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Cretaceous high-potassium intrusive rocks in the Yueshan-Hongzhen area of east China: Adakites in an extensional tectonic regime within a continent

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Adakites are generally associated with subduction zones (i.e., at convergent plate margins). This paper reports geochemical and isotopic data for early Cretaceous high-potassium adakitic intrusive rocks in the Yueshan-Hongzhen area of east China, which occur in an extensional tectonic regime within a continent. Based on petrology and geochemistry, these adakitic intrusive rocks are classified into two groups. One group (the Hongzhen adakitic granites) is characterized by high SiO_2 (69–75%) contents and K_2O/Na_2O (>1.0), low MgO (or $Mg^{\#}$) values, Ni and V concentrations, low $\varepsilon_{Nd}(t)$ (−17.01~−18.13), and high $(^{87}Sr/^{86}Sr)_i$ (0.7071~0.7072). The other group (the Yueshan and Zongpu adakitic rocks) is characterized by relatively low SiO_2 (58–67%) contents and K_2O/Na_2O (<1.0), high MgO ($Mg^{\#}$) values, Ni and V concentrations, as well as relatively high $\varepsilon_{Nd}(t)$ (−6.63~−9.62) and low $(^{87}Sr/^{86}Sr)_i$ (0.7064~0.7069). Both groups are associated with the contemporary Dongling metamorphic core complex, A-type granites, and some per-alkaline igneous rocks that are formed only in an extensional setting. The tectonic setting and chemical compositions suggest that: (1) the adakitic intrusive rocks in the Yueshan-Hongzhen area were formed in an extensional tectonic regime within a continental plate; (2) the Hongzhen adakitic granites were most likely derived directly from partial melting of mafic material with high potassium contents at the base of the continental crust at pressures of ~1.2 GPa, leaving residual garnet ± hornblende ± plagioclase in the source; (3) the Yueshan and Zongpu adakitic rocks were most probably derived from dehydration melting of basaltic materials delaminated into underlying mantle at pressures >1.2 GPa, leaving residual garnet + pyroxene in their sources. Both groups of adakitic rocks have high La/Yb and Sr/Y, indicating that the crustal thickness in the Yueshan-Hongzhen area exceeded 40 km when the adakitic magmas were generated in the early Cretaceous. The present thickness of the crust in the Yueshan-Hongzhen area is only ~31 km, and therefore the crust appears to have been thinned by at least ~10 km since the early Cretaceous. The relatively high MgO, Ni, and V values of the Yueshan and Zongpu adakitic rocks suggest that adakitic magmas interacted with mantle rocks, possibly concurrently with delamination of the lower crust.

Keywords: adakite, delamination, lower crust, high potassium, east China

INTRODUCTION

In the past decade, Cenozoic adakites (i.e., andesitic and dacitic magmas characterized by low abundances of Y and heavy rare earth elements (HREE), and high Sr/Y and La/Yb) have been documented as possible examples of slab melting in subduction zones (Defant and Drummond, 1990, 1993; Kay *et al.*, 1993; Morris, 1995; Drummond *et al.*, 1996; Kepezhinskas *et al.*, 1996; Stern and Kilian, 1996; Martin, 1999; Gutscher *et al.*, 2000; Sajona *et al.*, 2000; Xu, J. F. *et al.*, 2000; Aguillón-Robles *et al.*, 2001; Yogodzinski *et al.*, 2001, and references therein). These adakites have also been considered to be modern analogues of Archean high-Al trondhjemites, tonalites and granodiorites (TTG) due to their geochemical similarity (Defant and Drummond, 1990; Drummond and Defant, 1990; Martin, 1999). However, some rocks with adakitic compositional features have been argued to be alternative origins, e.g., partial melting of mafic lower crust (Atherton and Petford, 1993; Muir *et al.*, 1995; Petford and Atherton, 1996; Johnson *et al.*, 1997), assimilation and fractional crystallization (AFC) processes involving basaltic magmas (Feeley and Hacker, 1995; Wareham *et al.*, 1997; Castillo *et al.*, 1999). Experimental studies (e.g., Rapp *et al.*, 1991, 1999; Sen and Dunn, 1994; Rapp, 1995; Rapp and Waston, 1995; Springer and Seck, 1997) have shown that mafic materials can melt to produce adakites at pressures equivalent to crustal depths in excess of 40 km (i.e., ~1.2 GPa), providing the source contains residual garnet. Nevertheless, most reported adakites and adakitic rocks occur in arc settings or convergent plate margins. In such settings, subduction of oceanic crust or arc basalt underplating can cause the crust be magmatically thickened, so an adakitic

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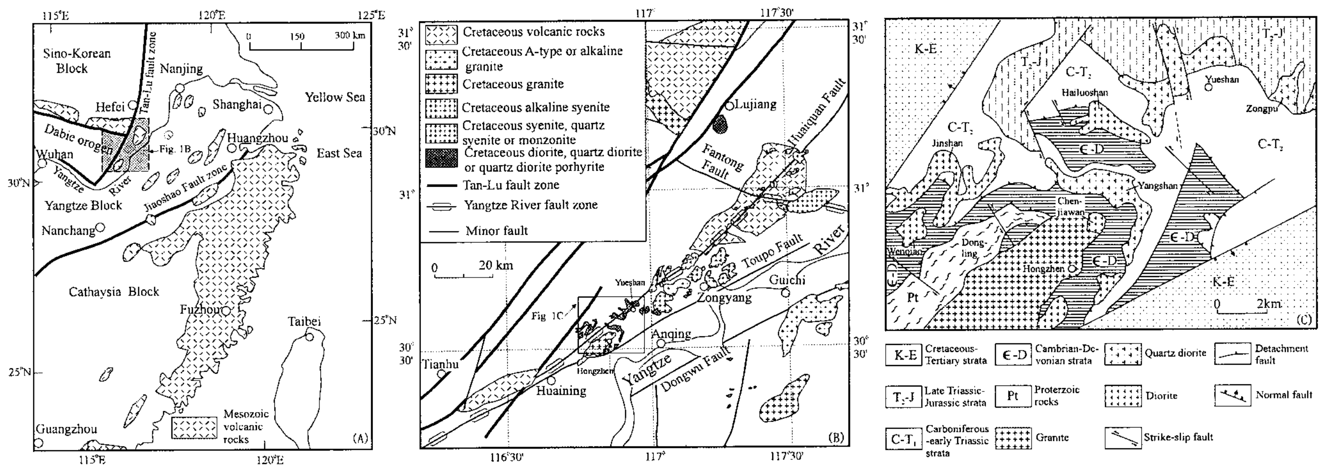

Fig. 1. Geological sketch map of the Yueshan-Hongzhen and adjacent areas. (A) Location of the Yueshan-Hongzhen and adjacent area in east China; (B) Geological sketch map of the Anqing-Lujiang and adjacent area, showing distribution of Cretaceous plutons, volcanic rocks and faults (or fault zones) in the area (after Tang et al., 1998); (C) Geological sketch map of the Yueshan-Hongzhen area, showing distribution of Cretaceous plutons associated with the Dongling metamorphic core complex (after Li, 1993; Tang et al., 1998).

magma may be derived either by partial melting of the slab or of thickened lower crust. Some adakitic rocks in the South America have been argued to originate from the thickened lower crust (Kay and Abbruzzi, 1996; Petford and Atherton, 1996; Monzier *et al.*, 1997; Arculus *et al.*, 1999; Garrison and Davidson, 2003). Therefore, it is still unclear how to distinguish adakitic rocks generated by lower crust melting from those produced by slab melting.

Xu *et al.* (2002) have recently documented adakitic rocks in the Ningzhen area of eastern China that are produced by partial melting of delaminated lower crust. In this paper, we present a detailed account of the petrology and geochemistry of Cretaceous adakitic intrusive rocks in the Yueshan-Hongzhen area of east China. Although these rocks have geochemical characteristics (e.g., low Y and HREE values, and high Sr/Y and La/Yb) similar to adakites, they were most likely formed in an extensional regime within a continent (rather than a subduction zone setting), because they are associated with contemporary extensional tectonics (metamorphic core complexes), A-type granites and peralkaline igneous rocks. In contrast with the Ningzhen adakitic examples, we conclude that only some of adakitic rocks in the Yueshan-Hongzhen area were derived from delaminated lower crust, but others come directly from a lower crustal source.

REGIONAL GEOLOGY

The Yueshan-Hongzhen area is situated to the west of Anqing city, southeast Anhui Province, east China (Figs. 1(A) and (B)). Tectonically, the Yueshan-Hongzhen area is located in the east of the Yangtze Block and to the east of the Dabieshan Orogen. The famous Tan-Lu deep fault zone passes through the west of the Yueshan-Hongzhen area (Figs. 1(A) and (B)). It may be noted that the Dongling metamorphic core complex is the most important tectonic component within the Yueshan-Hongzhen area (Li, 1993; Tang *et al.*, 1998); the core of this complex consists of Dongling metamorphic rocks of Proterozoic age (Xing *et al.*, 1993), and its limbs are mainly composed of Cambrian-Jurassic strata (Fig. 1(C)). Cretaceous-Tertiary fault basins occur on the west and east sides of the metamorphic core complex (Fig. 1(C)). On the basis of tectonic setting, sedimentary strata, and magmatism, it has been suggested that the Dongling metamorphic core complex possibly started uplifting from the Late Jurassic, and extension of the continental crust lasted until Late Cretaceous in the Yueshan-Hongzhen area (Li, 1993; Xing *et al.*, 1993; Tang *et al.*, 1998).

The plutons in the Yueshan-Hongzhen area are distributed along detachment faults between different layers (e.g., core and limbs) of the Dongling metamorphic core complex (Fig. 1(C)). These plutons were formed during the Cretaceous (136–122 Ma), and exposed as stocks, dikes, and sills with individual outcrop areas in the range of 55–0.5 km^2. Among these plutons, the smallest is the Chenjiawan Diorite Pluton (<1 km^2) and the biggest is the Hongzhen Granite Pluton (about 55 km^2). The Hongzhen pluton has been dated at 122 Ma (^{40}Ar-^{39}Ar plateau age of biotite, Zhou *et al.*, 1988). The Yueshan pluton with an irregular shape (approximately 11 km^2) has been dated at 136 Ma (^{40}Ar-^{39}Ar plateau age of hornblende, Chen *et al.*, 1991). The Yangshan and

Zongpu plutons have, respectively, been dated at 133 Ma (K-Ar age of biotite) and 132 Ma (K-Ar age of hornblende) (Qiu and Dong, 1993). In addition, near the Yueshan-Hongzhen area, Cretaceous-aged (133–90 Ma) A-type granites and peralkaline igneous rocks, e.g., riebeckite-aegirine granites, arfvedsonite-bearing syenites and pseudoleucite phonolites in the Lujiang-Zongyang area have been recognized (Zhang *et al.*, 1988; Xing and Xu, 1994; Tang *et al.*, 1998; Wang, 2000) (Fig. 1(B)). In summary, the Dongling metamorphic core complex, A-type granites, and peralkaline igneous rocks are collectively consistent with an extensional regime in the late Jurassic-Cretaceous, at the same time as the intrusive rocks in the Yueshan-Hongzhen area were emplaced.

Tectonic setting of the intrusive rocks

It is generally accepted that the Yueshan-Hongzhen region of east China has been a part of the present Eurasian continent, since the North China and South China continental blocks were accreted in the Triassic Period (Li *et al.*, 1993; Hacker *et al.*, 1998; Meng and Zhang, 1999). Extensive granitic and intermediate-felsic volcanic rocks of Cretaceous and Jurassic ages are exposed in this region (Fig. 1(A)). Although it has been proposed that igneous rocks in the southeast of China are related to possible westward subduction of the Mesozoic paleo-Pacific Plate (Lapierre *et al.*, 1997; Zhou and Li, 2000, and references therein), there is no well-documented evidence to support the hypothesis that south China was associated with a subduction zone at that time (Li, 2000). In contrast, other some studies have argued that igneous rocks in east China were produced in a non-arc setting during the Mesozoic (Xu *et al.*, 1987; Gilder *et al.*, 1996; Li, 2000, and references therein). Based on the close association of Cretaceous A-type granites, within-plate mafic rocks, and high-potassium calc-alkaline igneous rocks, a number of fault basins as well as other Cretaceous metamorphic core complexes in southeast China (e.g., north orthogneiss unit of the Dabie orogen (Hacker *et al.*, 1998; Ratschbacher *et al.*, 2000), Lushan (Lin *et al.*, 2000) and Wugongshan of Jiangxi province (Faure *et al.*, 1996), some researchers have suggested an "extensional tectonic regime within a continent" for southeast China during the Cretaceous (Gilder *et al.*, 1996; Li, 2000). We suggest that the Yueshan-Hongzhen intrusive rocks were also developed in this tectonic setting.

PETROGRAPHY

Five plutons in the Yueshan-Hongzhen area have been investigated in this study. These plutons mainly consist of diorite, quartz diorite, quartz monzodiorite, granodiorite and granite. The Hongzhen pluton is composed of granites with fine-medium granular texture, with a mineral assemblage comprising: plagioclase (20–35%), K-feldspar (25–40%), quartz (30–32%), biotite (3–8%), minor hornblende (<5%), and accessory minerals (<1%) including titanite, magnetite and apatite. The Yueshan pluton consists of quartz diorite, quartz monzodiorite and granodiorite. These rocks show medium-fine-grained or inequigranular in texture, and the mineralogy consists of plagioclase (50–75%), hornblende (8–20%), K-feldspar (3–15%), quartz (5–15%), biotite (1–2%) and minor pyroxene (<1.0%), and accessory minerals (<1%) including titanite, apatite and magnetite. The Zongpu pluton consists of quartz diorite and granodiorite with fine-medium-grained granular texture. Its mineral association is similar to the Yueshan intrusive rocks. The Yangshan pluton comprises only quartz diorites with medium-grained granular texture; it has a higher biotite (5–15%) and lower hornblende content (5–10%) than those of the Yueshan intrusive rocks. The Chenjiawan pluton is diorite with a medium-grained granular texture, and a mineral association comprising is plagioclase (40–45%), hornblende (50–55%), pyroxene (1–2%), biotite (1%), Kf-plagioclase (1%), quartz (1%) and accessory minerals (<1%) including titanite, apatite and magnetite.

ANALYTICAL METHODS

Fresh rock samples of the intrusive rocks in the Yueshan-Hongzhen area were collected for elemental and isotopic analysis. Major elements were determined by gravimetry and AAS (wet chemistry) (analytical procedure described in detail by Gao *et al.*, 1995). Trace elements, including the rare earth element (REE), were analyzed by a Perkin-Elmer ELAN 6000 inductively-coupled plasmu source mass spectrometer (ICP-MS) at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. The analytical procedure for the ICP-MS analysis is similar to that described by Li (1997). An international standard solution containing the single element Rh was used to monitor signal drift during counting. The international standard BCR-1 was chosen to calibrate element concentrations. Analytical precision for most elements is better than 5%. Sr and Nd isotopic compositions were determined using a Finnigan MAT-262 Mass Spectrometer operated in a static multi-collector mode at Institute of Geology and Geophysics, Chinese Academy of Sciences. The detailed analytical procedure is similar to that described by Li and McCulloch (1998). The $^{87}Sr/^{86}Sr$ ratio of the NBS987 standard and $^{143}Nd/^{144}Nd$ ratio of the La Jolla standard measured during this study were 0.710234 ± 7 ($2\sigma_m$) and 0.511838 ± 8 ($2\sigma_m$), respectively. Procedural blanks were <100 pg for Nd and <1 ng for Sr. The measured $^{143}Nd/^{144}Nd$ and $^{86}Sr/^{88}Sr$ for the standard ratios were normalized to 0.7219 and 0.1194, respectively.

Table 1. Major and trace elemental compositions of intrusive rocks from the Yueshan-Hongzhen area

	1	2	3	4	5	6	7	8	9	10	11
Rocks	High-Mg diorite		Quartz diorite		Adakitic granites				Adakitic rocks		
Plutons	Chenjiawan		Yangshan		Hongzhen				Yueshan		
Sample	aq-3	aq-3-2	aq-1	aq-2	aq-5	aq-5-2	aq-6	aq-6-2	00YS002	00YS003	00YS004
Major elements (%)											
SiO_2	54.22	54.23	60.26	59.80	70.11	69.85	70.37	70.03	61.40	61.91	60.09
TiO_2	0.81	0.80	1.02	1.04	0.33	0.32	0.31	0.33	0.64	0.59	0.59
Al_2O_3	15.16	15.41	18.01	18.11	14.66	14.78	14.60	14.78	15.63	15.65	15.89
Fe_2O_3	2.17	2.26	0.90	0.55	0.77	0.64	0.82	0.88	2.70	2.59	2.86
FeO	5.13	5.03	4.35	4.60	1.65	1.77	1.58	1.53	2.65	2.55	2.72
MnO	0.13	0.14	0.10	0.08	0.04	0.04	0.04	0.03	0.08	0.07	0.08
MgO	6.07	6.04	2.04	2.10	0.97	1.05	0.94	0.93	2.47	2.39	2.55
CaO	7.96	7.86	3.60	3.54	2.15	2.14	2.18	2.15	4.54	4.51	4.81
Na_2O	3.41	3.40	4.57	4.76	3.75	3.78	3.72	3.79	4.59	4.57	4.77
K_2O	2.38	2.40	3.43	3.61	4.05	4.05	3.92	3.99	3.53	3.47	2.93
P_2O_5	0.25	0.25	0.34	0.38	0.08	0.09	0.08	0.08	0.37	0.35	0.40
CO_2	0.07	0.02	0.09	0.14	0.09	0.22	0.24	0.20	0.89	0.72	1.19
H_2O	1.95	1.90	0.97	1.00	0.87	0.95	0.88	0.99	0.11	0.14	0.68
Σ	99.71	99.74	99.68	99.71	99.52	99.68	99.68	99.71	99.59	99.51	99.55
$Mg^{\#}$	60	60	41	42	42	44	42	42	46	47	46
Na_2O/K_2O	1.43	1.42	1.33	1.32	0.93	0.93	0.95	0.95	1.30	1.32	1.63
Trace elements (ppm)											
Sc	29.8	28.5	11.5	11.0	3.76	3.04	3.64	2.99	8.46	7.59	8.58
V	160	157	86.2	79.0	30.3	33.5	27.3	24.7	118	108	126
Cr	168	132	29.9	21.5	12.3	12.3	10.7	11.7	18.3	13.9	12.2
Co	26.1	25.5	10.1	10.4	4.89	6.62	4.37	7.30	14.4	12.1	14.6
Ni	74.7	68.8	14.8	12.2	8.31	7.73	7.76	7.50	10.9	11.7	9.5
Ga	17.8	18.0	23.5	22.4	16.7	16.9	16.4	16.8	23.2	19.8	21.2
Rb	54.4	54.8	112	122	99.1	94.2	97.6	87.2	74.9	63.5	56.6
Sr	818	820	527	569	454	458	433	421	1567	1305	1982
Y	24.3	21.6	35.4	34.3	9.62	8.57	10.2	8.79	15.7	15.4	14.1
Zr	70.6	95.0	198	218	126	131	101	137	55.0	68.9	66.9
Nb	13.0	12.0	22.5	21.9	9.24	8.87	9.63	5.99	10.0	8.43	8.75
Cs	0.20	0.20	2.24	2.75	0.98	0.97	1.06	1.07	0.52	0.61	1.40
Ba	610	618	1164	1273	1571	1618	1387	1405	1140	1161	798
Hf	2.44	2.84	4.72	5.18	3.68	3.82	3.04	3.84	2.36	2.40	2.80
Ta	0.57	0.55	1.12	1.05	0.86	0.89	0.93	0.60	0.54	0.48	0.54
Pb	8.24	6.79	18.2	11.2	22.4	21.2	22.7	21.2	12.3	12.2	12.6
Th	4.85	4.86	22.5	15.1	9.28	9.43	9.21	9.11	13.89	11.31	12.18
U	0.76	0.76	2.88	1.60	1.73	1.98	1.73	1.80	2.90	2.44	3.36
La	44.81	44.43	83.36	70.27	39.62	39.53	39.01	43.24	55.68	44.87	49.96
Ce	80.86	79.55	166.40	138.40	64.06	65.61	63.17	74.71	106.88	93.22	98.81
Pr	9.66	9.48	18.22	14.86	6.65	6.77	6.63	7.15	11.46	10.47	10.53
Nd	35.16	34.71	63.93	53.05	21.60	22.13	21.86	23.38	44.68	38.86	41.08
Sm	6.10	5.81	10.05	8.83	3.15	3.13	3.27	3.20	7.63	6.20	7.84
Eu	1.73	1.70	2.42	2.41	0.69	0.70	0.69	0.72	1.89	1.57	1.79
Gd	4.92	4.61	7.32	6.71	2.07	1.84	2.21	1.72	5.19	4.12	4.84
Tb	0.76	0.72	1.18	1.10	0.32	0.31	0.35	0.32	0.63	0.58	0.60
Dy	4.22	4.06	6.29	5.98	1.69	1.76	1.81	1.72	3.30	2.83	2.94
Ho	0.80	0.78	1.16	1.14	0.31	0.32	0.34	0.32	0.61	0.50	0.58
Er	2.17	2.16	3.13	3.06	0.87	0.88	0.91	0.89	1.74	1.38	1.48
Tm	0.32	0.31	0.45	0.45	0.13	0.13	0.13	0.13	0.23	0.20	0.21
Yb	2.13	2.00	2.86	2.82	0.84	0.84	0.85	0.88	1.38	1.29	1.32
Lu	0.34	0.33	0.44	0.44	0.14	0.14	0.14	0.13	0.21	0.20	0.18
Sr/Y	34	38	15	17	47	53	42	48	100	85	141
La/Yb	21	22	29	25	47	47	46	49	40	35	38
Eu/Eu*	0.96	1.00	0.86	0.96	0.83	0.90	0.79	0.94	0.92	0.95	0.89

Table 1. (continued)

	12	13	14	15	16	17	18	19	20	21	22
Rocks	Adakitic rocks										
Plutons	Yueshan								Zongpu		
Sample	00YS005	00YS006	00YS007	01yst-1	01yst-2	01yst-3	01yst-4	01yst-5	ZP-1	ZP-1-2	ZP-2
Major elements (%)											
SiO_2	60.56	60.60	60.76	61.42	60.67	62.80	61.04	60.22	60.20	59.84	63.95
TiO_2	0.63	0.65	0.67	0.70	0.64	0.60	0.63	0.65	0.66	0.65	0.49
Al_2O_3	15.88	15.88	15.90	16.06	16.49	15.71	16.09	16.00	15.95	16.00	16.51
Fe_2O_3	2.63	2.76	2.71	2.55	2.63	2.32	2.09	2.40	0.29	0.45	1.80
FeO	2.85	2.80	2.75	2.75	2.73	2.50	2.88	3.13	4.44	4.25	2.00
MnO	0.08	0.08	0.08	0.10	0.10	0.09	0.09	0.10	0.07	0.08	0.07
MgO	2.91	2.63	2.63	2.79	2.49	2.63	3.17	2.91	3.23	3.22	1.89
CaO	4.76	4.84	4.76	4.50	4.86	4.21	5.00	5.20	5.46	5.53	4.49
Na_2O	4.59	4.60	4.56	4.50	4.82	4.42	4.38	4.82	4.72	4.88	4.98
K_2O	3.24	3.44	3.48	3.29	3.04	3.19	2.90	2.92	2.74	2.78	2.19
P_2O_5	0.39	0.39	0.40	0.25	0.26	0.25	0.31	0.31	0.37	0.37	0.22
CO_2	0.93	0.85	0.77	0.05	0.07	0.07	0.07	0.12	0.52	0.50	0.14
H_2O	0.09	0.11	0.09	0.69	0.85	0.87	0.98	0.86	1.02	1.06	0.89
Σ	99.54	99.63	99.56	99.65	99.65	99.66	99.63	99.64	99.67	99.61	99.62
$Mg^\#$	50	47	47	50	47	51	54	50	55	55	48
Na_2O/K_2O	1.42	1.34	1.31	1.37	1.59	1.39	1.51	1.65	1.72	1.76	2.27
Trace elements (ppm)											
Sc	9.71	8.95	9.93	11.82	9.15	8.95	12.5	11.4	10.7	10.2	6.19
V	128	132	130	131	120	105	111	125	110	111	64.6
Cr	20.9	13.9	15.3	22.0	19.9	26.5	38.7	29.9	50.8	53.7	25.5
Co	15.7	14.2	13.7	14.8	13.6	13.4	15.5	15.3	18.0	18.1	9.13
Ni	13.9	10.8	12.6	15.1	10.8	15.3	24.0	17.8	29.0	27.2	11.9
Ga	21.8	21.9	21.2	21.3	21.3	19.8	19.9	21.1	20.4	20.2	19.6
Rb	75.2	69.2	72.9	76.8	69.5	65.3	60.8	62.3	47.5	47.5	38.4
Sr	1535	1547	1497	1533	1489	1507	1478	1664	1569	1572	1566
Y	13.8	14.3	15.6	13.4	13.1	13.6	13.7	12.8	13.9	12.6	11.2
Zr	92.8	58.7	66.7	130	114	81.2	143	128	151	108	124
Nb	8.76	9.88	9.52	7.91	6.94	7.13	6.05	6.97	7.34	6.98	7.30
Cs	2.33	0.61	0.68	1.37	0.77	1.26	0.91	1.01	0.51	0.52	0.27
Ba	1124	1185	1286	1266	1036	1109	1368	1164	1219	1245	1339
Hf	3.44	2.44	2.44	3.78	3.49	2.75	4.00	3.73	4.10	3.26	3.35
Ta	0.38	0.53	0.50	0.54	0.45	0.47	0.42	0.48	0.38	0.37	0.37
Pb	15.8	12.3	14.1	14.8	13.6	17.0	14.7	14.9	8.49	7.65	14.2
Th	12.5	13.1	11.2	12.2	7.82	9.92	8.77	10.8	9.29	8.27	5.06
U	3.19	2.98	2.45	2.50	2.26	2.34	2.08	2.75	2.07	1.96	1.69
La	51.86	56.50	54.15	47.50	39.54	41.18	40.48	47.10	45.56	47.58	28.49
Ce	101.79	108.68	101.80	88.58	73.52	81.98	78.52	90.52	87.16	90.64	56.68
Pr	10.78	11.84	12.08	10.91	9.10	10.56	9.90	11.27	10.49	10.85	7.03
Nd	42.69	44.62	44.77	38.60	32.10	37.56	35.38	39.54	38.86	40.45	26.12
Sm	6.93	7.37	6.96	6.28	5.39	6.24	5.75	6.29	6.01	6.11	4.23
Eu	1.92	1.97	1.74	1.61	1.50	1.54	1.45	1.59	1.53	1.56	1.12
Gd	4.99	5.28	4.55	4.00	3.57	4.03	3.96	3.97	3.86	3.33	2.73
Tb	0.57	0.63	0.61	0.55	0.49	0.56	0.52	0.52	0.53	0.49	0.39
Dy	3.11	3.07	3.00	2.58	2.38	2.67	2.62	2.45	2.56	2.59	1.98
Ho	0.57	0.57	0.52	0.45	0.43	0.46	0.46	0.43	0.46	0.46	0.36
Er	1.43	1.58	1.38	1.18	1.15	1.19	1.24	1.12	1.24	1.23	0.96
Tm	0.21	0.21	0.20	0.17	0.18	0.17	0.18	0.16	0.18	0.17	0.14
Yb	1.30	1.50	1.26	1.12	1.12	1.06	1.17	1.02	1.10	1.08	0.94
Lu	0.16	0.17	0.20	0.17	0.18	0.17	0.19	0.16	0.17	0.17	0.15
Sr/Y	111	108	96	114	113	110	108	130	113	125	140
La/Yb	40	38	43	42	35	39	34	46	41	44	30
Eu/Eu*	1.00	0.97	0.95	0.98	1.04	0.94	0.93	0.97	0.97	1.06	1.01

$Mg^\# = 100 \times Mg^{2+}/(Mg^{2+} + Fe_{total})$, $Eu^*/Eu = Eu_N/(Sm_N + Gd_N)^{1/2}$, adakitic rocks: adakitic quartz diorite-quartz monzodiorite-granodiorite.

RESULTS

Major and trace elements

Major and trace element analytical results of 22 fresh rock samples from the Yueshan-Hongzhen area are presented in Table 1. Compositional variations of major and trace elements are shown in Figs. 2 and 3, respectively. These samples are mostly high-potassium except for sev-

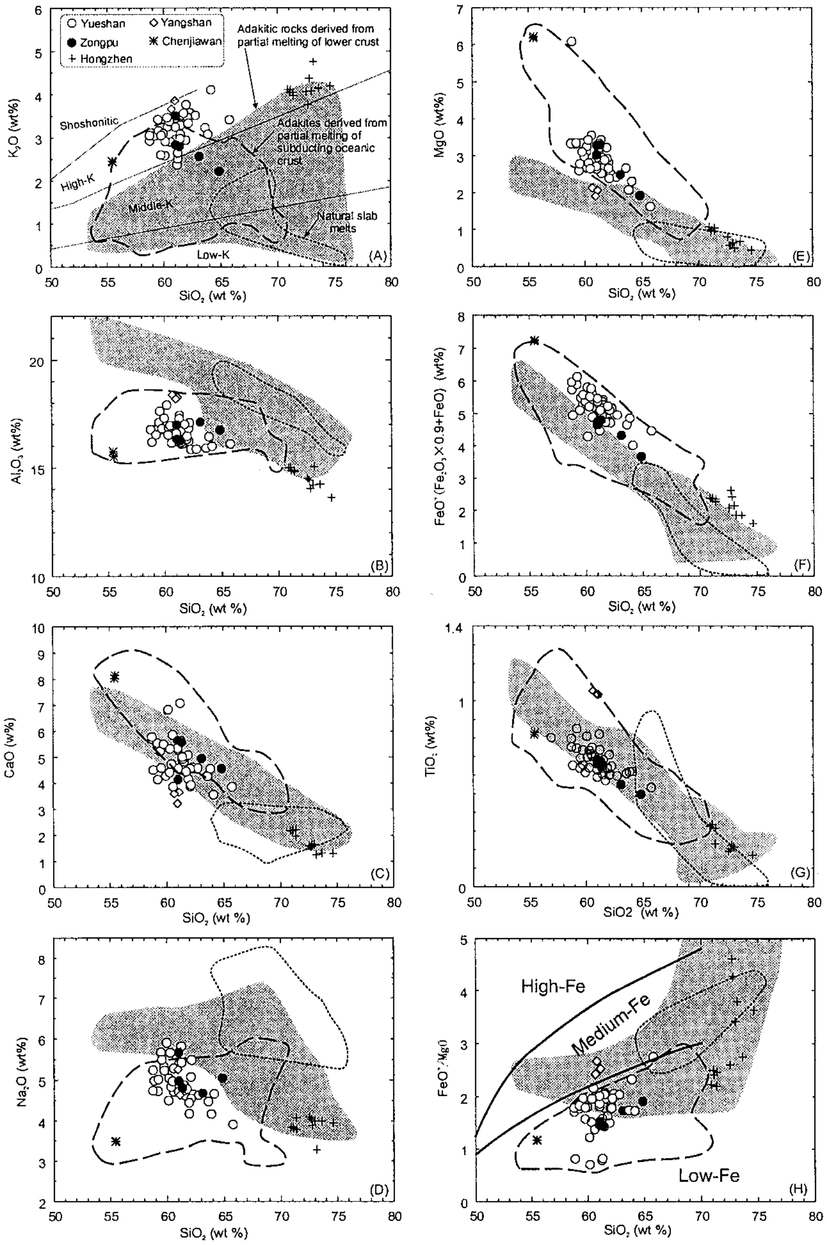

Fig. 2. Hacker diagrams showing the major element variations of the intrusive rocks in the Yueshan-Hongzhen area. Original K_2O vs. SiO_2 (wt%) classification diagram (A) is after Peccerillo and Taylor (1976) and original FeO^*/MgO vs. SiO_2 (wt%) (H) is after Arculus (2003). Some of the data from the Yueshan pluton are after Qiu (1992). Fields of adakites derived from slab melting (field circled by broad-brush dashed) is constructed using data from these sources: Defant and Drummond, 1990, 1993; Kay et al., 1993; Morris, 1995; Drummond et al., 1996; Stern and Kilian, 1996; Kepezhinskas et al., 1996; Martin, 1999; Sajona et al., 2000; Aguillón-Robles et al., 2001; Yogodzinski et al., 2001, and references therein; data for adakitic rocks derived from lower crust melting (gray shadow field) are from: Atherton and Petford, 1993; Muir et al., 1995; Petford and Atherton, 1996; Johnson et al., 1997; and natural (pure) slab melts that have not reacted with the mantle wedge (field circled by thin dashed) are from Kepezhinskas et al. (1995) and Sorensen and Grossman (1989).

eral samples from Yueshan and Zongpu plutons that are medium-potassium (Fig. 2(A)). There is a wide range in SiO_2 content in the samples from 54 to 75%, but there are two compositional gaps. One gap is between 55 and 58% SiO_2 that separates the most mafic Chenjianwan diorite from the intermediate-felsic rocks in the Yueshan, Yangshan, and Zongpu plutons. The other gap is between 67 and 70% SiO_2 and separates the intermediate-felsic rocks from the granites in Hongzhen pluton. Among five plutons, the Hongzhen granites are characterized by high SiO_2 (69–75%), Ba (1387–1618 ppm), low Al_2O_3 (13.6–15.0%), CaO (1.3–2.2%), TiO_2 (1.02–1.04%), MgO (0.44–1.05%), Sr (421–458 ppm), and Yb (0.85–0.89 ppm). Quartz diorites of the Yangshan pluton show the highest Al_2O_3 (18.0–18.1%), TiO_2 (1.02–1.04%), Y (34–35 ppm), and Yb (2.82–2.86 ppm) contents (Table 1). The Chenjiawan diorites have the highest MgO (6.04–6.07%), FeO* (Fe_2O_3 × 0.9 + FeO) (7.06–7.08%), $Mg^\#$ (~60, = $Mg^{2+}/(Mg^{2+} + Fe_{total}) \times 100$, with Fe_{total} as Fe^{2+}), Ni (69–75 ppm), V (157–160 ppm), and the lowest SiO_2 (54~55%) contents, similar to high-Mg diorites reported by Smithies and Champion (2000). The Yueshan and Zongpu plutons have similar compositional characteristics in major and trace elements (Figs. 2 and 3), e.g., high Al_2O_3 (15.0–17.0%), Na_2O (3.80–6.0%), MgO (1.58–6.16%), Sr (1300–2000 ppm), Ni (9–29 ppm), and V (65–175 ppm) contents. Both the Yueshan and Zongpu intrusive rocks are low-Fe suites, but the Yangshan intrusive rocks are medium suites and the Hongzhen granites are low-medium-Fe suites (Fig. 2(H)) (Arculus, 2003).

Chondrite-normalized REE patterns show that all samples are enriched in light (L) relative to heavy (H) REE without obvious Eu anomalies (Figs. 4(A) and (B)). The REE patterns of the Hongzhen granites also display clear concavities of middle REE (La/Sm_{CN} = 7.9–8.5), which likely implies the presence of some residual hornblende in the source (Gromet and Silver, 1987). N-MORB-normalized patterns show that all samples are enriched in Ba and other large-ion lithophile elements (LILE), and depleted in Nb, Ta and Ti (Figs. 4(C) and (D)). The sam-

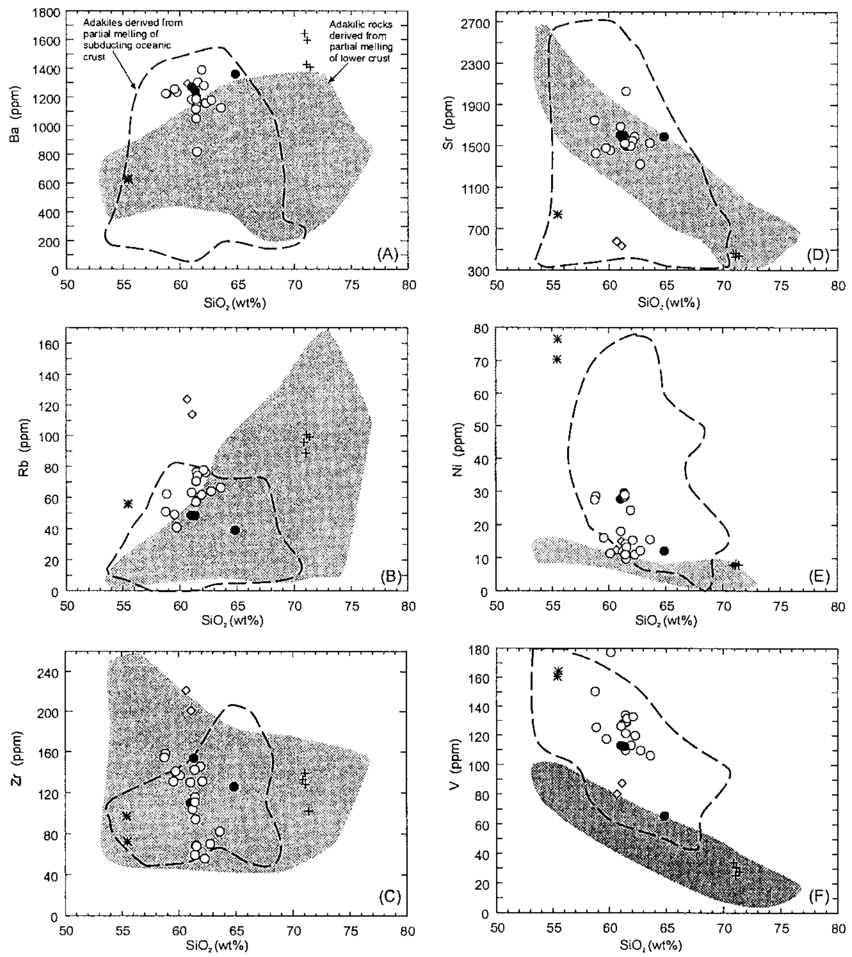

Fig. 3. Compositional variations of trace elements of the intrusive rocks in the Yueshan-Hongzhen area. Data sources for adakites formed by slab lower crust melting are the same as in Fig. 2.

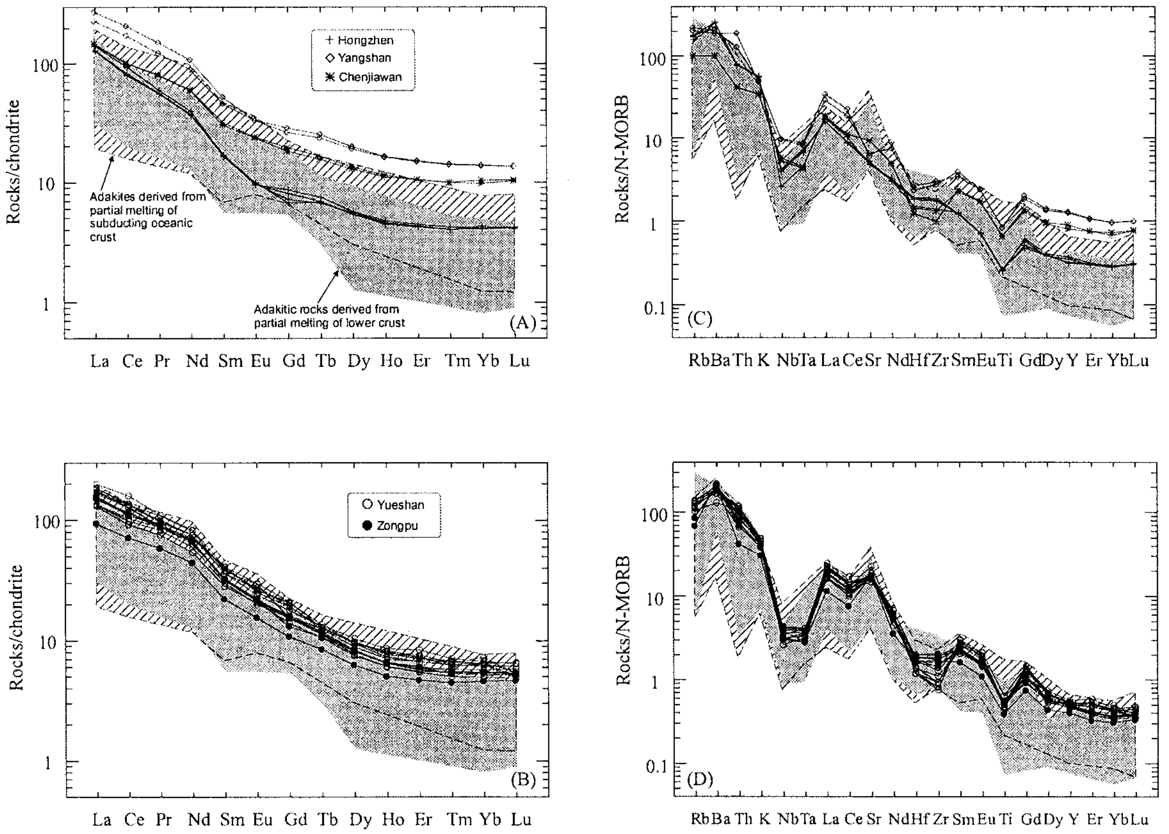

Fig. 4. Chondrite-normalized REE abundances (A, B) and N-MORB normalized multi-elements patterns for the intrusive rocks in the Yueshan-Hongzhen area. Chondrite and N-MORB REE values are from Boynton (1984) and Sun and McDonough (1989), respectively. Data for adakites are after Defant and Drummond (1990, 1993), Kay et al. (1993), Morris (1995), Drummond et al. (1996), Stern and Kilian (1996), Kepezhinskas et al. (1996), Martin (1999), Sajona et al. (2000), Aguillón-Robles et al. (2001), Yogodzinski et al. (2001), and references therein. Data for adakitic rocks derived from partial melting of lower crust are after Atherton and Petford (1993), Muir et al. (1995), Petford and Atherton (1996), and Johnson et al. (1997).

ples of Chenjiawan, Zongpu, and Yueshan have distinctly positive Sr anomalies (δSr (Sr$_{MN}$ (i.e., N-MORB-normalized)/(Ce$_{MN}$ + Nd$_{MN}$) = 1.17–3.13)), but Yangshan and Hongzhen intrusive rocks, respectively, display clear (δSr = 0.38–0.49) and weak (δSr = 0.71–0.88) negative Sr anomalies, hinting at the presence of residual plagioclases in the sources (Defant and Drummond, 1990; Martin, 1999).

In the Sr/Y versus Y diagram (Fig. 5), all samples from the Hongzhen, Zongpu and Yueshan plutons plot in the field of adakite and Archean TTG, but the Yangshan quartz diorite and Chenjiawan diorite fall in or near the field of normal arc andesite, dacite and rhyolite. In Figs. 2–4, with the exception of high K_2O contents (Fig. 2(A)), the Yueshan and Zongpu intrusive rocks have major and trace element characteristics that are similar to adakites derived from slab melting (Defant and Drummond, 1990), but different from adakitic rocks formed by lower crustal melting (Atherton and Petford, 1993; Muir *et al.*, 1995; Petford and Atherton, 1996; Johnson *et al.*, 1997) and natural slab melts that have not reacted with the mantle wedge (Sorensen and Grossman, 1989; Kepezhinskas *et al.*, 1995) in Al_2O_3, Na_2O, MgO, Ni, and V contents (Figs. 2–4). On the other hand, although the Hongzhen granites also plot in the field of adakite and Archean TTG in Fig. 5, they have MgO, Ni and V contents (Figs. 2(D), 3(E) and 3(F)) different from the adakites derived from slab melting but similar to adakitic rocks derived from lower crust melting. In addition, they have slightly higher K_2O (Fig. 2(A)), Ba (Fig. 3(A)) and lower Al_2O_3 (Fig. 3(B)), CaO (Fig. 3(C)) contents than those of adakitic rocks by lower crust melting (Atherton and Petford, 1993; Muir *et al.*, 1995; Petford and Atherton, 1996; Johnson *et al.*, 1997) and the natural slab melts (Sorensen and Grossman, 1989; Kepezhinskas *et al.*, 1995). However, MgO, Ni and V contents are similar to those of both of the latter adakite types.

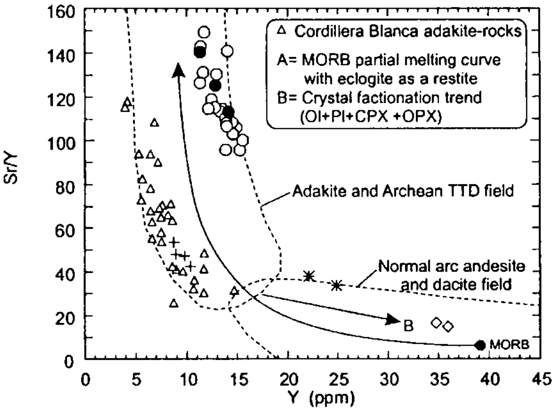

Fig. 5. Sr/Y vs. Y discrimination diagram contrasting adakites and "normal" arc andesite-dacite (after Defant and Drommond, 1990, and Atherton and Petford, 1993). The data for the Yueshan plutons are the same as Fig. 2. Data for the Cordillera Blanca rocks are after Petford and Atherton (1996).

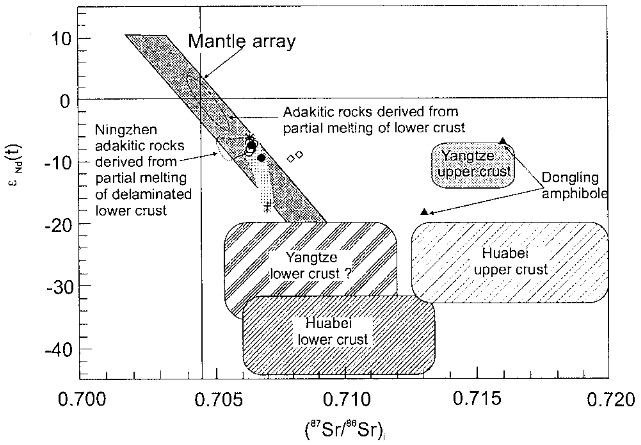

Fig. 6. Nd-Sr isotopic diagrams for the intrusive rocks in the Yueshan-Hongzhen area. Data for upper and lower crust of the Yangtze and Huabei Blocks are after Jahn et al. (1999). Data for the Dongling Proterozoic amphibolites are after Xing et al. (1993). Data of adakitic rocks derived from lower crustal melting are after Atherton and Petford (1993), Muir et al. (1995) and Petford and Atherton (1996), and Data for the Ningzhen adakitic rocks derived from partial melting of delaminated lower crust are from Xu et al. (2002).

Sr-Nd isotopes

Sm-Nd and Rb-Sr isotope data for intrusive rocks in the Yueshan-Hongzhen area are listed in Table 2. All of the samples have ^{147}Sm/^{144}Nd ratios (~0.1) similar to the average value of continental crust (Taylor and McLennan, 1985). These intrusive rocks have relatively homogeneous initial Sr isotopic ratios ranging from 0.7064 to 0.7083, but have a relatively large variation of Nd iso-

Table 2. Sr-Nd isotopic data of intrusive rocks in the Yueshan-Hongzhen area

No.	Sample	Sm (ppm)	Nd (ppm)	^{147}Sm/^{144}Nd	^{143}Nd/^{144}Nd	$2\sigma_m$	t (Ma)	$f_{Sm/Nd}$	$\varepsilon_{Nd}(t)$	T_{DM} (Ga)	Rb (ppm)	Sr (ppm)	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	$2\sigma_m$	$(^{87}Sr/^{86}Sr)_i$
1	aq–1	10.05	63.93	0.0956	0.512085	10	132	–0.51	-9.08	1.37	112.2	527	0.6166	0.709505	13	0.7083
2	aq–2	8.83	53.05	0.1013	0.512055	10	132	–0.49	-9.77	1.48	121.8	569	0.6200	0.709182	16	0.7080
3	aq–3	6.10	35.16	0.1055	0.512245	10	136	–0.46	-6.08	1.27	54.4	818	0.1923	0.706803	17	0.7064
4	aq–5	3.15	21.60	0.0887	0.511656	9	122	–0.55	-17.47	1.82	99.1	454	0.6323	0.708207	17	0.7071
5	aq–6	3.27	21.86	0.0909	0.511682	11	122	–0.54	-17.01	1.82	97.6	433	0.6528	0.708354	14	0.7072
6	aq–6–2	3.11	19.47	0.0967	0.511629	11	122	–0.51	-18.13	1.98	100.8	452	0.6451	0.708204	10	0.7071
7	ZP–1	6.01	38.86	0.0941	0.512162	10	132	–0.52	-7.55	1.26	47.5	1569	0.0875	0.706690	14	0.7065
8	ZP–2	4.23	26.12	0.0986	0.512060	12	132	–0.50	-9.62	1.44	38.4	1566	0.0710	0.707005	14	0.7069
9	01yst–1	6.28	38.60	0.0990	0.512211	11	136	–0.50	-6.63	1.25	76.8	1533	0.1449	0.706731	20	0.7065
10	01yst–3	6.24	37.56	0.1011	0.512179	9	136	–0.49	-7.29	1.31	65.3	1507	0.1254	0.706828	18	0.7066
11	01yst–4	5.75	35.38	0.0989	0.512135	8	136	–0.50	-8.13	1.35	60.8	1478	0.1190	0.706682	20	0.7065
12	01yst–5	6.29	39.54	0.0968	0.512182	10	136	–0.51	-7.16	1.26	62.3	1664	0.1083	0.706633	17	0.7064
13	00YS001	7.57	48.96	0.0936	0.512126	7	136	–0.52	-8.20	1.30	6.59	1498	0.0127	0.706544	8	0.7065
14	00YS002	6.85	41.67	0.0997	0.512141	5	136	–0.49	-8.02	1.35	76.8	1450	0.1534	0.706763	9	0.7065
15	00YS003	6.40	39.92	0.0970	0.512105	9	136	–0.51	-8.67	1.36	79.6	1456	0.1582	0.706703	14	0.7064
16	00YS005	6.51	39.72	0.0992	0.512142	7	136	–0.50	-7.99	1.34	78.2	1287	0.1759	0.706838	12	0.7065
17	00YS006	7.11	42.96	0.1001	0.512134	11	136	–0.49	-8.16	1.36	74.2	1530	0.1404	0.706734	9	0.7065
18	00YS007	6.99	43.06	0.0981	0.512157	6	136	–0.50	-7.68	1.31	75.3	1538	0.1416	0.706777	6	0.7065

topic compositions, with their $\varepsilon_{Nd}(t)$ values ranging from −6.08 to −18.13. The Hongzhen granites have the lowest $\varepsilon_{Nd}(t)$ values (−17.01~−18.13) close to that of the Yangtze lower crust (Fig. 6), and the Yueshan, Zongpu and Chenjiawan intrusive rocks have relatively high ε_{Nd} values (−6.08~−9.62). The Hongzhen granites have initial $^{87}Sr/^{86}Sr$ ratios (0.7071~0.7072) slightly higher than the Yueshan, Zongpu and Chenjiawan groups (0.7064~0.7069). Samples of the Yangshan quartz diorites have the highest initial $^{87}Sr/^{86}Sr$ ratios (0.7080~0.7083). Although the Yueshan, Zongpu and Hongzhen intrusive rocks have some major and trace elements characteristics similar to adakite (Fig. 5), their low $\varepsilon_{Nd}(t)$ values (−6.63~−18.13) and high initial $^{87}Sr/^{86}Sr$ ratios (0.7064~0.7072) are distinctly different from those of adakites derived from slab melting (Defant and Drummond, 1990; Martin, 1999), but are similar to those of adakitic rocks derived by lower crust melting (Atherton and Petford, 1993; Muir *et al.*, 1995; Petford and Atherton, 1996).

DISCUSSION

The geochemical data indicate that the rocks from the Yueshan, Zongpu and Hongzhen plutons have a number of compositional characteristics that are similar to adakite and adakitic rocks, with the exception of rocks from the Chenjiawan and Yangshan plutons. As mentioned above, several hypotheses for the origins of adakitic rocks have been suggested: slab melting, AFC processes involving basaltic magma, and lower crust melting. Let us examine these possibilities for the adakitic rocks in the Yueshan-Hongzhen area.

Slab melting

The Yueshan and Zongpu intrusive rocks have elemental composition characteristics similar to slab melt-derived adakites (Drummond *et al.*, 1996; Smithies, 2000). For example, their MgO, Ni and V contents are similar to typical adakites but higher than natural (pure) slab melts that have not reacted with the mantle wedge (Sorensen and Grossman, 1989; Kepezhinskas *et al.*, 1995) (Figs. 2(E), 3(E) and 3(F)). Moreover, both Yueshan and Zongpu intrusive rocks and typical adakites are low-Fe in Fig. 2(H). However, the adakitic rocks in the Yueshan-Hongzhen area were probably not derived by partial melting of subducting oceanic crust based on the following evidence. Firstly, Cretaceous metamorphic core complexes, A-type granite, alkaline or peralkaline igneous rocks associated with adakitic intrusive rocks in the Yueshan-Hongzhen strongly suggest that an extensional tectonic regime within a continent prevailed rather than a subduction zone during the Cretaceous. Secondly, the adakitic rocks have low $\varepsilon_{Nd}(t)$ values (−6.63~−18.13) and high initial $^{87}Sr/^{86}Sr$ ratios (0.7064~0.7072) obviously different from those of adakites by partial melting of MORB from a basaltic slab (Defant and Drummond, 1990; Kay *et al.*, 1993; Stern and Kilian, 1996; Martin, 1999). Although seawater alteration of basaltic oceanic crust can produce a marked increase in the $^{87}Sr/^{86}Sr$ ratios, $^{143}Nd/^{144}Nd$ ratios are extremely stable (e.g., Menzies *et al.*, 1993). So, isotopic data are inconsistent of with a subducted slab source for Yueshan-Hongzhen adakitic rocks.

Assimilation and fractional crystallization

It has been suggested that some rocks with adakitic characteristics can be derived by AFC processes involving basaltic magma (Feeley and Hacker, 1995; Wareham *et al.*, 1997; Castillo *et al.*, 1999). However, similar crustal AFC processes seem unlikely to produce the Yueshan-Hongzhen adakitic rocks. In the Yueshan-Hongzhen area, so far, basalt or gabbro has not been found, and the most mafic igneous rocks derived from a mantle source are the Chenjiawan high-Mg diorites that have small outcrop areas (less than 1 km^2). $\varepsilon_{Nd}(t)$ values (−6.08) of the Chenjiawan high-Mg diorite are also higher than those of the Yueshan and Zongpu intrusive rocks (−6.63~−9.62), and the Hongzhen granite (−17.01~−18.13), suggesting a difference in the isotopic characteristics of their sources. The Yueshan, Zongpu and Hongzhen intrusive rocks have initial Sr isotopic ratios (0.7064~0.7072) similar to or slightly higher than that (0.7064) of the Chenjiawan high-Mg diorite. Although the Yueshan-Hongzhen intrusive rocks display a very weak negative correlation on $\varepsilon_{Nd}(t)$ versus $(^{87}Sr/^{86}Sr)_i$ diagram (Fig. 6), which suggests that the adakitic rocks might be produced by the crustal AFC processes involving the Chenjiawan high-Mg mafic magma with less crustal materials, such a small volume of the Chenjiawan mafic magmas (less than 1 km^2) could not be responsible for the large volumes of adakitic rocks by magmatic fractionation, e.g., the Hongzhen adakitic pluton is exposed over an area of 55 km^2. Moreover, unlike the Camiguin and Volcán Ollagüe volcanic rocks and western Palmer land intrusive rocks, in which the silicic members with adakitic compositions are believed to be generated through AFC processes (Feeley and Hacker, 1995; Wareham *et al.*, 1997; Castillo *et al.*, 1999), the intrusive rocks in the Yueshan-Hongzhen area do not show a successive composition variation, and they are separated by two compositional gaps (55~58% and 66~70% SiO_2) into three groups: the most mafic Chenjiawan diorite, intermediate-felsic Yueshan, Zongpu and Yangshan intrusive rocks, and high-SiO_2 Hongzhen granite. Major and trace elements also have considerably scatter on Figs. 2 and 3. In addition, approximately constant Nd/Sr (Fig. 7(A)) and high Sr concentrations of the Yueshan and Zongpu adakitic rocks (Fig. 3(D)) suggest

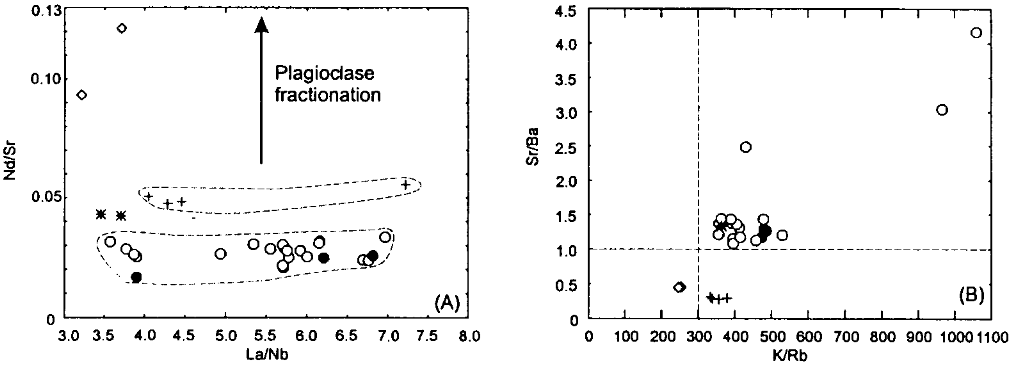

Fig. 7. Nd/Sr vs. La/Nb and Sr/Ba vs. K/Rb diagrams. Increasing Nd/Sr in igneous rocks is consistent with plagioclase fractionation (Bourdon et al., 2002). Data for the Yueshan plutons are the same as cited in Fig. 2. In (A), the Nd/Sr of the adakitic rocks from the Yueshan-Hongzhen area do not display obvious variations with the increasing of La/Nb, inconsistent with plagioclase fractionation. In (B), the Yueshan and Zongpu adakitic rocks have high Sr/Ba and K/Rb ratios, implying few residual plagioclases and amphiboles in the source, whereas the Hongzhen adakitic granites show rather low Sr/Ba and K/Rb ratios, indicating a few residual plagioclases and amphiboles in the source.

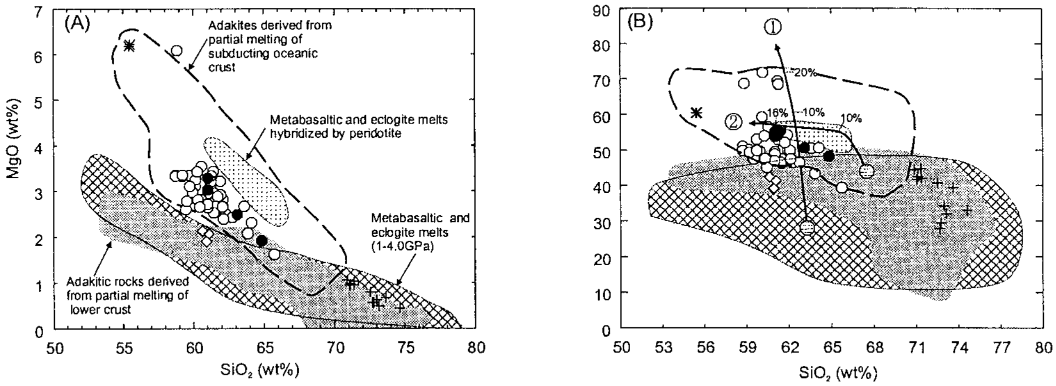

Fig. 8. MgO and Mg$^{\#}$ vs. SiO$_2$ diagrams for the intrusive rocks in the Yueshan-Hongzhen area. The Hongzhen adakitic granites have MgO and Mg$^{\#}$ values similar to the experimental melts of metabasalt or eclogite at pressures of 1.0–4.0 GPa (Rapp et al., 1991, 1999; Sen and Dunn, 1994; Rapp and Watson, 1995; Winther, 1996; Springer and Seck, 1997; Skjerlie and Patiño Doudce, 2002, and references therein) and adakitic rocks derived from partial melting of lower crust (gray shadowed field) (Atherton and Petford, 1993; Muir et al., 1995; Petford and Atherton, 1996; Johnson et al., 1997). The Hongzhen values are lower than adakites derived from slab melting (Defant and Drummond, 1990, 1993; Kay et al., 1993; Morris, 1995; Drummond et al., 1996; Stern and Kilian, 1996; Kepezhinskas et al., 1996; Martin, 1999; Sajona et al., 2000; Aguillón-Robles et al., 2001; Yogodzinski et al., 2001, and references therein) and experimental melts that have interacted with peridotite (e.g., Rapp et al., 1999). However, the Yueshan and Zongpu adakitic intrusive rocks have MgO and Mg$^{\#}$ values similar to adakites derived from slab melting and experimental melts that have interacted with peridotite (e.g., Rapp et al., 1999), and clearly higher than the experimental melts of metabasalts or eclogite at pressures of 1.0–4.0 GPa and adakitic rocks derived by partial melting of lower crust (gray shadowed field). Mantle AFC curves are after Stern and Kilian (1996) (curve 1) and Rapp et al. (1999) (curve 2), and show the proportion of assimilated peridotite.

that the high-Mg mafic magma could not evolve to form magma with adakitic composition features by fractional crystallization of plagioclase (the most important rock-forming mineral). Therefore, crustal AFC processes involving basaltic magma cannot produce Yueshan-Hongzhen adakitic rocks.

Partial melting of lower crustal rocks

Partial melting of mafic rocks in the lower crust is another mechanism that may yield adakitic magma (Gromet and Silver, 1987; Atherton and Petford, 1993; Muir *et al.*, 1995; Petford and Atherton, 1996), possibly in response to crustal thickening achieved through underplating of mantle-derived mafic magmas (emplaced at the base of the arc crust). Adakitic magmas may be produced directly from lower crustal sources heated by underplating mafic magmas (Gromet and Silver, 1987; Atherton and Petford, 1993; Muir *et al.*, 1995; Petford and Atherton, 1996). Adakitic magmas formed directly from the lower crust generally have relatively low MgO contents or $Mg^{\#}$ (Sen and Dunn, 1994; Rapp *et al.*, 1991, 1999; Rapp and Watson, 1995; Winther, 1996; Springer and Seck, 1997; Skjerlie and Patiño Doudce, 2002, and references therein) (Fig. 8). It must be noted that in the Yueshan-Hongzhen area, only the Hongzhen adakitic granites have relatively low MgO contents or $Mg^{\#}$, similar to the experimental melts of mafic rocks (Fig. 8) or natural slab melts (Fig. 2). They also have low Ni and V contents similar to crust-derived adakitic rocks (Figs. 3(E) and (F)), high initial $^{87}Sr/^{86}Sr$ ratios (0.7071~0.7072), and low ε_{Nd} values (−17.01~−18.13) similar to those of crustal rocks. Thus, Hongzhen adakitic granites were most possibly derived by lower crust melting.

Hongzhen adakitic granites have some geochemical characteristics similar to a typical adakite, e.g., high Sr/Y and La/Yb ratios and very low Yb and Y contents (Figs. 4(A) and 5, Table 1), indicating that residual garnet existed in the source (Defant and Drummond, 1990). On the other hand, the concavity of the middle REE (Figs. 4(A) and (C)) and moderate low K/Rb (329~357) (Fig. 7(B)) indicate that residual hornblende likely existed in the source regions (Arth and Hanson, 1975; Gromet and Silver, 1987). Low CaO, Al_2O_3 and Sr contents (Figs. 2(B), 2(C) and 3(D)), weak negative Sr anomalies, and very low Sr/Ba (<0.30) (Fig. 7(B)) are consistent with residual plagioclase persisting in the source as well (Arth and Hanson, 1975; Barnes *et al.*, 1996; Martin, 1999). In the $(La/Yb)_c$-$(La/Sr)_c$ diagrams (Fig. 9), the compositions of the Hongzhen granite exhibit a transition from a gabbroic- to an eclogitic source trend. We suggest the Hongzhen granite was likely derived by partial melting of crustal rocks in the garnet ± hornblende ± plagioclase stability field, and the solid residua are possibly garnet-bearing amphibolites. In addition, the Nd-Sr isotopic compositions of the Hongzhen granite are different from those of the Proterozoic Dongling amphibolites (Xing *et al.*, 1993) (Fig. 6), suggesting that the latter was not the source of the adakitic rocks. On the basis of Nd-Sr isotopic data, Chen and Jahn (1998) suggested that an old crust (probably lower crust) likely was an important contributor to the granitic intrusive rocks of the Yangtze Block (e.g., granites in southeast Anhui Province). The Hongzhen granites are also in the southeast Anhui Province, and have low ε_{Nd} (−17.01~−18.13) and relatively high initial $^{87}Sr/^{86}Sr$ ratios (0.7071~0.7072) similar to those of the lower crustal rocks of the Yangtze Block (Fig. 6), consistent with the possibility that the latter is possibly source rock.

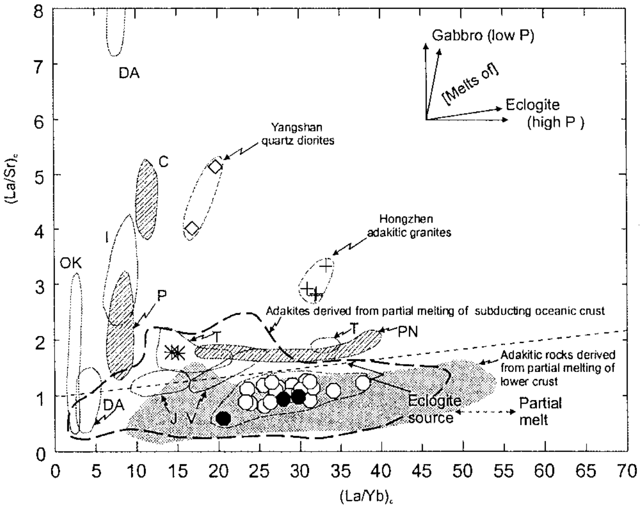

Fig. 9. Chondrite-normalized La/Yb vs. La/Sr for eclogite related to intermediate-felsic melts (after Kay and Kay, 1991). The data for the Yueshan plutons are the same as in Fig. 2. Trends for gabbro at shallow levels and eclogite at depth are shown (after Kay and Kay, 1991) for reference. Tertiary Andean magmas of 28°–33°S are transitional from a gabbroic (Dona Ana (DA), Pulido (P), Infiernillos (I), Cantarito (C)) to an eclogite trend (Tortolas (T), Jotabeche (J), Vallecito (V), Piras Negras (PN)) (after Kay and Kay, 1991).

Partial melting of delaminated lower crust

Unlike the Hongzhen adakitic granites, the Yueshan and Zongpu adakitic rocks have relatively high Al_2O_3 (Fig. 2(B)), Na_2O (Fig. 2(C)), Ni (Fig. 3(E)), V (Fig. 3(F)) and MgO ($Mg^{\#}$) (Figs. 8(A) and (B)), and are low-Fe suites (Fig. 2(H)); these are characteristic similar to adakite derived by slab melting. It is generally believed that reaction between pristine slab-melt and peridotite in the subarc mantle wedge (e.g., Rapp *et al.*, 1999) results in high MgO ($Mg^{\#}$) values of typical adakites. However, as discussed above, the Yueshan and Zongpu adakitic rocks cannot have been derived by partial melting of a subducting slab. On the other hand, their relatively high SiO_2 (58~66%) contents imply that they could not have been directly generated by partial melting of mantle peridotites because low degree partial melts of mantle peridotite cannot yield dacitic magmas (Green and Ringwood, 1968; Wyllie, 1977; Green, 1980; Jahn and Zhang, 1984). Experimental results (Baker *et al.*, 1995) from melting of anhydrous lherzolite also show that the composition of low % partial melts are not more silicic than andesite (~55% SiO_2). Therefore, the Yueshan and Zongpu adakitic rocks cannot have been directly derived from the partial melting of peridotite. It appears that the only scenario that can explain the elevated MgO ($Mg^{\#}$), Ni, and V values and low Al_2O_3, Na_2O and SiO_2 of the

Yueshan and Zongpu adakitic rocks is partial melting of lower crust delaminated into the mantle, similar to the case of the Ningzhen adakitic intrusive rocks (Xu *et al.*, 2002). In this case, a delaminated section of the lower crust may be heated by relatively hot mantle and partially melted (e.g., Kay and Kay, 1993). The melt will pass through the mantle as it rises towards the surface, elevating the MgO ($Mg^{\#}$), Ni and V values, and decreasing in Al_2O_3, Na_2O and SiO_2 contents by the interaction between mantle and melt (Kepezhinskas *et al.*, 1995). Note in support of this suggestion that the Yueshan and Zongpu adakitic rocks have Nd-Sr isotopic compositions different from the lower crustal rocks of the Yangtze Block, but similar to the Ningzhen adakitic intrusive rocks derived from partial melting of delaminated lower crust (Fig. 6), confirming that mantle materials most probably were important (in part) in the petrogenesis of the Yueshan and Zongpu adakitic rocks.

The Yueshan and Zongpu intrusive rocks have high Sr/Y and La/Yb and low Yb and Y contents (Figs. 4 and 5, Table 1) similar to adakite, indicating the presence of residual garnet in the source (Defant and Drummond, 1990). The lack of Eu anomalies, unusually high Sr contents (positive Sr anomalies) and high Sr/Ba (1.1–4.5) preclude significant residual plagioclase in the source (Fig. 7(B)) (Arth and Hanson, 1975; Barnes *et al.*, 1996; Martin, 1999). The moderate and high K/Rb (355–1060) and lack of concavity of the middle REE are inconsistent with the persistence of hornblende as a major residual phase in the source (Fig. 7(B)) (Arth and Hanson, 1975; Gromet and Silver, 1987; Barnes *et al.*, 1996). In the $(La/Yb)_c$-$(La/Sr)_c$ diagrams (Fig. 9), the compositional trends of the Yueshan and Zongpu adakitic rocks are close to those controlled by eclogite. Therefore, garnet + clinopyroxene should be the major residual phases in the sources of the Yueshan and Zongpu adakitic rocks in contrast with the case for the Hongzhen granite. In summary, the Yueshan and Zongpu adakitic rocks are most probably produced by the partial melting of mafic rocks delaminated into the underlying mantle, and transformed into an eclogitic mineralogy.

High K_2O contents and possible source rocks

Although the adakitic intrusive rocks in Yueshan-Hongzhen area share most compositional characteristics with typical adakites, their K_2O contents are clearly higher. Adakitic intrusive rocks in Yueshan-Hongzhen area are mainly high-potassium, but their K_2O contents and Na_2O/K_2O are variable. The Yueshan and Zongpu adakitic rocks have high Na_2O/K_2O (>1.0), but the Hongzhen adakitic granites have low Na_2O/K_2O (<1.0). As mentioned previously, the Yueshan and Zongpu adakitic rocks have initial ε_{Nd} values distinctly different from the Hongzhen adakitic granites (Fig. 6, Table 2), implying that different sources were involved. We conclude that relatively high K_2O of the Hongzhen adakitic granites is most likely inherited from high K_2O contents of mafic materials in their source, most probably high-K mafic rocks or shoshonitic rocks (Rapp *et al.*, 2002). There are two possibility for the origins of relatively high K_2O contents in the Yueshan and Zongpu adakitic rocks: (1) mafic rocks in their source have high K_2O contents similar to high-K basalt (Ducea and Saleeby, 1998; Rapp *et al.*, 2002); (2) the source rocks have relatively low K_2O contents similar to low-K basalt or MORB, but the adakitic magma were generated by partial melting at rather high-pressure, resulting in relatively high K_2O content in the adakitic intrusive rocks (Ducea and Saleeby, 1998; Rapp *et al.*, 2002). Here we favor the first possibility.

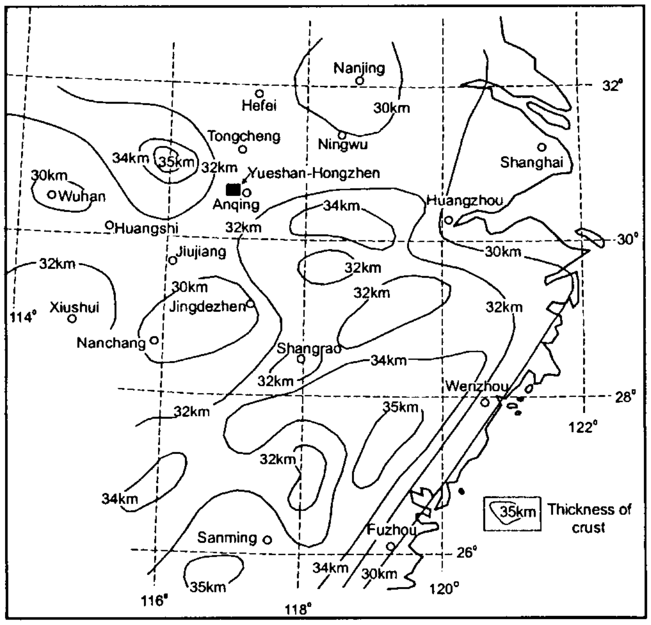

Fig. 10. Moho depths (km) in southeast China at present (after Wang (1992) and Tang et al. (1998)).

Geodynamic model for generating the adakitic magmas

Lower crust delamination may represent an important mechanism responsible for the differentiation of continental masses on Earth (Ducea and Saleeby, 1998). In the west of North and South America, lower crust delaminations have been recognized on the basis of xenolith populations, magmatism, and geophysical evidence (Kay and Kay, 1991, 1993; Zandt and Ruppert, 1996; Ducea and Saleeby, 1998). Xu *et al.* (2002) also reported adakitic intrusive rocks in east China that appear to have been generated during lower crust delamination. Relatively to the Ningzhen case (Xu *et al.*, 2002), the intrusive rocks in the Yueshan-Hongzhen area

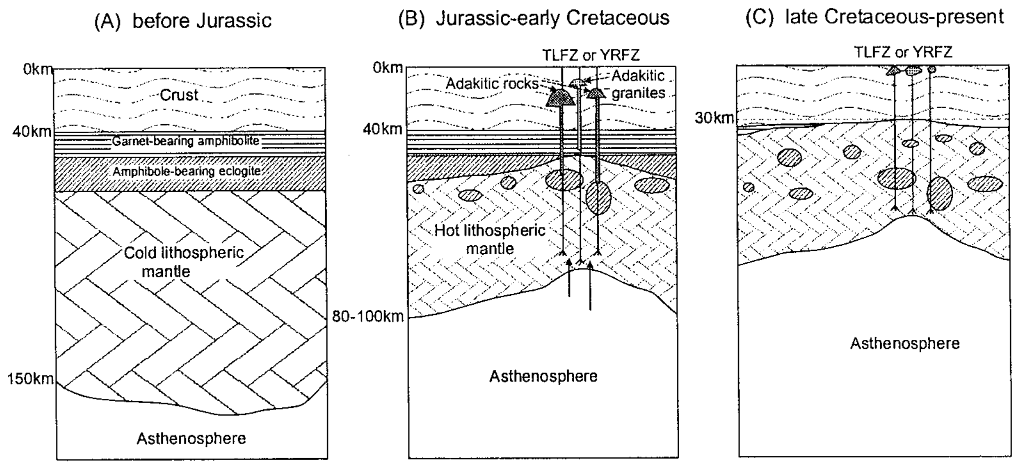

Fig. 11. A suggested model to produce the Yueshan-Hongzhen adakitic intrusive rocks via delamination of the lower crust during the Mesozoic in east China. (A) The relatively thick lithosphere and thick crust before the Jurassic. The lower portion of thick crust is likely composed of (upper) garnet-bearing amphibolites (the field filled with horizontal lines) and (deeper) amphibole-bearing eclogites (the field filled with diagonal lines). (B) The lithospheric mantle in east China was thinned (Zheng and Lu, 1999; Wu and Sun, 1999; Xu et al., 2000; Xu, 2001) and the thick crust was also removed through delamination during the Jurassic-early Cretaceous. (C) In late Cretaceous-present, extensive surface erosion and crustal extension during formation of metamorphic core complexes leads to further crustal thinning and adakitic intrusive bodies were exposed. TLFZ: Tan-Lu fault zone; YRFZ: Yangtze River fault zone.

are more complicated petrogenetically, being derived from several crustal sources at different depths as well as a mantle source. Among the five plutons, high-Mg diorites in the Chenjiawan pluton with the lowest SiO_2 are most likely products of partial melting of peridotite. Meanwhile, the Yangshan quartz diorites were possibly derived from crustal source at depth (<40 km). Adakitic rocks in the Yueshan-Hongzhen area are derived from different crust sources: the Hongzhen pluton source contained residual garnet ± hornblende ± plagioclase (source probably ~40 km (~1.2 GPa) (Rushmer, 1993; Wolf and Wyllie, 1994; Rapp and Watson, 1995)), whereas the sources of the Yueshan and Zongpu adakitic rocks were probably >40 km (residual garnet + clinopyroxene without residual hornblendes or plagioclase in their source (Rushmer, 1993; Wolf and Wyllie, 1994; Peacock *et al.*, 1994; Rapp and Watson, 1995)), and likely delaminated lower crust sections.

The geochemical data reveal that the crustal thickness (or the Moho depths) in the Yueshan-Hongzhen area most have been at least 40 km when the adakitic magmas were produced in the Cretaceous. The present crustal thickness in the Yueshan-Hongzhen area is ~31 km (Fig. 10) (Wang, 1992; Tang *et al.*, 1998). This implies that Mesozoic continental crust (>40 km) in the Yueshan-Hongzhen area has undergone thinning. An association with Dongling metamorphic core complex is consistent with both extension and some erosion since the Cretaceous. Given the fact that Mesozoic-Cenozoic volcanic and sedimentary rocks are still preserved in and near the Yueshan-Hongzhen area (Fig. 1(B)), it is unlikely that erosion has removed ≥10 km of crust since the early Cretaceous. We conclude that delamination could also explain the thinning of the Mesozoic crust in the Yueshan-Hongzhen area through the removal of eclogitic material from the base of the crust (Arndt and Goldstein, 1989; Kay and Kay, 1991, 1993). Delamination of the lower crust coupled with denudation of the metamorphic core complex have produced result in the present thinner crust in the Yueshan-Hongzhen area.

It has become widely accepted that at least 100 km of lithospheric mantle has been removed from beneath large areas of east China during the Mesozoic (Griffin *et al.*, 1998; Menzies and Xu, 1998; Zheng and Lu, 1999; Wu and Sun, 1999; Fan *et al.*, 2000; Xu, X. S. *et al.*, 2000; Xu, 2001; Gao *et al.*, 2002). Lithospheric thinning may have proceeded with a gradual upward migration of the lithosphere-asthenosphere boundary, or could proceed by penetration and disaggregation of old lithosphere by hot mantle materials, rising along lithospheric shear zones (e.g., Tan-Lu fault zone) (Zheng and Lu, 1999; Xu *et al.*, 2000; Xu, 2001). When the hotter asthenospheric material rose and replaced the colder lithospheric mantle, the flux of heat from the underlying asthenosphere could have triggered partial melting of mafic materials at the base of the crust or delaminated in the mantle. Given the time of lithospheric mantle thinning (during late Mesozoic-Tertiary) and age of the Yueshan-Hongzhen adakitic rocks

(Cretaceous), we suggest that generation of adakitic magmas in Yueshan-Hongzhen area was possibly related to the general lithosphere thinning process in east China (Figs. 11(A) and (B)).

In summary, we conclude that source materials in the lower portions of thickened crust in the Yueshan-Hongzhen area consisted of amphibole-bearing eclogitic and garnet-bearing amphibolitic materials with relatively high K_2O. When the eclogitic materials were delaminated, the temperatures along the contacts between hot mantle and the eclogitic materials would have been high enough to trigger dehydration melting of amphibole-bearing eclogitic materials at pressures >1.2 GPa (Rapp *et al.*, 1991; Wolf and Wyllie, 1994; Rapp and Watson, 1995), forming adakitic magmas (Fig. 11(B)). The Yueshan and Zongpu adakitic magmas are suggested to be generated by partial melting of a delaminated lower crust block, rather than newly exposed lower parts at the bottom of the crust, as the high MgO (or $Mg^{\#}$), Ni and V values of the Yueshan and Zongpu adakitic rocks requires interaction with mantle peridotites when the adakitic magmas ascend (Fig. 11(B)). The reacted adakitic magmas ascended into the upper crust to form Yueshan and Zongpu adakitic rocks. Meanwhile, newly exposed lower part (garnet-bearing amphibolite) at the bottom of the crust may be gradually heated by underlying relatively hot sub-crust mantle and started to melt at pressures of ~1.2 GPa, leaving the residual garnet ± hornblende ± plagioclase in the source. Such magmas would not be interacted with mantle peridotites, forming the Hongzhen adakitic granites with low $Mg^{\#}$ and Ni, V values. During delamination of the lower crust and generation of the adakitic magmas, the Dongling metamorphic core complex was uplifted by regional extension and upper crust in Yueshan-Hongzhen area were partially eroded. Both delamination of the lower crust and extension of upper crust resulted in the thinner crust at present (Fig. 11(C)).

CONCLUSIONS

(1) Adakitic rocks in the Yueshan-Hongzhen area were generated in an extensional tectonic regime within a continent rather than in an arc setting.

(2) The Hongzhen adakitic granites was most likely derived from partial melting of mafic material with high K contents at the base of the continental crust at pressures of ~1.2 GPa, leaving residual garnet ± hornblende ± plagioclase in the source.

(3) The Yueshan and Zongpu adakitic rocks were most probably derived from dehydration melting of delaminated mafic lower crust in the mantle at pressures >1.2 GPa, leaving residual garnet + pyroxene in the source. The higher K_2O contents in the Yueshan and Zongpu intrusive rocks relative to adakites were possibly inherited from compositional features of their source rocks with relatively high K_2O in the lower crust, or were products of partial melting of low-K mafic lower crust at high-pressure conditions.

(4) The lower crust delamination coupled with regional extension resulted in thinning of Mesozoic crust in the Yueshan-Hongzhen area.

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