but low MgO (0.39–1.27 wt%), CaO (0.62–1.79 wt%) and $\text{Mg\#}$ (0.11–0.30). The high total alkalis or alkaline affinity are due mainly to the extremely high Na_2O contents. On the Ab-An-Or normative diagram (O'Connor, 1965), they plot within the trondhjemite field, close to Ab apex (Fig. 4). Although the Zhantang andesites are trondhjemitic, here they are still referred as high-Na andesites because they are not plutonic rocks and almost contain no quartz.

The andesites are much low in Cr, Co and Ni (<14 ppm, <16 ppm and <13 ppm, respectively), and strongly depleted in Y and HREE (Y and Yb < 10 ppm and 0.75 ppm, respectively), but strongly enriched in Sr (525–1036 ppm) and Ba (594–1317

Table 1. Major and trace element compositions of Zhantang andesites and basalts

Sample	Andesites										Basalts						
	J3-1	J3-2	J3-4	J3-7	J3-8	J3-11	J3-12	J3-17	J3-18	J3-20	J4-1	J4-3	J5-1	J5-2	J5-3	J6-2	J6-5
SiO ₂ (wt %)	60.22	60.09	63.43	62.46	63.07	61.41	64.63	61.70	61.00	61.85	60.56	59.98	52.24	51.23	52.92	52.43	52.32
TiO ₂	0.94	0.90	0.84	0.82	0.81	0.85	0.83	0.80	0.81	0.80	0.84	0.85	0.99	0.96	0.95	0.96	0.95
Al ₂ O ₃	18.67	18.28	16.48	17.27	16.90	16.79	16.37	16.60	16.79	17.23	17.98	18.32	16.72	16.77	16.76	16.51	16.45
FeO	6.41	6.48	6.59	6.06	5.73	5.69	5.45	5.38	5.56	5.27	6.18	5.22	8.05	8.05	7.44	7.74	7.93
MnO	0.08	0.06	0.04	0.09	0.04	0.04	0.04	0.06	0.10	0.05	0.03	0.04	0.14	0.14	0.14	0.14	0.13
MgO	0.87	0.75	0.51	0.58	0.39	0.73	0.47	1.27	1.14	1.11	1.00	0.99	6.81	7.00	7.19	7.15	6.95
CaO	0.83	0.85	0.66	0.62	1.10	1.56	0.74	1.79	1.45	1.31	0.92	0.72	8.41	8.28	8.35	8.12	8.39
Na ₂ O	6.91	7.12	7.19	7.27	7.22	7.76	6.91	6.98	8.46	8.22	6.59	7.75	2.77	2.88	2.88	3.06	3.22
K ₂ O	2.45	2.68	2.14	2.60	2.71	2.76	2.46	3.06	2.39	2.06	3.38	3.54	1.65	1.60	1.55	1.70	1.66
P ₂ O ₅	0.20	0.22	0.43	0.37	0.37	0.42	0.41	0.41	0.41	0.40	0.34	0.38	0.28	0.29	0.26	0.37	0.38
LOI	2.60	2.55	1.23	1.39	1.20	1.72	1.02	1.46	1.45	1.29	1.89	2.03	1.49	2.34	1.21	1.34	1.43
Total	100.18	99.48	99.54	99.53	99.54	99.73	99.33	99.51	99.56	99.59	99.71	99.82	99.55	99.54	99.65	99.52	99.81
Mg#	0.20	0.17	0.12	0.15	0.11	0.19	0.13	0.30	0.27	0.27	0.23	0.25	0.60	0.61	0.63	0.62	0.61
Na ₂ O+K ₂ O	9.36	9.80	9.33	9.87	9.93	10.52	9.37	10.04	10.85	10.28	9.97	11.29	4.42	4.48	4.43	4.76	4.88
Na/K	4.28	4.03	5.09	4.24	4.04	4.26	4.26	3.46	5.37	6.05	2.96	3.32	2.55	2.73	2.82	2.73	2.94
ASI	1.20	1.13	1.07	1.09	1.00	0.90	1.06	0.92	0.88	0.95	1.11	1.02	0.77	0.78	0.77	0.76	0.74

Sample	Andesites														Basalts				
	J3-1	J3-2	J3-4	J3-7	J3-8	J3-11	J3-12	J3-17	J3-18	J3-20	J4-1	J4-3	J5-1	J5-2	J5-3	J6-2	J6-5		
Sr (ppm)	849	782	592	640	675	1036	618	710	525	625	581	651	591	683	685	663	688		
Ba	1310	1281	695	1084	1161	1200	753	1317	742	666	594	735	504	492	481	530	593		
Rb	42	45	49	65	62	64	59	74	52	44	129	129	45	41	42	44	46		
Cs	2.67	2.67	3.17	4.03	5.77	7.77	3.36	5.93	2.23	2.49	30.46	24.50	16.22	12.89	15.40	12.88	12.78		
U	1.19	1.13	1.99	0.96	2.02	0.77	1.53	0.77	0.90	0.84	1.65	1.37	1.32	1.17	1.23	1.28	1.40		
Th	2.82	2.91	3.00	2.97	3.11	3.32	3.09	3.39	3.35	3.31	3.74	3.73	5.88	5.53	5.86	6.73	7.01		
Y	6	6	7	8	7	8	7	8	9	8	9	10	21	20	21	20	22		
Zr	165	164	162	166	152	150	154	149	158	145	157	157	147	142	146	147	152		
Hf	4.59	4.57	4.59	4.96	4.22	4.38	4.38	4.04	4.53	4.03	4.53	4.45	4.31	4.02	4.19	4.15	4.43		
Nb	8.3	7.8	8.0	8.0	7.4	7.1	7.1	7.1	7.9	7.1	7.4	7.5	8.8	8.3	9.1	8.5	8.6		
Ta	0.36	0.36	0.32	0.35	0.33	0.35	0.35	0.31	0.30	0.31	0.34	0.35	0.43	0.41	0.44	0.40	0.44		
Sc	10	11	11	12	10	11	10	11	12	12	14	13	26	25	25	25	25		
V	61	56	98	112	55	83	90	94	100	93	114	116	208	196	205	196	206		
Cr	10	10	13	11	10	10	10	12	9	14	9	11	235	222	240	179	187		
Co	14	11	8	16	9	7	9	16	16	12	9	10	34	33	34	31	33		
Ni	9	8	8	12	8	11	7	13	12	9	13	13	109	106	110	97	100		
La	21.70	25.68	20.77	22.82	25.07	29.68	22.62	32.02	31.92	31.52	27.41	35.89	28.16	27.23	28.34	29.75	31.30		
Ce	53.47	44.27	47.52	56.10	52.73	57.72	53.54	64.40	65.85	65.60	57.29	66.82	58.34	55.69	57.38	60.47	63.62		
Pr	5.74	6.70	5.59	6.24	6.28	7.35	5.67	7.54	7.90	7.70	7.03	8.14	6.91	6.55	6.78	7.09	7.44		
Nd	31.78	32.84	22.44	25.70	24.78	29.20	23.01	31.20	31.81	30.35	29.77	32.96	27.62	26.78	27.83	29.33	30.12		
Sm	4.76	4.85	3.97	4.23	4.17	4.69	4.14	4.76	4.97	4.80	4.78	5.42	5.64	5.39	5.67	5.51	6.22		
Eu	1.01	1.21	0.95	1.13	1.15	1.48	0.97	1.40	1.43	1.41	1.13	1.22	1.50	1.46	1.46	1.48	1.50		
Gd	2.48	2.67	2.56	2.79	2.80	3.21	2.59	3.40	3.37	3.17	3.24	3.44	4.65	4.74	4.82	4.69	4.94		
Tb	0.29	0.31	0.34	0.33	0.31	0.36	0.34	0.36	0.41	0.37	0.37	0.42	0.72	0.64	0.67	0.71	0.78		
Dy	1.29	1.37	1.40	1.61	1.47	1.78	1.63	1.57	1.74	1.71	1.70	1.77	3.91	3.60	3.64	3.88	3.84		
Ho	0.26	0.25	0.28	0.30	0.26	0.28	0.26	0.29	0.31	0.29	0.30	0.31	0.73	0.74	0.74	0.69	0.82		
Er	0.69	0.61	0.82	0.80	0.62	0.72	0.68	0.77	0.82	0.78	0.77	0.86	2.08	2.02	2.11	2.18	2.15		
Tm	0.09	0.09	0.09	0.12	0.11	0.10	0.09	0.12	0.09	0.11	0.11	0.10	0.33	0.30	0.31	0.31	0.31		
Yb	0.59	0.60	0.59	0.68	0.58	0.66	0.59	0.64	0.69	0.58	0.69	0.75	1.94	1.92	1.95	1.90	2.00		
Lu	0.08	0.07	0.08	0.09	0.08	0.07	0.07	0.08	0.08	0.08	0.08	0.09	0.27	0.27	0.26	0.29	0.28		
Eu/Eu*	0.90	1.03	0.91	1.01	1.03	1.16	0.90	1.06	1.07	1.10	0.87	0.86	0.90	0.88	0.85	0.89	0.83		
La/Yb	37	43	35	33	43	45	38	50	46	55	40	48	14	14	15	16	16		
Sr/Y	139	135	87	80	96	133	85	84	59	78	68	69	28	34	33	32	31		
Rb/Sr	0.05	0.06	0.08	0.10	0.09	0.06	0.10	0.10	0.10	0.07	0.22	0.20	0.08	0.06	0.06	0.07	0.07		

FeO, total Fe; LOI, loss on ignition; Mg# = $100 \times \text{mol MgO} / (\text{mol MgO} + \text{FeO})$; ASI = $\text{mol Al}_2\text{O}_3 / (\text{mol Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO})$.

Fig. 4. CIPW normative Ab-An-Or plot (O'Connor, 1965) showing that Zhantang andesites fall in trondhjemite field.

ppm), exhibiting high ratios of Sr/Y and La/Yb (59–139 and 33–55, respectively) and strongly fractionated REE patterns (Fig. 5). The high Sr/Y and La/Yb ratios and the low Y and HREE feature are distinguished markedly from the continental/island arc andesite-dacite-rhyolite (ADR) suites (Table 2) and the arc felsic rocks in the coastal area of SE China (Fig. 5). The andesites also have small or negligible Eu anomalies (Eu/Eu^* close to 1 ± 0.1) and low Rb/Sr ratios (mostly < 0.1), suggesting little, if any, fractional crystallization.

Major and trace element compositions of the basalts

The basalts range in SiO_2 content from 51.23 to 52.92 wt% (Table 1). They are medium-K to high-K calc-alkaline and have high concentrations of mafic constituents (FeO, MgO and CaO) and high Mg# (60–63). For the trace elements, the basalts are enriched in highly incompatible elements and depleted in high field strength elements relative to the incompatible elements (Table 1 and Figs. 5 and 6). Compared with the Zhantang andesites, they are remarkably higher in V, Cr, Co, Ni, Y, and HREE, whereas Rb, Ba, Sr, LREE, Zr, Hf, Nb, Ta, and U are generally comparable to or lower than those of the andesites.

Fig. 5. Chondrite normalized REE patterns for the Zhantang andesites and basalts. The REE patterns for the Mesozoic felsic rocks in the coastal area of SE China are shown for comparison. Chondrite normalizing values from Sun and McDonough (1989).

Fig. 6. Primitive mantle normalized spidergram for the Zhantang andesites and basalts. Primitive mantle normalizing values from Sun and McDonough (1989).

The basalts are associated temporally and spatially with the Zhantang andesites, but they are not the parental magmas of the latter, that is, the andesitic magmas were impossibly produced by fractional crystallization of the basaltic magmas. Two lines of evidence preclude this possibility. First, the extremely high Na_2O contents of the andesites require the basaltic parental magma to fractionate effectively Ca-rich plagioclase, which would significantly deplete the Al_2O_3 and Sr contents of the residual melt. This is inconsistent with the generally higher contents of these two com-

Table 2. Compositional comparisons of Zhantang andesites with average adakite/TTG, arc ADR suites and experimental melts

	Cenozoic adakite	Archaean high Al-TTG	Continental arc ADR	Island arc ADR	Zhantang andesites (n = 12)	R ₁ (1.2–3.2 GPa) (n = 13)	R _{2–4} SW (1.0–3.2GPa) (n = 59)	WW (1.0 GPa) (n = 14)
SiO ₂	63.89	70.2	63.87	67.72	61.70	63.85	66.55	62.29
TiO ₂	0.61	0.33	0.68	0.49	0.84	1.22	0.95	0.38
Al ₂ O ₃	17.4	15.74	17.02	15.44	17.31	18.03	16.59	20.40
FeO	4.21	2.56	4.34	4.43	5.84	4.13	4.25	4.72
MnO	0.08	0.04	0.11	0.11	0.06	0.08	0.07	0.06
MgO	2.47	1.09	2.22	1.48	0.82	1.11	1.09	2.11
CaO	5.23	3.17	4.8	3.98	1.05	2.37	3.79	8.18
Na ₂ O	4.4	4.87	4.38	3.29	7.37	6.96	5.16	1.56
K ₂ O	1.52	1.88	2.37	2.95	2.69	2.11	1.51	0.33
P ₂ O ₅	0.19	0.12	0.21	0.11	0.36			
Sr	869	495	424	229	690	927*		
Ba	485	746	501	514	945	1002		
Rb	30	50	83	109	56	63		
Cs	1.19	1.73	9.45	0.76	4.01	3.3		
U	0.99	1.03	3.61	0.67	1.26	0.48		
Th	3.52	5.98	13.2	4.96	3.23	0.58		
Y	9.5	6.8	27.4	28.5	7.7	6		
Zr	117	149	190	133	157	272		
Hf	3.5	3.4	5.5	2.6	4.44	7.0		
Nb	8.3	5.4	15	15.8	7.6	5.4		
Ta	0.53	0.55	1.17	0.49	0.34			
Sc	9.1	4	12.1	10.9	11.5	8.5		
V	72	38	84	71	89			
Cr	54	36	29	21	11			
Co	13	15	12	19	11			
Ni	39	19	19	9	10			
La	17.55	29.84	29.94	32.01	27.26	36.3		
Ce	34.65	51.63	60.15	55.27	57.11	32.5		
Nd	20.14	19.92	28.27	17.85	28.82	18.7		
Sm	3.15	2.79	5.28	6.4	4.63	4.51		
Eu	0.97	0.91	1.18	3.6	1.21			
Gd	2.25	2.04	4.26	6.99	2.98	3.14		
Tb	0.37	0.25	0.72	0.76	0.35			
Dy	1.43	1.16	3.57	6.88	1.59	1.74		
Er	0.76	0.59	2.2	5.03	0.75	1.10		
Yb	0.91	0.46	2.44	4.26	0.64	1.1		
Lu	0.15	0.09	0.39	0.47	0.08	0.15		
Mg#	48	41	41	34	20	32	33	44
ASI	0.96	1	0.92	1	1.03	1.01	0.97	1.14
Na ₂ O+K ₂ O	5.92	6.75	6.75	6.24	9.96	9.07	6.67	1.89
Na/K	3.08	3.08	2.15	1.73	4.15	5.47	7.07	7.08
Sr/Y	91	73	15	8	89	155		

FeO, Mg# and ASI as in Table 1; *Trace element data for R₁ from Rapp et al. (1999) at 3.8 GPa; Average Cenozoic adakite, Archean high-Al TTG, continental arc ADR and island arc ADR from Drummond et al. (1996); R₁, R_{2–4}SW and WW are, respectively, the average compositions of partial melts of the alkali-rich basalt, basalts compositionally close to average N-MORB, and the low-K and Na, high-Mg and Ca basaltic amphibolite. For sources of data, see text.

Table 3. Nd and Sr isotopic compositions of Zhantang andesites and basalts

Sample	Andesites						Basalts	
	J3-1	J3-2	J3-4	J3-11	J3-18	J4-3	J5-1	J6-2
Sm (ppm)	5.112	5.540	4.151	4.619	4.310	5.476	5.421	5.681
Nd (ppm)	32.36	35.98	24.68	29.23	26.62	35.19	27.04	29.16
$^{147}\text{Sm}/^{144}\text{Nd}$	0.09555	0.09313	0.1017	0.09559	0.09793	0.09413	0.1172	0.1178
$^{143}\text{Nd}/^{144}\text{Nd}$	0.512437	0.512408	0.512390	0.512466	0.512436	0.512430	0.512566	0.512571
$(\pm 2\sigma)^*$	0.000010	0.000009	0.000008	0.000011	0.000009	0.000010	0.000009	0.000011
$(^{143}\text{Nd}/^{144}\text{Nd})_i$	0.512384	0.512356	0.512333	0.512313	0.512382	0.512378	0.512501	0.512505
$\epsilon\text{Nd}(T)$	-2.82	-3.36	-3.81	-2.26	-2.87	-2.95	-0.54	-0.45
Rb (ppm)	39.00	43.65	50.43	66.67	54.14	118.80	46.60	42.56
Sr (ppm)	870.70	807.50	530.50	1072.00	450.90	592.90	681.80	695.10
$^{87}\text{Rb}/^{86}\text{Sr}$	0.1293	0.1561	0.2744	0.1797	0.3467	0.5786	0.1973	0.1768
$^{87}\text{Sr}/^{86}\text{Sr}$	0.708136	0.708432	0.708283	0.708050	0.707500	0.708907	0.707100	0.706989
$(\pm 2\sigma)^*$	0.000019	0.000020	0.000016	0.000020	0.000020	0.000020	0.000020	0.000020
$(^{87}\text{Sr}/^{86}\text{Sr})_i$	0.70798	0.708243	0.707952	0.707833	0.707081	0.708208	0.706862	0.706775

*Errors quoted for $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ are 2 sigma standard deviation. The initial Sr and Nd isotopic ratios and $\epsilon\text{Nd}(T)$ value are calculated using $T = 85$ Ma as the approximate formation age.

ponents in the andesites than in the basalts (Table 1). Second, although the low Mg, Cr, Co, and Ni contents of the andesites may be explained by removal of olivine and pyroxene from parental magmas, their low Y and HREE contents require fractionation of amphibole that is enriched these elements. However, there is no amphibole present in the basalts, which contradicts the fractionation of amphibole.

Sr and Nd isotopic compositions and magmatic source of the andesites and basalts

The Rb-Sr and Sm-Nd isotopic compositions for eight representative samples of the Zhantang andesites and basalts are listed in Table 3. The initial isotopic ratios were calculated based on the approximate emplacement age of 85 Ma. The andesite samples exhibit small ranges of initial Sr and Nd isotopic ratios, with $(^{87}\text{Sr}/^{86}\text{Sr})_i$ from 0.7071 to 0.7082 and $\epsilon\text{Nd}(T)$ from -2.3 to -3.8. Two basalt samples have almost identical isotopic ratios, with $(^{87}\text{Sr}/^{86}\text{Sr})_i$ and $\epsilon\text{Nd}(T)$ approximately at 0.7068 and -0.5, respectively. These data show that the andesites are higher in $(^{87}\text{Sr}/^{86}\text{Sr})_i$ but lower in $\epsilon\text{Nd}(T)$ than the basalts, which suggest that either both the rocks involved different sources or the former underwent higher degree of crustal contamination.

Figure 7 shows the Sr and Nd isotopic ratios of the Zhantang andesites and basalts and the Precambrian basement of SE China. It is clear that the Zhantang andesitic magmas were not derived from the Precambrian basement. Also these magmas, with the negative $\epsilon\text{Nd}(T)$ and relatively high $(^{87}\text{Sr}/^{86}\text{Sr})_i$, cannot be explained as mixing products of a mantle magma and the pre-Cretaceous continental crust components because of their special composition feature and the small variations in Sr and Nd isotopic ratios. As mentioned above, the andesites have extremely high Na_2O contents (up to 8.46%) and low Y and HREE contents (as low as 6 ppm for Y and 0.58 ppm for Yb, respectively). Most mantle-derived magmas and crustal rocks, however, have relatively low Na_2O and high Y and HREE contents. No mixing model therefore can account for the compositional characteristics of the andesites: one end-member in such a model would require higher Na_2O and lower Y and HREE (a nearly unlikely case) than the andesites. The small variations in Sr and Nd isotopic compositions (Table 3) also suggest that there is little, if any, involvement of wall-rock components during ascent and crystallization of the andesitic magmas. An enriched mantle source can explain the Sr and Nd isotopic compositions of the Zhantang andesites and basalts, as indicated by the nega-

Fig. 7. Plot of $(^{143}\text{Nd}/^{144}\text{Nd})_i$ vs. $(^{87}\text{Sr}/^{86}\text{Sr})_i$ for the Zhantang andesites and basalts. The fields of the Precambrian basement of SE China and some adakites with MORB-like isotopic composition are also shown. This plot shows that of Zhantang andesites are distinctive in Sr and Nd isotopic compositions from adakites.

tive $\epsilon\text{Nd}(T)$ and relatively high $(^{87}\text{Sr}/^{86}\text{Sr})_i$ for many Mesozoic basalts in SE China (e.g., Xie *et al.*, 2001). However, the Zhantang andesitic magmas were impossibly derived directly from the mantle in terms of their low MgO, Cr, Co, and Ni contents.

DISCUSSION

Compositional comparison of the Zhantang andesites and adakites

According to Defant and Drummond (1990) and Drummond *et al.*, (1996), the distinctive geochemical characteristics of adakite include $\text{SiO}_2 > 56\%$, high Sr (>400 ppm), $\text{Al}_2\text{O}_3 (>15\%)$ and $\text{Na}_2\text{O} (>3.5\%)$, low Y (<18 ppm) and HREE ($\text{Yb} < 1.8$ ppm), high Sr/Y (>20 – 40) and La/Yb (>20), small or negligible Eu anomaly. The Zhantang andesites show many of these characteristics, particularly in the trace element contents and the Sr/Y and La/Yb ratios. However, the Zhantang andesites are different from adakite in some major element contents. Available compositional data (from 11 Cenozoic adakite localities) show that the Na_2O contents of all the suggested adakites are lower than 5.8% (Fig. 8) with an average of 4.4% (Table 2), except one sam-

ple from Mindanao, Philippines containing 7.36% Na_2O (Sajona *et al.*, 1993). The Na_2O contents (6.59–8.46%) of the Zhantang andesites are significantly higher than those of adakites, and the K_2O contents are also generally higher, whereas the CaO contents are clearly lower and the MgO contents are also lower at a given silica content (Fig. 8). These major element differences or the atypical adakite features imply that the Zhantang andesites may be different from typical adakites in source composition and/or petrogenesis.

Compositional comparison of the Zhantang andesites and experimental partial melts of basalt: Effect of protolith composition on partial-melt composition

The diagnostic trace-element characteristics for adakitic rocks are the high Sr/Y and La/Yb ratios and the depletion of Y and HREE. Garnet enriched in Y and HREE is, therefore, a necessary residual phase during melting of basalt, while plagioclase enriched in Sr is minor or absent in the residue (Rapp and Watson, 1995). Partial melting of hydrated basaltic rocks at low pressures (≤ 8 kbar; Beard and Lofgren, 1991; Rushmer, 1991) do not produce liquids in equilibrium with garnet, whereas garnet + clinopyroxene $\pm$

Fig. 8. Compositional comparison of Zhantang andesites with adakite. The data for adakite are from the following localities: Aleutian Arc, Alaska (Kay, 1978; Yagodžinski *et al.*, 1995); Cook Island, Chile (Puig *et al.*, 1984); Baja of California, Mexico (Rogers *et al.*, 1985; Aguillón-Robles *et al.*, 2001); Sierra Madre, Mexico (Cameron and Cameron, 1985); Skagway, Alaska (Barker *et al.*, 1986); El Valle and La Yeguada Volcanoes, Panama (Defant *et al.*, 1991); Cerro Pampa, Argentina (Kay *et al.*, 1993); Mindanao, Philippines (Sajona *et al.*, 1993); Southwest Japan (Morris, 1995); Austral Andes (Stern and Killian, 1996); Quimsacocha, Ecuador (Beate *et al.*, 2001).

Fig. 9. Compositional comparison of Zhantang andesites with high pressure (≥ 10 kbar) partial melts of basalts. The adakite field is also shown for comparison.

Table 4. Compositional data on experimental starting materials and average N-MORB

	R ₁	R ₂₋₄ SW					WW	N-MORB
		R ₂	R ₃	R ₄	S	W		
SiO ₂	51.19	48.60	48.30	47.60	46.88	49.10	48.50	50.45
TiO ₂	1.18	2.06	0.72	1.19	1.22	1.30	0.40	1.62
Al ₂ O ₃	16.62	17.03	15.30	14.18	15.00	14.80	14.40	15.26
FeO	11.32	10.69	10.70	13.77	8.70	14.20	8.50	10.43
MnO	0.23	0.21	0.19	0.19	0.26	0.20	0.20	—
MgO	6.59	6.07	8.40	6.86	8.25	6.50	10.80	7.58
CaO	5.49	9.66	12.60	10.99	11.28	11.40	14.40	11.30
Na ₂ O	4.33	3.30	2.27	2.56	2.51	2.30	1.70	2.68
K ₂ O	0.82	0.21	0.08	0.19	0.80	0.30	0.20	0.11
Na ₂ +K ₂ O	5.15	3.51	2.35	2.75	3.31	2.60	1.90	2.79
Na/Ca	0.71	0.29	0.16	0.21	0.20	0.18	0.13	0.21
NK/FMC	0.38	0.22	0.13	0.15	0.19	0.14	0.06	0.17

R₁, R₂, R₃ and R₄ from Rapp and Watson (1995), corresponding to No. 1 (alkali-rich basalt), No. 2 (high-Al basalt), No. 3 (low-K olivine tholeiite) and No. 4 (low-K Archaean greenstone), respectively, in the Table 1 of Rapp and Watson (1995); S: basaltic amphibolite from Sen and Dunn (1994); W: synthesized tholeiite from Winther (1996); WW: low-Na and K, high-Mg and Ca amphibolite from Wolf and Wyllie (1994); N-MORB: average N-MORB from Hofmann (1988); NK/FMC = (mol Na + K)/(mol Fe²⁺ + Mg + Ca).

amphibole ± plagioclase as residual phases are generally present in melting experiments at pressures of ≥10 kbar and temperatures of 850–1150°C (Rapp *et al.*, 1991; Winther and Newton, 1991; Sen and Dunn, 1994; Wolf and Wyllie, 1994; Rapp, 1995; Rapp and Watson, 1995; Winther, 1996). Rapp *et al.* (1999) pointed out that adakitic liquids are produced by melting of hydrated basalt at 10–40 kbar. Wyllie and Wolf (1993) suggested that garnet-in reactions occur at pressures slightly less than 10 kbar, depending on the bulk composition of basalt.

Based on the pressure constraint for the generation of adakitic liquids, compositional data on partial melts of basalt for comparison were selected from the experiments with pressures ≥10 kbar. Those experimental glasses that contain <56% SiO₂, are unlike natural adakite compositions and are not considered here. The selected data are then divided into three groups based on the compositional difference of their starting materials. The first group (13 samples, named as R₁, compositional range in Fig. 9, average composition in Table 2) corresponds to the data of Rapp *et*

al. (1991, 1999), Rapp (1995), Rapp and Watson (1995) at 12–38 kbar. Its starting material is an alkali-rich basalt (Table 4), having relatively high total alkalis (Na₂O + K₂O) and Na/Ca and low calcemic constituents (CaO, FeO, MgO, MnO, and TiO₂). The second group (59 samples, named as R₂₋₄SW, see Fig. 9 and Table 2) includes the data from Rapp and Watson (1995) at 16–32 kbar, Sen and Dunn (1994) at 15 and 20 kbar, and Winther (1996) at 10–30 kbar. Their starting materials R₂, R₃ and R₄ (Rapp and Watson, 1995), S (Sen and Dunn, 1994), and W (Winther, 1996) (see Table 4) are compositionally close to the average N-MORB (Hofmann, 1988), except that the R₂ has slightly higher Na₂O content and the S has higher K₂O content than the average N-MORB. The third group (14 samples, named as WW) is the data of Wolf and Wyllie (1994) at 10 kbar. Its starting material is a low-K and Na, high-Mg and Ca amphibolite.

The experimental data show that protolith (starting material) composition exerts significant effect on partial melt composition, and that the three-group partial melts are compositionally dif-

ferent from each other, particularly in the Al_2O_3 , CaO and Na_2O (Fig. 9). The partial melt WW is highest in Al_2O_3 and CaO but lowest in Na_2O , whereas the partial melt R_1 has highest Na_2O content (up to 8.9%) but lowest CaO content (<4.5%). The partial melt R_{2-4}SW generally overlaps the adakite field except that the latter is significantly higher in MgO at a given SiO_2 content (Fig. 9). This is consistent with the fact that MORB is the protolith of adakites. The high MgO content of adakite relative to the experimentally produced equivalent has been interpreted as a consequence of interaction of adakite melt with mantle wedge during magma ascent (e.g., Rapp *et al.*, 1999; Xu *et al.*, 2000, 2002).

In comparison, the Na_2O , CaO and MgO contents of the Zhantang andesites do not fall in the R_{2-4}SW field (Fig. 9), suggesting the Zhantang andesites were not derived from a N-MORB protolith. The Zhantang andesites are compositionally rather similar to the partial melt R_1 . Their Na_2O , K_2O , Al_2O_3 , and FeO contents fall generally in the R_1 melt field, only the CaO and MgO contents of some samples are slightly lower than those of this melt at a given silica content. Therefore, the Zhantang andesitic magmas suggest to be produced by partial melting of alkali-rich basaltic protolith, and they may represent an extremely high-Na example of adakite-like magmas produced by partial melting of such a basaltic protolith.

Petrogenetic model for the Zhantang adakite-like andesitic magmas

Three petrogenetic models have been proposed for the generation of adakitic magmas: (1) partial melting of subducting slab (e.g., Defant and Drummond, 1990), (2) partial melting of basaltic lower crust (e.g., Atherton and Petford 1993), and (3) fractionation and contamination of mantle-derived magmas with garnet-bearing lower continental crust (e.g., Feeley and Hacker, 1995).

Fractionation and contamination of mantle-derived magmas with garnet-bearing lower crust was proposed to interpret petrogenesis of the adakite-like rocks in Volcan Ollague, Andean Cen-

tral Volcanic Zone (Feeley and Hacker, 1995). Garnet as a separated phase rapidly depletes a magma in Y and HREE with little effect on the Sr and LREE contents, and results in high Sr/Y and La/Yb ratios in the residual magma. This model is therefore easy to reconcile the low Y and HREE contents and high Sr/Y and La/Yb ratios of the Zhantang andesitic magmas, but still difficult to account for the other features of the magmas. As mentioned above, the extremely high Na content of the andesites would require an extremely high degree of fractional crystallization, but their high Sr content and negligible Eu anomaly are not consistent with an origin related to plagioclase fractionation. Furthermore, the low Rb/Sr (mostly <0.10), high Na/K (up to 6.0) (Table 1) also suggest that little fractional crystallization was involved. The small variations in Sr and Nd isotopic compositions (Table 3) do not support likewise significant contamination of crustal component. Thus Zhantang andesitic magmas were not produced by fractionation and contamination of mantle-derived magmas with garnet-bearing lower crust.

We suggest that slab melting also was not involved in producing the Zhantang adakite-like magmas, mainly considering that these magmas were not associated spatially and temporally with subduction. The Cretaceous volcanic arc in SE China developed predominantly in the coastal area, whereas the Huichang Basin, the host of the Zhantang andesites, lies inboard of the Cretaceous arc magmatism site (Fig. 1). Furthermore, the subduction of paleo-Pacific plate underneath SE China is believed to have disappeared by the end (about 100 Ma) of Early Cretaceous (Qiu *et al.*, 1999; Zhou and Li, 2000), while the host rocks of the Zhantang andesites are the Late Cretaceous sandstones, which suggests the eruption of the Zhantang magmas lagged behind the subduction. In addition, the Zhantang andesites are different in Na_2O and CaO contents from slab-derived adakites (Fig. 8), and their Sr and Nd isotopic ratios are also significantly distinguished from those of typical adakites (Fig. 7). The geological setting together with these chemical and isotopic data

suggest that subducting slab was not involved in producing the Zhantang andesitic magmas.

Partial melting of underplated basaltic lower crust may be a more appropriate model for the generation of the Zhantang andesitic magmas. Atherton and Petford (1993) have pointed out that Na-rich magmas similar to adakite can also be produced by partial melting of newly underplated basaltic rocks beneath a thickened continental crust. The geochemical features of leucogranites and tonalities from the Cordillera Blanca fits the criteria established for adakite. However, the 60 Ma of age for the subducting slab and the location of these rocks, 300 km inboard of the present trench, suggest that the subducting oceanic crust was too old and cold to melt. Consequently, Atherton and Petford (1993) and Petford and Atherton (1996) suggested that these rocks were produced by melting of basaltic lower crust. Adakite-like rocks from the South Island, New Zealand (Muir *et al.*, 1995), the Klamath Mountains of California and Oregon (Barnes *et al.*, 1996), the Antarctic Peninsula (Wareham *et al.*, 1997), and the eastern China (Zhang, Q. *et al.*, 2001) were subsequently interpreted as the products of partial melting of mafic lower crust, formed in response to crustal thickening achieved through underplating of mantle-derived mafic magmas. The Zhantang adakite-like andesites are also considered as the products of partial melting of mafic lower crust, though they require a compositionally peculiar basaltic protolith.

Generation of the Zhantang andesitic magmas

Pressure, temperature, and H_2O activity of the basaltic source are crucial in understanding the generation of adakitic magmas. Though fluid-present melting of ocean crust in subduction zones is possible (Prouteau *et al.*, 1999), partial melting of basaltic rock in the Zhantang case is considered to occur in fluid-absent conditions, as interstitial pore fluid is unlikely to be present in the lower crust (Prouteau *et al.*, 1999). Recent numerical models suggested that the appropriate pressure-temperature conditions for the generation of adakitic magmas *via* fluid-absent melting of mafic

lower crust can be achieved (Petford and Gallagher, 2001): when a mantle-derived magma intrudes lower crust, the average temperature of the country rock on the top of the magma sill generally exceeds 900°C with maximum temperatures in excess of 1000°C in the pressure range of lower crust. Thus the crystallizing basaltic magmas underplated in lower crust may provide sufficient heat to increase geothermal gradient and to cause melting of surrounding amphiboles that have solidus lower than 800°C (e.g., Rapp and Watson, 1995).

The Eastern Nanling Range has a crustal thickness over 36 km (≥ 11 kbar of lithostatic pressure, Fig. 3a), and is one of the most conspicuous sites for the Late Mesozoic basaltic underplating in SE China, as indicated by the relatively low T_{DM} (Nd model age) of many Late Mesozoic granitoids in this region (Fig. 3b). Production of mantle-derived magmas and underplating were related to decompression and asthenospheric upwelling during extension and rifting of lithosphere in the Late Mesozoic (Li, 2000). The magma-underplating thickened the crust in this area and caused rise in temperature at the base of the crust to achieve the *P-T* conditions for generating adakitic magmas. Melting of a basaltic amphibolite in the lower crust might have taken place in response to underplating and magmatically thickening of the crust to produce the Zhantang adakitic magmas, leaving residues of garnet, clinopyroxene, amphibole and little or no plagioclase. We have demonstrated that the generation of the extremely high-Na Zhantang andesitic magmas require a Na- and alkali-rich basaltic protolith. Mafic magmas that underplate continental lower crust are likely to be equivalents of basaltic lavas or dykes. There are many Late Mesozoic mafic rocks in the Eastern Nanling Range, including calc-alkaline, alkaline, and shoshonitic lavas or dykes (Li and McCulloch, 1998; Chen *et al.*, 1999; Zhang, B. T. *et al.*, 2001). It is possible that underplated alkali-rich basaltic amphiboles are present in the lower crust of this region, and they may be the source rock of the Zhantang andesites.

CONCLUSIONS

The Late Cretaceous Zhantang andesites are extremely high-Na, and high-Al trondhjemitic rocks, with high concentrations of Sr and Ba, low concentrations of Y and HREE, and high Sr/Y and La/Yb ratios, similar to modern adakite. Petrogenetic models for adakitic rocks can be applied to account for the generation of these magmas.

The lack of subduction during the Late Cretaceous, the difference of Na₂O and CaO contents from modern adakites and their significant distinction in Sr and Nd isotopic compositions from MORB suggest that subducting slab was not involved in producing these magmas.

The high Sr content, negligible Eu anomaly, low Rb/Sr and K/Na ratios and small variations in Sr and Nd isotopic compositions indicate that they were also not produced by fractionation and contamination of mantle-derived magmas with garnet-bearing lower crust.

Partial melting of underplated basaltic lower crust is a plausible generation model for the Zhantang adakite-like andesites, though a compositionally peculiar protolith is required to account for their extremely high-Na and low-Ca feature. The Zhantang andesites are compositionally comparable to the experimentally produced partial melts of the alkaline-rich basalt (Rapp and Watson, 1995). The source is, therefore, most likely similar to that of the alkaline-rich basalt.

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