Geochemistry of high-Mg andesites and adakitic andesite from the Sanchazi block of the Mian-Lue ophiolitic melange in the Qinling Mountains, central China: Evidence of partial melting of the subducted Paleo-Tethyan crust

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Major and trace element and Nd and Pb isotopic compositions of volcanic rocks from the Sanchazi (SCZ) block of the Mian-Lue ophiolitic melange in the Qinling Mountains, central China were analyzed to provide insights into the subduction processes during the Late Paleozoic along the margins of the paleo-Tethyan ocean. All igneous rocks from the SCZ block show characteristics typical of arc volcanic rocks such as depletion in high field-strength elements (HFSE) and enrichment in large-ion-lithophile elements (LILE) relative to normal mid-ocean ridge basalts (N-MORB). Included among these arc rocks are high-Mg andesites (HMAs) and an adakitic andesite. The adakitic andesite has a steep REE pattern, low Y and Yb, and high La/Yb values, which is similar to those of typical adakites derived by partial melting of subducted basaltic crust. The HMAs from the SCZ block also have adakitic affinities except that they have lower La/Yb (~ 10) and Al_2O_3 (< 15 wt.%). Both the adakitic andesite and HMAs have higher MgO, Ni, and Cr contents than the normal andesites and basalts. The age-corrected Nd-Pb isotopic compositions of the HMAs and adakitic andesite show an enriched isotopic signature relative to the MORB-type rocks in the Mianlue area, suggesting that the former probably contain components from sediments or continental crust materials. The data reveal that the adakitic andesite and HMAs in the SCZ block were most probably produced by partial melting of an eclogitic oceanic crust and/or subducted sediments, followed by interaction of the melt with the overlying mantle wedge, and finally by a possible contamination of the melt by the crustal materials. Our result infers that seafloor spreading was active in the paleo-Tethyan ocean, and an ancient island arc system was present along the proto-Qinling area in the Late Paleozoic. The paleo-Tethys ocean separated the South China and North China blocks in Late Paleozoic. The final integration between above two blocks is suggested to have occurred in the Triassic.

INTRODUCTION

It is widely believed that most arc magmas are derived from hydrous melting of peridotites in the mantle wedge induced by fluids released from the subducted lithosphere (e.g., Gill, 1981; Kushiro, 1990; Arculus, 1994). However, adakites and adakitic rocks in some modern island and continental arcs that were produced by partial melting of subducted basaltic crust have recently attracted great attention (e.g., Defant and Drummond, 1990; Drummond and Defant, 1990). A similar slab melting process is also proposed to play an important

role in the formation of the Archaean crust (Drummond and Defant, 1990). Although typical adakites are dacitic in composition, adakitic andesites and related high-Mg andesites (HMAs) have also been detected in some arcs (e.g., in Baja California, southern Chile, and Aleutians—Rogers *et al.*, 1985; Saunders *et al.*, 1987; Kay *et al.*, 1993; Yogodzinski *et al.*, 1995; Yogodzinski and Kelemen, 1998). Apparently, the components from slab melting can not only directly produce arc volcanic rocks (i.e., adakites), but also influence the production of HMAs and adakitic andesite (Yogodzinski *et al.*, 1994, 1995; Yogodzinski and

Kelemen, 1998; Stern and Kilian, 1996). For example, recent investigations emphasized the contribution of melts from subducted lithosphere in the formation of high-Mg (or Mg-) andesites (Yogodzinski *et al.*, 1995; Yogodzinski and Kelemen, 1998; Shinjo, 1999). Thus, partial melting of a subducted oceanic basaltic crust and interaction of the melt generated with the overlying mantle wedge is increasingly becoming popular as a model for the formation of HMAs and adakitic andesites.

Although most adakite and adakitic rocks are thought to be related to the partial melting of subducted oceanic crust, there are still some rocks with adakitic feature to be argued other origin interpretation, e.g., partial melting of mafic rock in lower crust (Atherton and Petford, 1993; Barnes *et al.*, 1996), AFC process of basaltic magma (Castillo *et al.*, 1999). Recently, Shimoda *et al.* (1998) forwarded that the Setouchi HMAs with adakitic compositional signature has a significant components attributed from partial melting of subducted sediments. Thus, adakites and the rocks with adakitic compositional feature probably have multiple origins, and the identification of the origin of adakitic rocks is of important scientific significance.

So far, studies of adakites and adakite-related volcanic rocks mostly focus on modern arcs and Archaean terranes. Here we report an adakitic andesite and the associated high-Mg andesites of Late Paleozoic age found in a tectonic block within the Paleo-Tethyan ophiolitic melange in the Qinling orogenic belt, Central China. It must be noted that geological history of the Qinling orogen and the timing of collision between the South and North China block (craton) have been controversial. Two different issues on the timing of collision have been proposed—e.g., the middle Paleozoic (Gao *et al.*, 1995); and the Triassic (Li *et al.*, 1996; Zhang *et al.*, 1996). The presence of the Mian-Lue Tethyan ophiolitic melange (Xu *et al.*, 1994, 1998; Zhang *et al.*, 1995, 1996) and the related arc volcanic rocks found in this belt (Xu *et al.*, 1998; Lai *et al.*, 1998) indicate that an ancient ocean-arc system possibly occurred in

Qinling area, Central China in the Late Paleozoic (Feng *et al.*, 1996). The high-Mg and adakitic andesites reported in this paper indeed confirm that subduction of an ancient oceanic lithosphere in the Qinling area occurred in the Late Paleozoic, further indicating that the South and North China block were still separated at that time. Thus, this study also provides important information on the tectonic evolution of the Qinling and Dabieshan orogenic belts.

The main objective of this study is to better understand the arc magmatic processes attendant to the subduction of the Paleo-Tethyan (~350 M.Y.) oceanic lithosphere in the Late Paleozoic. Specifically, this paper is to (1) present the geochemical characteristics of adakitic andesite and high-Mg andesites, (2) propose a model for the origin of the adakitic andesite and high-Mg andesites, and (3) provide the information on integration process between the North and South China block (craton).

GEOLOGICAL SETTING

The Qinling orogen is located in Central China and connect eastward to the Dabieshan orogen that bears ultra-high pressure metamorphic rocks, which separates the North China block from the South China block (Fig. 1). In the Qinling area, the North and South Qinling orogens were, respectively, regarded as the southern margin of the North China block and the northern margin of the South China block. It was believed that the South and North China blocks collided along the Sangdan suture zone that lined the South Qinling and North Qinling orogens. In recent years, an important discovery of an ophiolitic and tectonic melange in the Mian-Lueyang area (or call the Mian-Lue belt) in the southwest region of South Qinling orogen (Xu *et al.*, 1994, 1998; Xu and Han, 1996; Zhang *et al.*, 1995, 1996; etc.) has fueled interests in the orogenic evolution of the Qinling area.

The Mian-Lue ophiolitic and tectonic melange consists of a series of ophiolite blocks, arc volcanic rock blocks, meta-sedimentary rock blocks,

Fig. 1. Tectonic framework of Qinling orogen and adjacent South China and North China blocks (cratons), and geological map of the Sanchazi volcanic arc block in the Mian-Lue ophiolitic and tectonic melange. MLB: Mian-Lue ophiolitic and tectonic suture belt, SDB: Shang-Dan suture belt, South Qinling: the South Qinling orogenic belt, North Qinling: the North Qinling orogenic belt. 1. serpentized harzburgite; 2. N-NORB-type rocks; 3. Sanchazi arc volcanic rock; 4. meta-sedimentary rocks; 5. siliceous rock with radiolarians fauna; 6. Qiaozigou volcanic rock block; 7. fracture; 8. other blocks in Mian-Lue melange.

and basement metamorphic blocks. The ophiolitic blocks were termed as the Mian-Lue North ophiolite (MLNO) (Xu *et al.*, 1994, 1998). The geochemistry and Nd and Pb isotopic composition of a typical ophiolite in the MLNO, the Hunshuiguan-Zhuangke block, have been studied in detail by Xu *et al.* (2000). The studies indicated that a possible paleo-ocean represented by the MLNO was formed during the Late Paleozoic (Xu

and Han, 1996; Xu *et al.*, 1998; Zhang *et al.*, 1995; Feng *et al.*, 1996). This Late Paleozoic paleo-ocean is thought to be a part of paleo-Tethys that was possibly connected southwestward to the typical Sanjiang paleo-Tethys (Xu and Han, 1996; Xu *et al.*, 1998), and extended eastward to the Suizhou-Jingshan area on the southern side of the Dabieshan orogen where similar ophiolite blocks have also been found (Dong *et al.*, 1999). On the

other hand, some studies showed that the Mian-Lue ophiolitic and tectonic melange belt was produced by the collision of the South China block and South Qinling orogen in the Triassic that were previously separated by the Tethyan ocean in the Late Paleozoic (Zhang *et al.*, 1995, 1996). Two different tectonic models for the Mian-Lue belt have been forwarded—one model proposes that the Mian-Lue Tethys was only an extinct basin above continental basement (Zhang *et al.*, 1995; Li *et al.*, 1996), whereas the other model posits that Paleo-Tethys is a full-scale ocean with a trench-oceanic-arc system (Xu *et al.*, 1998; Lai *et al.*, 1998).

Arc volcanic rocks have been found in the Mian-Lue ophiolitic and tectonic melange belt (Xu *et al.*, 1998; Lai *et al.*, 1998). Of the arc volcanic rock blocks, the Sanchazi block (hereafter call the SCZ block) is the most typical. The SCZ block is located in the Sanchazi area of Lueyang county, to the west of the Hunshuiguan-Zhuangke ophiolitic block (Fig. 1). These two blocks are separated by a major fault. The SCZ block is mainly composed of mafic igneous rocks and a few peridotite slices as well as some meta-sedimentary rocks. The mafic igneous rocks can be divided into two groups based on their texture—coarse-grained and fine-grained mafic rocks. The former are meta-gabbros and meta-diorites, and the latter are arc meta-basalts and meta-andesites. These arc volcanic rocks underwent greenschist-facies metamorphism. Almost all the original igneous mineral were replaced by a metamorphic mineral assemblage (e.g., albite-chlorite-epidote-quartz), except for a small amount of original phenocrystic phases (e.g., Hb and Pl) that are still preserved in a few relatively coarse-grained andesitic rocks. Geochemical feature of rocks in the block is also clearly distinct from that of the igneous rocks in the Hunshuiguan-Zhuangke ophiolitic block that have normal seafloor basaltic affinity (Xu *et al.*, 1998, 2000), suggesting that rocks in the SCZ block were derived in a paleo island arc environment (see below).

The exact isotopic-age of SCZ arc volcanic rocks has not been determined yet. Li *et al.* (1996)

reported Sm-Nd whole rock isochron age (242 Ma) of the volcanic rocks from the Heigouxia Valley ophiolitic block in the Mian-Lue belt close to the SCZ block, but suggested that it might represent the metamorphic age. Therefore, volcanic rocks among ophiolitic and arc-origin blocks in the Mian-Lue belt were most likely generated prior to 242 Ma. In addition, siliceous sedimentary rocks of possible deep-water origin (Fig. 1) and with the Early Carboniferous radiolarians fauna (e.g., *Albaillella* sp.; *Latentifistula* cf. *ruetae*; *Entactinia variospina*) within the Mian-Lue melange have also been discovered close to the SCZ block (Feng *et al.*, 1996). The age of these fossils infers that the paleo-Tethyan oceanic basin and related paleo-island arc existed in the Mian-Lue area in about the Early Carboniferous (Xu and Han, 1996; Xu *et al.*, 1998; Feng *et al.*, 1996). In summary, the age of ancient SCZ arc is probably at ~350 Ma (Early Carboniferous).

SAMPLE AND ANALYTICAL METHODS

All samples studied here were collected in the Pianqiaogou valley and along the two sides of the Kang-Lue highway that cut across the SCZ block. They were metamorphosed to greenschists rocks and some rocks also show slight calcareous alteration. All samples were examined under the microscope and then grouped accordingly into different rock types. From each rock type, only the least-altered representative samples were selected for analyses. The samples chosen were first split into small chips and soaked in the 4N hydrochloric acid for one hour in order to leach out secondary carbonate minerals, and then powdered. The powders were measured by gravimetry and AAS for their major element compositions (analytical procedure described by Gao *et al.*, 1995). Trace elements, including the rare earth element (REE), were analyzed by inductively coupled mass spectrometry (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). Trace element concentrations were drift corrected

using the standard sample BCR-1; analytical uncertainties are generally better than 5% for most elements but 10% for other several elements. Nd and Pb isotopic ratios of the rocks were analyzed on VG 354 Thermal Ionization mass spectrometer (TIMS) also at the Guangzhou Institute of Geochemistry. The analytical procedure for TIMS is described in detail by Li and McCulloch (1998). Nd isotopic ratios were measured in metal form,

mass fractionation corrected to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ and are reported relative to $^{143}\text{Nd}/^{144}\text{Nd} = 0.511860$ for the La Jolla Standard. Analytical uncertainty for $^{143}\text{Nd}/^{144}\text{Nd}$ measurements is ± 2 sigma. Pb isotopic ratios were corrected for mass fractionation using replicate analyses of the standard NIST SRM 981 and using the values of Todt *et al.* (1984); the analytical precision are about ± 0.005 for $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ and

Fig. 2. REE and incompatible trace element diagram of arc volcanic rocks from the SCZ block. a, REE pattern; b, trace element pattern, which only shows those alteration-resistant incompatible elements and the mobile element—Sr. The adakitic andesite shows the lowest HREE contents among all arc volcanic rocks in the SCZ block. The adakite from the Cook Island (Stern and Kilian, 1996) and Adak-type Mg-andesite from the West Aleutians (Yogodzinski *et al.*, 1995) are shown in the figure for comparison. Normalizing values of the Chondrite and Primary mantle are after Sun and McDonough (1989).

± 0.01 for $^{208}\text{Pb}/^{204}\text{Pb}$. The total procedural blanks are $\text{Sm} < 5 \times 10^{-11}$ g, $\text{Nd} < 2 \times 10^{-10}$ g and $\text{Pb} < 2 \times 10^{-10}$ g.

ALTERATION EFFECT

Although the basalts and andesites from the SCZ block are altered in different degree and slightly metamorphosed, their contents of alteration-resistant trace elements show coherent, subparallel concentration patterns except mobile element—Sr (Fig. 2). These consistent patterns indicate that in general the samples still may preserve the bulk of their original alteration-resistant trace element composition. This inference is consistent with previous studies which showed that the concentration of some of the trace elements such as the high field-strength elements (HFSE) and rare earth elements (REE) in igneous rocks is not generally affected by rock alteration (e.g., Ludden and Thompson, 1978; Bienvenu *et al.*, 1990). However, it is possible that some mobile elements (K, Rb, Ba, Sr, etc.) have been mobilized by alteration and metamorphism. Thus, we will only use the alteration-resistant elements, i.e., HFSE and REE, in the discussion below. In addition,

previous studies have also shown that only severe seawater alteration can affect the $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of oceanic rocks (e.g., Cheng *et al.*, 1987; McCulloch *et al.*, 1981) because seawater is extraordinary low in Nd (4×10^{-6} ppm—Mahoney *et al.*, 1998). Similar to Nd isotopic ratios, Pb isotopic ratios of oceanic rocks are generally not affected by sea-water alteration because the Pb content of seawater is also low (2×10^{-6} ppm—Mahoney *et al.*, 1998). Thus, we believe that the Nd, Pb isotopic ratios of our samples reported here may not be modified by alteration/metamorphism and may most probably represent original isotopic signature of these rocks.

GEOCHEMICAL RESULTS

Major and trace elements data of representative samples from the SCZ block are given in Table 1. In the SCZ block, two kinds of fine- and coarse-grained mafic rocks were identified based solely on their SiO_2 contents—andesitic and basaltic rocks, with the former volumetrically dominant over the latter. All the basaltic and andesitic rocks belong to the calc-alkaline rock series because they are plotted in a calc-alkaline trend on

Fig. 3. Nb/Y-Zr/TiO₂ classifications for rocks from the SCZ block, original diagram is after Winchester and Floyd (1976).

Fig. 4. Mg#, Cr and Ni—SiO₂ diagram for the volcanic rocks from the SCZ block. In Cr, Ni and Mg#—SiO₂ diagrams, adakitic and high-Mg andesites show a compositional trend distinctive from basalts and normal andesites in the SCZ block, suggesting that they are derived from the sources different from the latter. The original diagram of Mg#—SiO₂ is after Stern and Kilian (1996). Several data of SCZ samples are from Lai et al. (1998). Data of Mg-andesites of the Aleutians are after Yogodzinski et al. (1995). Data of HMAs from the Setouchi are after Shimoda et al. (1998). Data of high-Mg andesites in the Central Ryukyu are after Shinjo (1999).

Alk-FeO-MgO diagram (not shown). Because of alteration and metamorphic effects, the Nb/Y vs. Zr/TiO₂ classification schemes (Fig. 3) of Winchester and Floyd (1976) were used to verify the rock names, which indicated that they were basalts and andesites (Fig. 3). Furthermore, the andesites (SiO₂ > 53 wt.%) in the SCZ block, can further be divided into two subgroups—high-magnesian (or magnesian) andesite and normal andesite based on the definition of Crawford *et al.* (1989) on high-Mg andesite and boninite. The high-Mg andesites (HMAs) characteristically have higher Mg# (Mg/[Mg + Fe] > 0.6) and Cr, Ni concentration (Fig. 4) than normal andesites in the SCZ block and other modern island arcs (Kushiro, 1990; Arculus, 1994). The MgO contents of the HMAs from the SCZ block are similar to those of well-studied Setouchi HMA suite from Japan (Tatsumi and Ishizaka, 1982), although the former have slightly lower Mg# content than the latter does.

One sample stands out from the normal andesite group in the SCZ block. This sample (#106, Table 1) has relatively lower MgO content than the HMAs but has clearly higher MgO (Fig. 4) than the rest of the normal andesites in the SCZ block. Its geochemical characteristic is uniquely comparable to that of typical adakite that is widely believed to represent melt derived from melting of subducted oceanic crust (e.g., Defant and Drummond, 1990; Stern and Kilian, 1996). For example, sample 106 has high La/Yb (22.3), Al₂O₃ (17.37); low Y (11 ppm), Yb (1.01 ppm). It shows the most steep LREE pattern of all the igneous rocks in the SCZ block (Fig. 2) and plotted in the compositional evolution trend of the high-Mg andesite on SiO₂ vs. Cr, Ni, MgO diagrams (Fig. 4), indicating that it most likely has an genetic relation with the high-Mg andesites. In addition, sample 106 also has higher Cr, Ni contents distinct from arc basalts and normal andesites in the SCZ block which fall in another a compositional trend (Fig. 4), suggesting that it is not probably formed by direct partial melting of hydrous mantle wedge or arc basaltic magma differentiation beneath the SCZ subduction zone. Thus, this sam-

Table 1. Major, trace and REE composition of volcanic rocks in the SCZ block

Sample Rock type	106 adak-And.	037-2 Mg-And.	038 Mg-And.	040 Mg-And.	104 Mg-And.	105 Mg-And.	037-1 normal And.	039 normal And.	041 normal And.	093 Bas.	014 Bas.
SiO ₂	61.23	53.13	57.21	54.21	54.28	56.22	55.97	60.14	60.79	50.82	50.99
TiO ₂	0.51	0.85	0.89	0.92	0.87	0.83	0.87	1.07	0.98	0.90	0.87
Al ₂ O ₃	17.37	13.23	13.26	13.11	14.9	12.35	15.72	15.68	15.51	16.8	15.99
Fe ₂ O ₃	1.15	2.54	2.11	2.76	1.50	1.11	3.39	3.31	2.76	3.52	1.10
FeO	4.14	4.89	5.31	5.56	5.80	4.20	5.32	5.20	4.48	5.16	8.73
MnO	0.12	0.15	0.13	0.15	0.12	0.09	0.13	0.17	0.13	0.13	0.15
MgO	3.15	7.01	6.35	7.37	7.03	6.25	3.44	2.39	2.84	6.34	6.93
CaO	3.19	7.65	5.46	7.91	5.93	6.84	3.73	3.28	2.79	7.19	4.13
Na ₂ O	6.15	3.91	4.61	3.44	2.93	3.41	5.04	3.86	5.41	4.57	4.00
K ₂ O	0.15	0.99	1.56	2.11	3.15	1.75	2.02	1.48	1.00	0.80	0.82
P ₂ O ₅	0.19	0.33	0.46	0.44	0.32	0.33	0.24	0.28	0.31	0.13	0.34
H ₂ O	2.29				2.69	2.98		2.65		2.90	1.17
CO ₂	0.24				0.55	3.89				0.54	4.57
LOI		4.87	2.50	1.61			4.32		2.73		
Σ	99.88	99.55	99.85	99.59	100.07	100.25	100.19	99.51	99.73	99.8	99.79

Sample	106	037-2	038	040	104	105	037-1	039	041	093	014
Rock type	adak-And.	Mg-And.	Mg-And.	Mg-And.	Mg-And.	Mg-And.	normal And.	normal And.	normal And.	Bas.	Bas.
Fe*/Mg	1.63	1.02	1.14	1.08	1.02	0.83	2.43	3.42	2.45	1.31	1.4
Mg#	52.21	63.52	61.09	62.02	63.66	68.18	42.28	34.24	42.09	57.57	55.96
Cr	245	383	260	312	300	355	48	50	42	116	155
Ni	87	158	99	93	108	122	14	7	5	49	12
Co	26	27	24	33	29	31	21	18	15	33	32
Pb	2.6	2.2	5.5	8.4	4.3	3.9	3.2	3.4	2.8	1.4	1.4
Rb	7	15	34	44	76	43	52	37	14	15	23
Ba	120	235	572	860	1250	527	747	631	283	226	439
Sr	425	446	85	487	304	521	219	432	338	357	253
Ta	0.21	0.32	0.34	0.3	0.16	0.1	0.25	0.26	0.26	0.06	0.32
Nb	6.5	3.8	3.9	3.6	6.6	6.2	2.9	3.2	3.1	0.9	5.5
Hf	2.11	2.49	2.88	2.51	3.1	2.48	2.36	2.78	2.34	1.51	2.42
Zr	115	163	150	130	134	120	141	169	139	107	87
Y	11	17	17	20	17	15	21	30	30	16	20
Th	3.11	3.81	4.12	3.63	7	6.8	2.49	2.45	2.33	0.34	4.32
U	1.24	1.02	1.21	1.09	0.94	0.94	0.83	0.84	0.81	0.14	1.20
La	22.61	14.14	15.11	15.95	13.79	15.32	11.57	13.76	13.36	3.65	17.67
Ce	30.73	33.3	36.16	36.53	30.45	33.88	27.42	33.6	32.17	9.95	35.65
Pr	3.51	4.52	4.84	4.95	4.82	4.97	3.74	4.72	4.51	1.60	4.47
Nd	13.05	19.37	20.53	21.6	18.66	19.38	16.28	20.41	19.95	7.91	18.15
Sm	3.15	4.2	4.35	4.88	4.34	4.42	3.88	4.89	4.79	2.38	4.02
Eu	0.82	1.19	1.10	1.34	1.24	1.36	1.16	1.43	1.45	0.93	1.31
Gd	2.09	3.49	3.62	4.09	3.92	3.79	3.31	4.17	4.10	2.92	4.43
Tb	0.33	0.59	0.6	0.69	0.56	0.52	0.66	0.88	0.86	0.47	0.63
Dy	2.00	2.91	2.94	3.44	3.44	3.07	3.66	4.80	4.90	2.95	3.74
Ho	0.43	0.54	0.56	0.65	0.65	0.58	0.74	0.96	0.99	0.60	0.75
Er	1.15	1.68	1.75	1.94	1.84	1.59	2.25	2.98	2.96	1.71	2.23
Tm	0.17	0.22	0.23	0.25	0.27	0.23	0.30	0.41	0.41	0.24	0.32
Yb	1.01	1.43	1.52	1.65	1.72	1.49	2.10	2.82	2.74	1.48	2.10
Lu	0.15	0.22	0.22	0.25	0.27	0.23	0.31	0.41	0.41	0.19	0.30

adak And., adakitic andesite; normal And., normal andesite; Mg-And., high-Mg andesite; Bas., basalts. $Mg\# = MgO/(FeO^* + MgO)$; $Fe^*/Mg = (FeO^*/MgO)$.

ple is most probably related to adakitic melt from subducted oceanic crust or sediment (see below). In this study, we call it “adakitic andesite” because it is really an andesite, although it has some of the geochemical characteristics of adakite which generally is a dacite (>62 wt.% SiO_2). The adakitic andesite represents a small volume of outcrops within the SCZ block, however it is closely associated in time and space with the HMAs. The HMAs in the SCZ block, in turn, also share most of the geochemical features with an adakite (e.g., low Y, Yb, see Table 1) except relatively low Al_2O_3 (<15 wt.%) and La/Yb (9–10).

Chondrite-normalized REE patterns for the SCZ block samples are shown in Fig. 2a. As mentioned earlier, the adakitic andesite is the most strongly LREE-enriched and HREE-depleted of

the samples in SCZ block, showing a rather steep REE pattern much similar to typical adakites (Defant and Drummond, 1990). The HMAs in the SCZ block exhibit moderate enrichment in LREE, about the same REE concentration and distribution pattern of Setouchi HMAs (Tatsumi and Ishizaka, 1982). In contrast, normal andesites from the SCZ block only show slightly LREE enrichment and almost without any HREE depletion.

On primary mantle-normalized trace element spider diagram (Fig. 2b), all the rocks display depletion in high field strength elements (HFSE—Nb, Ti, Hf, and Ta, but Ta not shown in Fig. 2) as compared to primary mantle, which is a typical signature of arc volcanic rocks, confirming that these rocks from the SCZ block are indeed produced in a convergent margin environment. The

Fig. 5. $(\text{La}/\text{Yb})_N$ vs. $(\text{Yb})_N$ diagram for the adakitic and high-Mg andesites from the SCZ block. The original diagram is after Drummond and Defend (1990). Some typical adakites and Adak-type high-Mg andesites are plotted on this figure for comparison (Cook island—Stern and Kilian, 1996; Cerro Pampa—Kay *et al.*, 1993; Central Ryukyu—Shinjo, 1999; western Aleutians—Yogodzinski *et al.*, 1995; Aguilera of AVZ—Stern and Kilian, 1996). The MORB-type rocks from ophiolitic block in the Mian-Lue belt are after Xu *et al.* (1998). Adakitic gneiss from the Dabieshan are after Wang and Xu *et al.* (2000).

trace elemental features of the adakitic andesite and the HMAs in the SCZ block are similar to that of the adakitic rocks and Adak-type Mg-andesites from the Cook island and Aleutians (Stern and Kilian, 1996; Yogodzinski *et al.*, 1995) except various Sr concentration in Fig. 2.

In the $(\text{La}/\text{Yb})_N$ vs. $(\text{Yb})_N$ diagram (Fig. 5), adakitic andesite and HMA from the SCZ block plot within the typical adakitic high-Al TTD field. They show a compositional signature very close to those of the typical adakites and adak-type Mg-andesite from the Cook island, N-AVZ, and Aleutians on Fig. 5. (Stern and Kilian, 1996; Yogodzinski *et al.*, 1995). In contrast, the plots of normal andesites from the SCZ block are far from those of the typical adakites and fall in the com-

position field of normal arc andesite/Low-Al TTD (Fig. 5). The MORB-type rocks from the typical ophiolitic block in the Mian-Lue belt are plotted in Fig. 5 for comparison, they fall in the typical MORB field.

Four samples from the SCZ block were analyzed for their Nd and Pb isotopic ratios (Table 2 and Fig. 6). The samples show a large age-corrected isotopic compositional range—the low age-corrected Pb isotopic ratios are similar to those of the MORB-type rocks in the Mian-Lue belt, but the age-corrected Nd isotopic ratios are clearly lower than those of the latter. Of all the samples studied in this paper, one basalt sample (#093) has the highest $(^{208}\text{Pb}/^{204}\text{Pb})_{t=350\text{Ma}}$ ratio and $\epsilon_{\text{Nd}(350\text{Ma})}$ values. Whereas, the adakitic

Fig. 6. $\epsilon_{\text{Nd}(t=350\text{Ma})}$ vs. $(^{208}\text{Pb}/^{204}\text{Pb})_t$ diagram for the adakitic and high-Mg andesites from the SCZ block. $\epsilon_{\text{Nd}(t)}$ and age-corrected Pb isotopic ratios were calculated using $t = 350$ Ma. The adakitic and high-Mg andesite from the SCZ block show an enriched isotopic signature. The high-Mg andesites from the Setouchi and sediments from the Philippine sea (Shimoda *et al.*, 1998) are also plotted for comparison. Their isotopic ratios are also corrected to 350 Ma. N-MORB-type rocks in the Mian-Lue ophiolite are from Xu *et al.* (2000). DMM, EM1 and EM2 are mantle end-members (Zindler and Hart, 1986) and their values are also corrected to 350 Ma. Symbol significance on the figure: 1. Adakitic andesite of the SCZ arc block; 2. HMA of the SCZ arc block; 3. basalts of the SCZ arc block; 4. N-MORB-type rocks of the Mian-Lue ophiolitic block; 5. HMAs from Setouchi; 6. Sediments from the Philippine sea.

Table 2. Pb and Nd isotopic data of volcanic rocks in the SCZ block

Sample	104	106	093	014	014 (repeat)
Rock type	high-Mg andesite	adakite	basalt	basalt	basalt
U	0.94	1.24	0.14	1.20	1.17
Th	7.00	3.11	0.34	4.32	4.31
Pb	4.3	2.6	1.4	1.4	1.6
$^{238}\text{U}/^{204}\text{Pb}$	13.9	30.3	6.3	56.7	47.7
$^{232}\text{Th}/^{204}\text{Pb}$	107.5	78.4	15.7	210.9	181.6
$^{206}\text{Pb}/^{204}\text{Pb}$	18.646 ± 0.010	18.552 ± 0.010	17.855 ± 0.010	19.782 ± 0.020	19.765 ± 0.018
$^{207}\text{Pb}/^{204}\text{Pb}$	15.599 ± 0.010	15.541 ± 0.010	15.570 ± 0.010	15.666 ± 0.019	15.653 ± 0.015
$^{208}\text{Pb}/^{204}\text{Pb}$	38.707 ± 0.030	38.313 ± 0.021	37.903 ± 0.010	40.107 ± 0.041	40.009 ± 0.037
$(^{206}\text{Pb}/^{204}\text{Pb})_{t=350\text{Ma}}$	17.867	16.864	17.506	16.618	17.103
$(^{207}\text{Pb}/^{204}\text{Pb})_{t=350\text{Ma}}$	15.557	15.451	15.551	15.497	15.511
$(^{208}\text{Pb}/^{204}\text{Pb})_{t=350\text{Ma}}$	36.829	36.943	37.629	36.422	36.833
Sm	4.263	3.15	2.277	3.858	
Nd	18.272	13.05	7.621	17.627	
$^{147}\text{Sm}/^{144}\text{Nd}$	0.1411	0.1468	0.1807	0.1323	
$^{143}\text{Nd}/^{144}\text{Nd}$	0.512510 ± 8	0.512706 ± 11	0.512873 ± 12	0.511903 ± 17	
$\epsilon_{\text{Nd}}(t=350\text{Ma})$	3.52	-0.05	5.26	-11.5	

U, Th and Pb concentration were analyzed by ICP-MS; Sm, Nd and isotopic ratios were measured through isotopic dilution. Age-corrected isotopic ratios were calculated using $t = 350$ Ma.

andesite and HMA have lower $(^{208}\text{Pb}/^{204}\text{Pb})_{t=350\text{Ma}}$ ratios and $\epsilon_{\text{Nd}}(350\text{Ma})$ values than the basalt (#093) does. It must be noted that the adakitic and high-Mg andesites show an enriched Nd isotopic signature, which is distinctive from the typical adakite and adak-type Mg-andesites from the Cook island and Aleutians that generally have the depleted isotopic composition of MORB (Yogodzinski *et al.*, 1995; Stern and Kilian, 1996; Kay *et al.*, 1993). They also exhibit obviously lower $\epsilon_{\text{Nd}}(350\text{Ma})$ values than those of the MORB-type rocks from the ophiolitic block in the Mian-Lue belt (Fig. 6). On the other hand, the SCZ HMA and adakitic andesite have the enriched isotopic composition similar to that of the Setouchi HMAs (Shimoda *et al.*, 1998), except that the former have lower age-corrected Pb isotopic ratios. The Sample 093, 104 and 106 are plotted in the field (Fig. 6) between MORB-type rocks with depleted-isotopic feature from the ophiolitic block in the Mian-Lue belt and sediments with enriched isotopic feature from Philippine Sea. However, another basalt sample (#014) has very low $\epsilon_{\text{Nd}}(350\text{Ma})$ values. It is not clear yet why it shows even more enriched Nd isotopic signature than the sediments from Philippine Sea. A possible reason is that Nd-Pb

isotopic system of the sample 014 may be changed by sea-water alteration or it may be derived from an extremely enriched mantle source.

DISCUSSION

Some investigators believe that adakites from the Cook Island, Cerro Pampa, Mount St. Helens originate from partial melting of subducted oceanic basalts beneath a subduction zone with a little or no mantle wedge contribution (Stern and Kilian, 1996; Kay *et al.*, 1993; Defant and Drummond, 1993). However, others believe that some rocks with adakitic geochemical features may also form *via* water-undersaturated partial melting of the underplated mafic lower crust or previously subducted oceanic crust (Atherton and Petford, 1993; Peacock *et al.*, 1994; Barnes *et al.*, 1996). Recently, Castillo *et al.* (1999) also suggest that some arc volcanic rocks with adakite-like geochemical characteristics in the Central Mindanao Arc in southern Philippines can be derived from normal arc magmas by the combined process of shallow level crust assimilation and fractional crystallization (AFC) and have negligible connection to melting of subducted basaltic

crust. Thus, adakites and rocks with adakitic compositional signature probably have multiple origins.

In detail, the reported adakites from the Cook Island are generally thought to be formed by partial melting of eclogitic MORB, followed by limited interaction of the melt with the overlying mantle (>90% MORB, <10% mantle components), with little ($\leq 1\%$) participation of either subducted sediment or continental crust materials (Stern and Kilian, 1996). Thus, adakites in the Cook Island most probably contain a lot of components of pristine adakite melt. On the other hand, Adak-type Mg (or high-Mg) andesites (i.e., the supposed type example of adakites) were produced by extensive reaction between melts from subducted slab and peridotite or basaltic melt in mantle wedge (Yogodzinski *et al.*, 1994, 1995). These facts lead us to believe that there is a compositional gradation between a pristine adakitic and a primitive high-Mg andesitic melt. In addition, adakites and related rocks most probably contain, in different degrees, components of subducted sediment or continental crust (Stern and Kilian, 1996; Kay *et al.*, 1993). Therefore, adakites and rocks with adakite-like geochemical signature comprise a series of rocks which are generated by mixture of at least three end-member components including melts from subducted slab, contributions from the peridotite mantle and contributions from subducted sediment or crustal materials.

Components from subducted slab

As mentioned earlier, the adakitic andesite and HMAs from the SCZ block show a lot of compositional characteristics that are similar to typical adakites. Thus, the major question concerns the origin of these rocks. The HMAs from the SCZ block have a relatively low SiO_2 content (54–57%), which argues against direct melting of mafic rocks in the lower crust, since melts generated by a moderate degree of partial melting of the mafic lower crust are felsic. Moreover, the adakitic andesite from the SCZ block has higher SiO_2 content than the HMAs, but all the adakitic andesite and HMAs from the SCZ block have

higher Mg# than the rocks derived from melting of the lower crust in Cordillera (>52 vs. 29.35–45.37 Mg#—Atherton and Petford, 1993). Such a high Mg# as well as high Cr and Ni of these rock most likely results from significant interaction of the original “silicic” melt with the mantle wedge. This argument was also used by Stern and Kilian (1996) to interpret origin of the adakites from the AVZ with high Mg#, which were thought not to be derived by direct melting of the mafic lower crust. In addition, the high-Mg andesite—adakitic andesite—normal andesite rock association in the SCZ is identical to the rock association in the Klamath Mountain with adakitic signature that were thought to be generated by melting of the lower crust (Barnes *et al.*, 1996).

The adakitic andesite has a steep LREE pattern and high $(\text{La/Yb})_N$ (Fig. 2), which also make it hard to produce this rock through an AFC process because the accompanying basalts and normal andesite in the SCZ block do not have low HREE contents. More importantly, unlike the silicic rocks with adakite-like compositions that are generated through an AFC process (Castillo *et al.*, 1999), the adakitic andesite and HMAs in the SCZ block have high Cr and Ni concentrations (higher than those in the basalts and normal andesites in the SCZ, see Table 1 and Fig. 4). These data suggest that the adakitic andesite and the HMAs could not be produced by differentiation from the basaltic and normal andesitic magma in the SCZ block. In addition, the volcanic rocks from the SCZ block, unlike the Camiguin rocks, do not display a successive compositional variation, and the adakitic andesites and HMAs form a compositional variation trend that is different from those of the basalts and normal andesites (Fig. 4). Moreover, the SCZ samples show a large isotopic compositional range (Fig. 6), indicating that they are most likely not derived from a homogeneous source. Therefore, it is very difficult to model the origin of the adakitic andesite and HMAs by AFC processes from a single parental magma that produced the basalts and normal andesites.

We argue that adakitic and high-Mg andesites from the SCZ block most probably contain com-

ponents of adakitic melts from partial melting of subducted oceanic basalts or sediments; subsequently, the resulting melt could interact with the overlying mantle wedge. This is consistent with Kay's (1978) argument about the adakite from Aleutians. The high-Mg andesite from the SCZ block are not likely the products of direct partial melting of a mantle wedge (see below). They share some geochemical characteristics with typical adakites and are associated with adakitic andesite, indicating a close relation to an adakitic melt. Adakitic andesite from the SCZ block possesses all major and trace element signatures of typical adakite. Its Y, Yb, La/Yb values as well as Nd, Pb isotopic ratios are also much similar to those adakites from Aguilera area in N-AVZ that were thought to be related to slab melting (Stern and Kilian, 1996). Thus, these facts led us to believe that the adakitic and high-Mg andesites most probably have an amount of components from a subducted oceanic basalt.

Origin of high-Mg andesite from the SCZ block

Two models have been forwarded to interpret the origin of HMAs: (1) crystallization of primary magma from direct partial melting of a hydrous mantle (Tatsumi and Ishizaka, 1982; Tatsumi and Maruyama, 1989), and (2) interaction of ascending melts from partial melting of subducted slab with overlying mantle (Kelemen, 1990, 1995; Yogodzinski *et al.*, 1994). The first model is based on some experiments indicating that HMAs can form via direct partial melting of the hydrous upper mantle under appropriate conditions (~1000–1150° and 10–15 kb—Tatsumi and Ishizaka, 1982; Hirose, 1997). These HMAs from direct partial melting of hydrous peridotite are expected to possess high Mg content or Mg#, olivine phenocrysts and depleted isotopic features due to their equilibration with peridotite (Yogodzinski *et al.*, 1994, 1995). However, the HMAs from the SCZ block do not have extremely high Mg# and olivine phenocrysts, inferring they did not crystallized from a primary andesitic magma.

The major and trace elemental compositions of HMAs in the SCZ block are very similar to those

of the well-known HMAs from the Setouchi and Central Ryukyu region in the Japan (Shimoda *et al.*, 1998; Shinjo, 1999). Although the Setouchi HMAs were originally thought to be typical primary magmas from the mantle wedge (Tatsumi and Ishizaka, 1982), more recent investigations suggest a different origin, i.e., initial melting of subducted sediments and subsequent interactions of such hydrous silicic melts with overlying mantle wedge (Shimoda *et al.*, 1998). Shinjo (1999) interpreted that the geochemical signature of HMAs from Central Ryukyu resulted from a reaction between mantle peridotite and ascending melts derived from partial melting of the oceanic crust. Our sample from the SCZ block also most probably underwent such a process of mantle-melt interaction. We assume that adakitic melts (liquid) with relatively high SiO₂, Al₂O₃, La/Yb and low MgO from subducted slab ascended into the mantle wedge which has relatively low SiO₂, Al₂O₃, La/Yb and high MgO. As a result of extensive interaction between adakitic melt and peridotite, the MgO content of the melt was elevated, but the SiO₂ and Al₂O₃ contents as well as La/Yb values were reduced. Because the mantle wedge is hotter than melt from slab melting, such a reaction most likely takes place. Kelemen (1990, 1995) used a simple reaction model between slab-melt and overlying peridotite to interpret why the average crust composition is close to that of HMA, and this interpretation was supported by experiment results. Carroll and Wyllie (1989) showed that the SiO₂ content was decreased and the MgO content was largely increased in the melt due to the reaction between hydrous silicic melts and peridotite at 15 kb. Of course, another possibility is that adakitic melt may mix with primary high-Mg andesitic and/or basaltic melt on their way to the surface to generate the HMAs. In either case, we consider that such processes are able to produce the compositional characteristics of both the HMAs and adakitic andesite in the SCZ block. The association of HMAs and adakitic andesite in the SCZ block and their geochemical affinity confirm that there is indeed a compositional gradation between a pristine adakitic melt and high-Mg

andesitic magma. The adakitic andesite and high-Mg andesites from the SCZ block were produced by interacting/mixing, to different extents, of an adakitic melt and mantle wedge/primary andesitic magma.

A component from subducted sediment or continental crust

The melts from slab melting and its reaction with overlying peridotites is a likely scenario for producing the geochemical attributes of adakitic andesite and HMAs from the SCZ block, but their Nd and Pb isotopic ratios suggest a slightly different interpretation. The adakitic andesite and HMAs all show much lower $\epsilon_{\text{Nd}(350\text{Ma})}$ values (Fig. 6) than the MORB-type rocks from the ophiolitic block within the Mian-Lue belt, indicating the role of an enriched subduction component in the production of adakitic andesite and HMA magma. Their age-corrected Nd isotopic ratios (Table 2) are also clearly distinct from the high $^{143}\text{Nd}/^{144}\text{Nd}$ values of the adakites and HMAs in the Cook Island and western Aleutian regions that most probably contain components only from the mantle wedge and oceanic basalts (Stern and Kilian, 1996; Yogodzinski *et al.*, 1995). These results lead us to believe that the component with enriched Nd isotopic feature such as crustal materials and/or subducted sediments were most probably involved in the generation of the adakitic andesite and HMA magma beneath the Mian-Lue subduction zone.

The adakitic andesite and HMAs from the SCZ block exhibit a relatively enriched Nd isotopic signature similar to that of the Setouchi HMAs except their relatively low age-corrected Pb isotopic ratios. Shimoda *et al.* (1998) suggested that subducting sediment could contribute significantly to the Setouchi HMA magma based on the radiogenic Nd, Pb and Sr isotopic signature of the Philippine Sea sediment. Thus, it is possible that our samples also contain some subducted sediment components. However, unlike the Setouchi HMAs, the SCZ HMAs have relatively low Al_2O_3 (<15 wt.% vs. >15 wt.% Al_2O_3 for the Setouchi HMAs) and low age-corrected Pb isotopic ratios. Hence, sediment component involvement in the genera-

tion of the SCZ adakitic andesite and HMAs is not likely as much as that in the generation of the Setouchi HMAs. On the other hand, an alternative explanation of the enriched Nd isotopic signature of the SCZ adakitic andesite and HMAs is related to the assimilation of the upper crust rocks. According to available data, the crustal basement rocks from upper crust in the Southern Qinling area also possess variable $\epsilon_{\text{Nd}(t)}$ values (−6.7 – +5.5, Huang and Wu, 1990), which can be another low $\epsilon_{\text{Nd}(t)}$ mixing component. Thus, it is also possible that the adakitic andesite and HMA magmas are contaminated by such a high $\epsilon_{\text{Nd}(t)}$ end-member from of crustal material.

Therefore, in summary, we argue that adakitic andesite and HMAs from the SCZ block most probably contain components of adakitic melts from partial melting of the basaltic portion of the subducted slab. We also believe that the high Cr, Ni contents and Mg# indicate that the pristine adakitic melt interacted with the overlying mantle wedge. Finally, we argue that the adakitic andesite and HMAs were also most probably influenced to a certain extent by subducted sediment or by upper crustal material because of their enriched Nd isotopic signature. However, based on present data, we can not estimate with certainty the amount of sediment or crust material involved in the generation of our samples.

Origin of basalts and normal andesites

The normal andesites in the SCZ block are characterized by lower Sr and higher HREE and Y contents and lower La/Yb values than the adakitic andesite and HMAs. They are very similar to normal orogenic andesite. For example, they show clear depletion in HFSE relative to N-MORB. Hence, these normal andesites from the SCZ block are most likely the melting products of a hydrous mantle wedge which is similar to the source mantle of typical orogenic andesites. On the other hand, basalts in the SCZ block have a complex genesis, which is indicated by their variable REE abundance patterns and isotopic compositions. For example, basalt sample 093 shows a relatively flat REE pattern and high $^{143}\text{Nd}/^{144}\text{Nd}$

ratio, and thus is most likely derived from a hydrous harzburgite source in the mantle wedge. In contrast, basalt sample 014 has a rather enriched L-REE pattern and low $^{143}\text{Nd}/^{144}\text{Nd}$ ratios (if this isotopic data is reliable), suggesting that it was probably originated from a relatively enriched mantle wedge.

Tectonic setting of the SCZ adakitic andesite and HMAs

The HMAs have unique geochemical characteristics and restricted occurrence in modern island arcs. They generally occur in the forearc environment in the near-trench region. Although several different models for the origin of high-Mg andesite formation were forwarded (seen for example, discussion above), they all include two important factors: a hot and young oceanic lithosphere subducted and a hot mantle wedge (e.g., Shiraki *et al.*, 1978; Meijer, 1980; Crawford *et al.*, 1981; Tatsumi and Ishizaka, 1982). Owing to a high geothermal gradients in the mantle wedge resulting from recent back-arc basin opening and subduction of relatively young and hot oceanic lithosphere, hydrous peridotites at shallow levels in the subforearc mantle wedge may be partially melted to produce primary HMA magma (Tatsumi and Maruyama, 1989). On the other hand, the adakitic magma can also be derived directly from partial melting of a relatively young and hot oceanic crust that is being subducted (e.g., Peacock *et al.*, 1994). Therefore, the same tectonic conditions are needed for either model of HMA and adakitic magma generation in the forearc. Our results hence suggest that both the adakitic andesite and HMA magma were probably formed in a paleo forearc setting.

Implications for the Qinling orogenic evolution

As mentioned above, the timing of final integration between the South and North China block (craton) has been controversial, e.g., middle Paleozoic (Gao *et al.*, 1995) or Triassic (Zhang *et al.*, 1995; Li *et al.*, 1993). The adakitic andesite and HMAs found in SCZ block strongly suggest that an ancient volcanic arc occurred in the Mian-

Lue area. Meanwhile, those MORB-type ophiolites (Xu *et al.*, 1998, 2000) also indicate that a paleo-oceanic basin existed at that time. Both the ocean basin and arc suggest that a paleo full oceanic-arc system might be present along paleo-Tethys subduction belt during the Late Paleozoic (~350 Ma, Early Carboniferous) in the Mian-Lue area of the Qinling Orogen. The paleo Tethyan ocean was a westward extension of the Suizhou-Jingshan Tethyan ocean in the southern side of Dabieshan belt (Dong *et al.*, 1999) (Fig. 1), implying that the Mian-Lue paleo ocean was a part of the larger paleo-Tethyan ocean. Thus, the South China and North China blocks were still separated by the Mian-Lue paleo Tethyan ocean in the Late Paleozoic. This infers that the final integration of these two continental blocks took place after ~ Carboniferous when the Mian-Lue paleo-Tethyan ocean disappeared. The collision time is most likely during the Triassic as is suggested by many collision and orogenic evidences recorded in Qinling area at that time (Li *et al.*, 1993, 1996; Zhang *et al.*, 1995, 1996). The recent study (Meng and Zhang, 1998) also supported above argument.

CONCLUSION

Adakitic andesite and HMAs have been recognized in the Sanchazi arc-block within the Mian-Lue ophiolitic and tectonic melange of the Qinling Orogen. Although all igneous rock from this block are highly enriched in LILEs and depleted in HFSE that are typical for subduction-zone lava, the adakitic andesite and HMAs have geochemical characteristics different from the normal andesites and basalts. The adakitic andesite from the SCZ block is characterized by the steep REE patterns, low Y and high $(\text{La}/\text{Yb})_{\text{N}}$ that are typical of adakites. The HMAs from the SCZ block also have adakitic affinities except for the lower La/Yb ratio and Al_2O_3 content. In addition, both the adakitic andesite and HMAs show a relatively enriched Nd isotopic signature, suggesting that they contain a little component from sediment or crustal materials. Our data reveal that adakitic andesite and HMAs in the SCZ block were not

generated by direct melting of mafic rocks in the lower crust or through an AFC process of a basaltic magma. It is most likely that these adakitic andesite and HMAs were produced by a series of events, starting with partial melting of an eclogitic subducted basalt or sediment, followed by interaction of the melt generated with the overlying mantle wedge, and/or finally assimilation with upper level crustal materials.

A full paleo ocean—arc system was present in the Mian-Lue area of the Qinling Orogen during the Late Paleozoic. The South China and North China blocks were still separated by the Mian-Lue paleo Tethyan ocean at that time. Thus, our results are in favor of the argument—it is in the Triassic that final integration occurred between the South China and North China block (craton).

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