Single-grain detrital muscovite Rb–Sr isotopic composition as an indicator of provenance for the Carboniferous sedimentary rocks in northern Dabie, China

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Low-grade metamorphic Paleozoic sedimentary rocks are exposed along the northern margin of the Qinling–Dabie orogenic belt that formed by the collision of the North and South China blocks during the Early Mesozoic. Geological provenance and tectonic setting of these low-grade sedimentary rocks are strongly debated. Recent studies have shown that they contain Paleozoic, Late Proterozoic and Late Archean detrital zircons, which points to an origin from different sources including rocks from the South and North China blocks. This study presents single-grain mineral Rb–Sr results for detrital muscovites and biotites from Carboniferous sedimentary sequences of the Beihuaiyang low-grade metamorphic zone exposed along the northern margin of the Dabie Mountains. About 15% of detrital muscovite grains are phengitic in composition with high Si/Al ratios of >3.3. Single grain Rb–Sr isotopic analyses show that both muscovites and phengites give a pooled age of about 420 Ma, implying Middle Paleozoic thermal and high-pressure metamorphic events in the source area(s). Rb–Sr isotopic evidence from detrital biotites suggests at least two different sedimentary sources of old crustal rocks and juvenile material. The latter probably comprised magmatic rocks related to the Paleozoic convergence along the southern margin of the North China block. Whole-rock Sm–Nd isotopic composition of the sedimentary rocks also demonstrates a mixture of sedimentary sources of different ages that confirm conclusions proposed previously from evidence of detrital zircon ages. We conclude that the Paleozoic detrital phengites originate from Paleozoic subduction and subsequent collision proposed for the North Qinling terrane. Our study shows that, single-grain detrital mica Rb–Sr isotopic characteristics can be a potential indicator for the provenance of geological complex terranes.

Keywords: Dabie, detrital muscovite, provenance, single-grain, Rb–Sr dating

INTRODUCTION

Rock fragments and detrital minerals as products of weathering and erosion of source rocks are useful media for studies of sedimentary sources and provenance of geological terranes. Material of sedimentary rocks can mainly derive from three major sources: (1) high-grade metamorphic rocks of deeply eroded cratonic basement, (2) young volcanic/plutonic rocks in accretionary terranes along active continental margins, and (3) recycled rock complexes of old crustal sections, especially in orogenic belts. These sources can often be distinguished by geochemical and isotopic compositions of whole-rocks and ages of detrital minerals characterized by high physical and/or chemical stability, such as zircon, garnet, and

apatite. They have been widely taken as indicators of provenance and tectonic evolution of fold belts or geological terranes (e.g., Valverde *et al.*, 2000; Nelson, 2001; Spiegel *et al.*, 2007; Oliver *et al.*, 2000). Ferromagnesian minerals susceptible to physical and chemical weathering processes have been less frequently used for tracing sedimentary sources, as their isotopic systems are considered to be easily influenced during weathering, erosion and transport processes. Isotopic closure temperatures of muscovite and biotite are estimated at ~450–500°C and ~350°C for the Rb–Sr isotopic system and ~350–400°C and ~300°C for the K–Ar system (e.g., Mezger, 1990; Villa, 1997; Jenkin *et al.*, 1995, 2001). Metamorphic temperatures of greenschist-facies normally range from about 350°C to 450°C. Hence, muscovite and biotite minerals of low-grade metamorphic rocks can preserve age information of their precursors. A few studies now have already demonstrated that isotopic ages of such minerals in sedimentary rocks of low maturity or low-grade

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Fig. 1. (a) Schematic geological map of the Dabie ultrahigh-pressure metamorphic terrane. (b) Rock units of the study area and sample localities (modified after Li et al., 2004). Abbreviations: HPU, Susong high-pressure metamorphic rock unit; UHPU, South Dabie ultrahigh-pressure metamorphic rock unit; NDDU, North Dabie gneiss dome unit; BHY, Beihuaiyang low-grade metamorphic zone; XGF, Xiangfan–Guangji fault; XMF, Xiaotian–Mozitan fault; TSF, Tong–Shang fault; EOC, Erlangping ophiolite complex; AKC, Archean Kongling complex.

metasedimentary rocks can be also potential indicators for provenance studies of geological terranes. For instance, Haines *et al.* (2004) have studied the ^{40}Ar – ^{39}Ar age patterns of detrital muscovite of the Adelaide Rift complex in southern Australia and revealed a Pan-African age information in sedimentary rocks, while Sm–Nd isotopic composition and detrital zircon ages of this rock complex only provided Paleo- to Mesoproterozoic sedimentary source information.

Low-grade metamorphic Paleozoic sedimentary rocks are exposed along the northern margin of the Qinling–Dabie orogenic belt, which formed by the collision of the North and South China (or Yangtze) blocks during Early Mesozoic (e.g., Mattauer *et al.*, 1985; Ames *et al.*, 1993, 1996; Cong *et al.*, 1995; Meng and Zhang, 2000). Geological provenance and tectonic setting of these low-grade rocks are controversially debated, being regarded as deposits along the passive margin of the northern Yangtze block (Okay *et al.*, 1993; Zheng *et al.*, 2005; Zhou *et al.*, 2001), or along the active continental margin of the southern North China block (Şengör *et al.*, 1988; Dong *et al.*, 1993; Chen *et al.*, 2003a; Li *et al.*, 2004). Recent studies have shown that these low-grade sedimentary rocks contain Late Archean, Late Proterozoic, and Early-Middle Paleozoic detrital zircons. These characteristics point to an origin of these sediments from different source terranes involving both the Yangtze and North China blocks (Chen *et al.*, 2003a; Li *et al.*, 2004). Li *et al.* (2004) have found abundant detrital zircon grains of Paleozoic age in most of the low-grade metamorphic Carboniferous sedimentary strata exposed along the northern part of the Dabie–Qinling orogenic belt. Part of the sedimentary sequence contains phengitic muscovite as detrital mineral phase (Li *et al.*, 2004). For a better understanding of the origin and provenance of the Paleozoic sedimentary sequence, more information on the age and origin of detrital phengites and on the isotopic characteristics of the sedimentary rocks is necessary.

In this study, we present Rb–Sr mica and Sr–Nd whole-rock data from the Carboniferous sedimentary rocks exposed in the northern part of the Qinling–Dabie orogenic belt. The data impose new constraints on the provenance and tectonic setting of this low-grade metamorphic zone. Single mica grains (i.e., detrital muscovite and biotite) were used for Rb–Sr dating. The single-grain or micro-sample technique was recently developed and, so far, has been explored for dating micas from magmatic and metamorphic rocks (Müller *et al.*, 2000a, b; Li *et al.*, 2005), sulfide minerals from ore deposits (Li *et al.*, 2008a; Han *et al.*, 2007), and foraminifera from marine sediments (Tong *et al.*, 2006). In the present study we show that the single-mica grain Rb–Sr analytical technique is a potential tool to study the origin of detrital minerals and the provenance of geological terranes.

GEOLOGICAL SETTING AND SAMPLES

The Dabie ultrahigh-pressure (UHP) collisional belt (Fig. 1a) constitutes the eastern part of the Qinling–Dabie orogenic belt in central China, which was formed by collision of the North China block and Yangtze blocks during Early Mesozoic (e.g., Ames *et al.*, 1993; Eide *et al.*, 1994; Cong *et al.*, 1995; Li, S.-G. *et al.*, 1993, 1999, 2000). The collision time has been constrained at about 230 Ma to 220 Ma by numerous radiometric studies (e.g., Ames *et al.*, 1993; Li, S.-G. *et al.*, 1993, 1999, 2000; Xu *et al.*, 2000; Zheng *et al.*, 2003). The most striking rocks are eclogites and their host gneisses of the South Dabie UHP zone. Typical UHP metamorphic mineral inclusions such as coesite and diamond found in garnet and zircon indicate deep subduction of continental crust during the collision (e.g., Liou *et al.*, 1996; Xu *et al.*, 1992; Okay *et al.*, 1993; Ye *et al.*, 2000). Geologically, the Dabie UHP belt (Fig. 1a) is made up of several major, tectonically juxtaposed zones (or units), i.e., from south to north, the foreland fold and thrust belt, the Susong high-pressure zone (HPU in Fig. 1a), the South Dabie ultrahigh-pressure metamorphic zone (UHPU), the North Dabie gneiss zone or dome (NDDU), and the Beihuiyang low-grade metamorphic zone (e.g., Hacker *et al.*, 1998). Late Mesozoic granites and diorites are widely distributed in the Dabie terrane and Cretaceous volcanic rocks are mainly exposed in the low-grade metamorphic zone.

Low-grade metamorphic rocks, particularly meta-sedimentary rocks, are exposed along the northern margin of the Dabie Mountains. These rocks can be found north of the Tong–Shang fault and the Xiaotian–Mozitan fault (Fig. 1a; Ma, 1991; You *et al.*, 1999). The Carboniferous sedimentary sequence has a total thickness of more than 2000 m (Ma, 1991; Wang *et al.*, 1994; Li, B. *et al.*, 2000). From bottom to top it is composed of the Huayuanqiang (D_3 ?– C_1), Yangshan (C_1), Daorenchong (C_{1-2}), Huyoufang (C_2), and Yangxiaozhuang (C_2) Formations (Li, B. *et al.*, 2000; Li *et al.*, 2004). Contacts between these five formations are described as conformable in the report of the Bureau of Geology and Mineral Resources of Hennan Province (1989), but fault contacts between them have also been proposed (Li, B. *et al.*, 2000; Jin, 1995). The Huayuanqiang Formation is a sequence of fluvial sediments, which consists of medium to coarse grained quartz sandstone with intercalated beds of mudstone, siltstone and conglomerate. The Yangshan Formation comprises coal-bearing clastic sediment consisting of quartz-pebble conglomerate and quartz sandstone with intercalated beds of siltstone, mudstone and coal. The Daorenchong Formation is composed of quartz sandstone and feldspathic quartz sandstone with intercalated quartz-pebble conglomerate, siltstone and shale beds. The Huyoufang Formation is the major part of the Carbonif-

erous sequence, and is mainly composed of feldspathic sandstone including micaceous and lithic feldspathic sandstone, subordinate conglomerate, siltstone, and silty or calcareous mudstone with fossil freshwater bivalves, sometimes occurring as rhythmic deposits. This formation is interpreted to have been deposited in a fluvial-lacustrine environment (Jin and Zhang, 1993). The Yangxiaozi Formation is composed of fine-grained conglomerate, sandstone, siltstone, shale and coal beds with rhythmic sedimentary layering. More detailed information on the Carboniferous sedimentary sequence is given in Li *et al.* (2004).

Accessory detrital mineral phases found in the Carboniferous sedimentary rocks are muscovite, biotite, zircon, tourmaline, and garnet (Li *et al.*, 2004). A mineral chemical study has shown that detrital tourmaline grains were derived from metapelites and metapsammities and partly from Li-poor granitoids and pegmatites (Li *et al.*, 2004). Detrital garnet was only found in the Huyoufang Formation (C₂). The grains belong to the almandine and Mn-almandine series and were likely derived from garnetiferous schists (Li *et al.*, 2004). Detrital zircons show a complex age spectrum but their U–Pb ages mainly range from 500 Ma to 360 Ma clustering around 480 Ma to 400 Ma (Li *et al.*, 2004). Detrital muscovites are widely distributed in the Carboniferous sequences. Amongst them, phengitic muscovites can be found in the Huyoufang (C₂) and Yangxiaozi (C₂) Formations.

For this study, eight representative meta-sedimentary rock samples were collected from the Carboniferous sequences. They include two quartz sandstones (M2 and M74) from the Yangxiaozi Formation (C₂), five arkoses and siltstones (M6, M13, M70, M78-1, and M78-2) from the Huyoufang Formation (C₂), and one arkose (M85) from the Daorenchong Formation (C₁₋₂). Sample localities are shown in Fig. 1b. Samples M13 and M70 contain detrital muscovite and biotite. Phengitic muscovite is found in sample M70.

ANALYTICAL METHODS

Whole-rock powders were obtained by crushing and splitting of about 5 kg of rock material. Muscovite and biotite were isolated from crushed rocks by standard mineral separation techniques and were handpicked for analysis under a binocular microscope. Chemical separation and mass spectrometric analyses were performed in the Laboratory for Radiogenic Isotope Geochemistry, Institute of Geology and Geophysics, Chinese Academy of Sciences (IGG CAS). All acids were doubly cleaned in a FEPT 2-bottle still and a Millipore-Element® equipment provided 18.2 MΩ purified water. Mineral composition was determined by a Cameca SX-51 electron microprobe located in the IGG CAS, using wavelength dispersive

analysis and an acceleration voltage of 15 kV. Major elements were determined by X-ray fluorescence spectrometry (located in the IGG CAS) with analytical uncertainties ranging from 1 to 3%. Trace (including rare earth) element concentrations were determined using an inductively coupled plasma mass spectrometer (ICP-MS) located in the School of Earth and Space Sciences, University of Science and Technology of China, Hefei, Anhui Province. For ICP-MS analyses samples were dissolved in a mixture of HF + HNO₃ acid solutions in Teflon bombs for 5 days at a temperature of 200°C. Analytical uncertainties for most elements are better than 5%.

Single grain mineral Rb–Sr analysis

Single grains of muscovite and biotite without alteration features and visible impurities were carefully chosen by handpicking under a binocular microscope. The micas were cleaned in analysis-grade alcohol to eliminate organic matter entrapped during mineral separation, and were subsequently washed in 0.1 N HCl solution to remove potential intergrowth minerals, such as carbonates, in order to increase the Rb/Sr and ⁸⁷Sr/⁸⁶Sr ratios (Brown *et al.*, 1989). The samples were spiked with a ⁸⁷Rb and ⁸⁴Sr tracer solution. 2 μl purified 1% H₃PO₄ was added to the samples to reduce the risk in loss of spike during drying, owing to the high boiling point of H₃PO₄ acid. A vapor digestion method using a Parr® bomb was applied for sample digestion. A rack with vessels for sample was put in a Teflon® bomb filled with 2 ml HF and 0.2 ml HNO₃. The bomb was then put in a steel liner to hold required pressure. The samples were dissolved at about 195°C for 48 hours. The HF solution that remained in the vessels was dried and replaced by 0.1 ml 3N HNO₃, then the vessels were heated again to convert fluoride salts to more soluble nitrate salts. After drying 0.2 ml 3N HNO₃ was added to the vessels. Separation and purification of Rb and Sr were performed on Teflon® columns (0.25 cm wide, 2 cm high for resin, and 0.68 cm wide, 1.5 cm high for reagent) with about 0.1 ml Sr-Spec® resin^[18] allowing to improve sensitivity and recovery. The eluates of Rb and Sr separation were loaded on the filaments with 2 μl purified 1% H₃PO₄ and dried. Total procedural blanks were 4 ± 1 pg for Rb and 6 ± 1 pg for Sr. The average ⁸⁷Sr/⁸⁶Sr ratio of the blank was 0.710.

Isotopic ratios of Rb and Sr were measured on an IsoProbe-T mass spectrometer located in the Laboratory for Radiogenic Isotope Geochemistry, which is equipped with seventeen collectors including nine Faraday cups, one Daly receiver, and seven ion counters. It has high sensitivity for precise Sr isotopic measurements on sub-nanogram samples with an internal precision of ⁸⁷Sr/⁸⁶Sr ratios better than 0.002%. For isotopic measurements, Sr micro-samples (<1 ng) were loaded with 2N HNO₃ and a purified Ta–HF emitter solution onto a single W filament.

Rb was loaded with 2N HNO₃ onto a single Ta filament. Sr isotopic ratios were measured in static Faraday multicollector mode. ⁸⁵Rb was monitored simultaneously by a Daly receiver to allow isobaric interference correction from ⁸⁷Rb on ⁸⁷Sr. Correction of mass fractionation for Sr isotopic ratios was based on ⁸⁸Sr/⁸⁶Sr = 8.37521 using a power law. Repeated analyses of the NBS 987 Sr standard gave a mean value of 0.710245 ± 0.000006 (*n* = 5, ± 2σ) for the ⁸⁷Sr/⁸⁶Sr ratio. More details on the analytical procedures are given in Li *et al.* (2005, 2008a, 2008b). Isochron calculation was performed with Isoplot software (Ludwig, 2001), using the decay constant of ⁸⁷Rb recommended by Steiger and Jäger (1977). Input errors (2σ) were 2% for ⁸⁷Rb/⁸⁶Sr and 0.01% for ⁸⁷Sr/⁸⁶Sr ratios.

Whole-rock Sm–Nd and Rb–Sr analysis

About 150 mg whole-rock sample powders were spiked with mixed ¹⁴⁹Sm–¹⁵⁰Nd and ⁸⁷Rb–⁸⁴Sr tracer solutions and decomposed for one week in a mixture of HF–HClO₄ under high temperature and pressure conditions. Rb–Sr and rare-earth elements were isolated on quartz columns by ion exchange chromatography with a 5-ml resin bed of AG 50W × 12. Nd and Sm were separated from other rare-earth elements on quartz columns using 1.7-ml Teflon powder coated with HDEHP, di(2-ethylhexyl)orthophosphoric acid, as cation exchange medium. Sr was loaded with a Ta–HF activator on pre-conditioned W filaments and was measured in single-filament mode. Sm, Nd, and Rb were loaded as phosphates on pre-conditioned Re filaments and measurements were performed in a double filament configuration. All isotope measurements were performed on an Isoprobe-T mass spectrometer. ⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd ratios were normalized to ⁸⁶Sr/⁸⁸Sr = 0.1194 and ¹⁴⁶Nd/¹⁴⁴Nd = 0.7219, respectively. Repeated measurements of Ames metal and NBS 987 Sr standard gave mean values of 0.512143 ± 0.000015 (*n* = 6) for ¹⁴³Nd/¹⁴⁴Nd ratio and 0.710246 ± 0.000018 (*n* = 5) for ⁸⁷Sr/⁸⁶Sr ratio (2σ errors). Total procedural blanks were <300 pg for Sr and <50 pg for Nd. Detailed analytical procedures are given in Chen *et al.* (2007).

ANALYTICAL RESULTS

Geochemical and Sr–Nd isotopic composition

Major and trace element concentrations of eight meta-sedimentary rock samples are given in Table 1. The analyzed samples show large variations in major and trace element contents. Two quartz sandstones from the Yangxiaozhuang Formation contain 86.2 to 95.5 wt.% SiO₂, while in arkoses and siltstones of the Huyoufang and Daorenchong Formations SiO₂ varies between 51.1 to 79.8 wt.%. Sample M13 likely contains significant

Fig. 2. Normalized trace and rare earth element concentrations of the Carboniferous sedimentary rocks. Normalizing values of chondrite and primordial mantle and average crustal composition taken from Sun (1982) and Taylor and McLennan (1985).

amount of carbonate minerals as indicated by high LOI. Rare earth elements (REE) show large variation in concentration but all samples except sample M13 have similar chondrite-normalized REE patterns with negative Eu anomaly (Fig. 2a), which are comparable with the pattern of the average continental crust (Taylor and McLennan, 1985). The total REE-content of sample M2 is low as this sample contains almost only quartz. Most of the samples (except samples M2 and M13) display significant depletion in Nb, Ti and Sr (Fig. 2b). All the samples contain high Cr (210–453 ppm), significantly higher than average upper crust (35 ppm; Taylor and McLennan, 1985) and average post-Archean shale (110–100 ppm; Taylor and McLennan, 1985; Krauskopf, 1967). In the La–Th–Sc ternary diagram, samples plot in the field for magmatic arc related sources (Fig. 3a; Bhatia and Crook, 1986; Girty *et al.*, 1993), while in the Th–Sc–Zr/10 diagram, only half of the samples plot in the field for mag-

Table 1. Major and trace element contents of the Carboniferous sedimentary rocks

Sample Formation Lithology	M2 YXZ SS	M6 HYF SS	M13 HYF SS	M70 HYF SS	M74 YXZ SS	M78-1 HYF SL	M78-2 HYF SS	M85 DYQ SS
SiO ₂	95.53	79.76	51.11	68.68	86.25	54.14	52.51	62.36
TiO ₂	0.41	0.49	0.69	0.93	0.75	1.12	0.79	0.94
Al ₂ O ₃	1.36	9.68	13.05	14.43	5.64	21.21	15.40	17.17
Fe ₂ O ₃	1.03	3.23	5.67	5.37	3.14	5.32	6.58	8.11
MnO	0.01	0.04	0.09	0.05	0.01	0.05	0.13	0.08
MgO	0.08	1.21	2.90	3.07	0.58	4.22	4.48	1.79
CaO	0.04	0.29	10.04	0.18	0.03	0.33	13.33	0.23
Na ₂ O	0.04	2.09	2.03	0.48	0.11	0.11	1.08	0.22
K ₂ O	0.10	1.09	1.62	2.40	1.02	4.64	3.90	2.20
P ₂ O ₅	0.04	0.08	0.19	0.08	0.09	0.05	0.17	0.16
LOI	0.73	2.47	12.52	4.81	2.05	9.03	0.98	7.16
Total	99.37	100.44	99.92	100.47	99.68	100.22	99.35	100.42
Ba	85.5	544.0	11.5	345.9	276.1	1193	726.7	809.2
Sc	1.62	7.10	7.99	38.12	18.55	35.40	17.03	20.50
Cs	0.56	0.87	0.20	2.91	2.30	10.84	4.99	10.90
Cr	452.7	322.6	184.9	211.3	249.1	298.5	194.2	210.2
V	16.49	56.67	379.3	125.5	62.5	225.8	186.4	125.8
Rb	6.56	36.55	0.70	84.69	45.76	251.2	157.5	107.3
Sr	102.3	123.9	302.9	18.5	26.3	49.9	270.5	45.0
Y	6.58	15.39	45.84	17.83	18.42	39.55	33.57	32.14
Zr	34.58	169.1	103.1	172.6	91.83	176.6	180.0	192.7
Nb	6.64	7.53	5.19	15.17	11.97	18.62	17.42	16.20
Ta	0.68	0.64	0.38	1.26	1.13	1.63	1.44	1.34
Hf	0.96	5.22	2.93	5.32	2.76	5.54	5.30	6.15
Pb	18.40	7.53	2.00	4.06	4.24	58.31	10.49	9.37
Th	1.81	8.43	0.61	13.28	6.87	26.88	14.15	12.43
U	1.00	1.53	0.12	1.86	2.30	6.61	11.31	3.25
La	8.24	30.81	6.19	34.71	21.11	66.37	35.58	45.90
Ce	14.32	55.72	14.94	58.17	44.33	136.40	72.47	73.75
Pr	1.75	6.37	2.55	8.00	5.58	17.15	8.89	11.27
Nd	6.27	22.47	13.20	27.88	21.42	63.95	34.33	43.15
Sm	1.21	3.95	4.21	4.83	4.16	12.08	6.78	8.32
Eu	0.33	0.85	1.60	0.92	0.95	3.08	1.38	1.88
Gd	1.25	3.25	6.00	3.93	3.65	10.28	6.67	7.42
Tb	0.23	0.50	1.19	0.61	0.56	1.58	1.08	1.10
Dy	1.37	2.70	7.65	3.31	3.32	8.38	6.13	6.13
Ho	0.27	0.56	1.66	0.67	0.70	1.66	1.24	1.23
Er	0.69	1.56	4.50	2.01	1.89	4.55	3.40	3.50
Tm	0.09	0.23	0.63	0.29	0.28	0.64	0.52	0.52
Yb	0.54	1.58	3.84	1.97	1.84	4.28	3.36	3.35
Lu	0.08	0.26	0.59	0.31	0.28	0.68	0.51	0.53

YXZ, the Yangxiaozi Formation (C₂); HYF, the Huyoufang Formation (C₂); DYQ, the Daorenchong Formation (C₁₋₂); SS, sandstone; SL, siltstone.

matic arc related sources (Fig. 3b; Bhatia and Crook, 1986), similarly when plotted in the Ti/Zr–La/Sc diagram (Fig. 4a). This scattered distribution is likely caused by several factors such as different source material of different sedimentary sequences, or fractionation of elements during weathering, erosion and transportation. All samples have low Sc/Cr ratios due to high Cr-contents and plot beyond the field for the magmatic arc related sources (Fig. 4b).

Table 2 presents the whole rock Rb–Sr and Sm–Nd isotopic data. Measured ⁸⁷Sr/⁸⁶Sr ratios of the samples range from 0.71365 to 0.76511. When calculated back to 320 Ma (boundary between C₁ and C₂), samples M70 and M78-1 give low initial ⁸⁷Sr/⁸⁶Sr ratios (<0.7011), whereas the other six samples have initial ⁸⁷Sr/⁸⁶Sr ratios between 0.7096 and 0.7177. Measured ¹⁴³Nd/¹⁴⁴Nd ratios vary from 0.511888 to 0.512104 and initial ¹⁴³Nd/¹⁴⁴Nd ratios, calculated back to 320 Ma, range from 0.511618 to

Fig. 3. Ternary diagrams of trace element composition of the Carboniferous sedimentary rocks. (a) La–Th–Sc plot (Bhatia and Crook, 1986; Girty *et al.*, 1993) and (b) Th–Sc–Zr/10 plot (Bhatia and Crook, 1986).

Fig. 4. (a) Ti/Zr vs. La/Sc diagram and (b) La/Y vs. Sc/Cr diagram showing trace element composition of the Carboniferous sedimentary rocks. Fields for tectonic settings are taken from Bhatia and Crook (1986).

0.511882, corresponding to $\epsilon_{\text{Nd}}(t)$ values of -11.86 to -6.72 (Fig. 5a). Compared to the basement rocks from the North China block (with Nd modal ages between 2.5 Ga to 3.5 Ga; see compilation in Wu *et al.*, 2005), the Carboniferous sedimentary rocks are characterized by much younger Nd modal ages (1.22 Ga to 2.25 Ga; Fig. 5b). In several samples the Sm/Nd ratio was higher or lower than the Sm/Nd ratio of average continental crust and modal ages range merely from 1.65 Ga to 2.07 Ga (Fig. 5c) when a two-stage modal age calculation method after Liew and Hofmann (1988) is used. The Nd isotopic characteristics of the Carboniferous sedimentary rocks are comparable with the sedimentary sequences of the Yangtze block, which have Nd modal ages clustering between 1.5 Ga and 2.0 Ga (Chen and Jahn, 1998).

Single-grain mica Rb–Sr analysis

Prior to Rb–Sr analysis, the chemical composition of separated mineral grains from samples M13 and M70 was determined by electron microprobe analysis. Analytical results show that all muscovite grains are potassic white micas (Table 3). In the Si vs. Al_{total} diagram (11 oxygen atom basis per formulae unit, pfu), four out of fifteen muscovite grains of sample M70 have high Si-content with Si contents >3.3 , Si pfu. Other grains from this sample cluster around 3.1 to 3.2 Si atoms pfu (Fig. 6). In sample M13 no muscovite with Si contents >3.3 pfu was detected.

Thirty-three detrital muscovite grains from samples M13 and M70 were selected for single-grain Rb–Sr isotope analysis. Sample M70 commonly contains small muscovite and biotite grains and only nine grains could

Table 2. Sm–Nd and Rb–Sr isotopic composition of the Carboniferous sedimentary rocks

Sample	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$ (2 σ)	$^{87}\text{Sr}/^{86}\text{Sr}$ (320 Ma)	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$ (2 σ)	$^{143}\text{Nd}/^{144}\text{Nd}$ (320 Ma)	$\epsilon_{\text{Nd}}(t)$	T_{DM} (Ga)	T_{DM2} (Ga)
M2	6.480	104.3	0.180	0.716615 $\pm$ 8	0.71580	1.184	6.073	0.1178	0.511962 $\pm$ 5	0.511715	–9.97	1.88	1.92
M74	46.54	24.90	5.425	0.742400 $\pm$ 8	0.71769	4.553	22.89	0.1203	0.511910 $\pm$ 7	0.511658	–11.08	2.02	2.01
M6	34.77	112.4	0.896	0.713647 $\pm$ 6	0.70957	4.012	22.39	0.1083	0.512008 $\pm$ 5	0.511781	–8.69	1.65	1.81
M13	80.64	332.3	0.702	0.712834 $\pm$ 4	0.70963	4.053	19.97	0.1227	0.512066 $\pm$ 4	0.511808	–8.15	1.81	1.77
M70	80.83	16.72	14.06	0.765112 $\pm$ 9	0.70107	2.984	24.09	0.0749	0.512039 $\pm$ 6	0.511882	–6.72	1.22	1.65
M78-1	230.5	43.06	15.56	0.751750 $\pm$ 9	<0.70	10.93	56.45	0.1171	0.512094 $\pm$ 5	0.511849	–7.36	1.66	1.70
M78-2	157.2	271.1	1.680	0.722333 $\pm$ 11	0.71468	7.260	34.14	0.1286	0.511888 $\pm$ 6	0.511618	–11.86	2.25	2.07
M85	94.64	40.19	6.840	0.746864 $\pm$ 9	0.71571	8.050	40.02	0.1216	0.512104 $\pm$ 5	0.511849	–7.35	1.72	1.70

T_{DM2} values are calculated after Liew and Hofmann (1988) using $T = 320$ Ma.

Fig. 5. Whole-rock Sm–Nd isotopic composition of the Carboniferous sedimentary rocks. (a) Initial ϵ_{Nd} values at 320 Ma. (b) T_{DM} values. (c) Two-stage model age values (T_{DM2}), calculated using $T = 320$ Ma and $^{147}\text{Sm}/^{144}\text{Nd}$ ratio of 0.12 for average crust after Liew and Hofmann (1988).

be analyzed by the single-grain Rb–Sr technique. Some of these grains were not analyzed by electron microprobe. From sample M13, twenty-three muscovite and eight biotite grains were chosen for analysis. Rb–Sr analytical results for biotite and muscovite are given in Table 4. In the $^{87}\text{Rb}/^{86}\text{Sr}$ vs. $^{87}\text{Sr}/^{86}\text{Sr}$ plot (Fig. 7), all muscovite grains define a linear trend and the analytical data can be regressed together, giving a pooled age of 419 ± 33 Ma and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7220 ± 0.0070 . As the detrital muscovite and phengite grains can have different formation/metamorphism ages and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, this isochron age is not considered as a geological meaningful result. However, considering the $^{87}\text{Sr}/^{86}\text{Sr}$ whole-rock ratios of the Carboniferous sedimentary rocks (0.7096 to 0.7177 at 320 Ma), it is reasonable to assume that the detrital muscovite grains crystallized not later than late Silurian (>420 Ma). Taking an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio

Table 3. Chemical composition of detrital muscovite grains

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	MgO	FeO	Na ₂ O	K ₂ O	H ₂ O	Total*
M70-g1	46.05	0.35	31.65	1.45	1.88	0.20	8.85	4.31	94.80
-g2	47.58	0.67	35.69	0.89	1.20	0.66	9.02	4.58	100.33
-g3	47.29	0.89	36.37	0.58	1.19	0.54	8.10	4.57	99.56
-g4	47.07	0.42	33.38	0.99	3.74	0.57	9.22	4.49	99.98
-g5	46.76	0.82	34.60	0.85	2.23	0.59	8.56	4.50	98.97
-g6	47.10	1.72	34.94	1.53	0.55	0.37	9.35	4.57	100.21
-g7	47.00	1.18	31.41	1.62	4.22	0.11	9.78	4.46	99.88
-g8	51.95	0.19	28.78	3.39	1.94	0.19	8.36	4.56	99.56
-g9	46.99	0.88	36.37	0.61	1.03	0.37	7.64	4.54	98.50
-g10	47.05	0.46	36.06	0.84	1.20	0.71	8.95	4.56	99.94
-g11	47.93	0.43	36.30	0.97	1.50	0.29	8.87	4.62	100.95
-g12	47.14	0.58	32.67	2.42	2.55	0.18	8.31	4.47	98.36
-g13	50.68	0.22	28.42	3.21	2.25	0.21	9.10	4.49	98.59
-g14	53.76	0.16	25.77	2.73	4.95	0.02	4.69	4.49	96.68
-g15	53.69	0.16	26.33	2.98	4.37	0.02	5.12	4.51	97.22
M13-g1	47.00	0.70	35.25	1.05	1.31	0.41	8.86	4.53	99.17
-g2	47.47	0.70	35.87	0.75	1.56	0.45	9.69	4.59	101.18
-g3	46.41	0.42	36.07	0.82	1.34	0.43	9.15	4.52	99.21
-g4	46.93	0.72	35.38	0.89	1.40	0.39	9.51	4.54	99.75
-g5	47.04	0.56	34.73	0.96	2.04	0.18	9.33	4.52	99.47
-g6	47.26	0.71	34.51	1.21	1.88	0.25	9.25	4.53	99.70
-g7	46.61	0.77	35.78	0.69	1.22	0.52	9.07	4.53	99.31
-g8	47.18	0.68	34.29	1.24	1.54	0.24	9.63	4.51	99.39
-g9	47.73	0.52	34.83	1.27	1.60	0.62	9.07	4.57	100.25
-g10	47.09	0.72	35.44	0.80	1.24	0.49	8.85	4.53	99.19
-g11	45.57	0.72	35.55	0.78	1.47	0.47	9.33	4.47	98.40

Sample	Si	Ti	Al	Mg	Fe	Na	K	Total*
M70-g1	3.20	0.02	2.59	0.15	0.11	0.03	0.79	6.89
-g2	3.12	0.03	2.75	0.09	0.07	0.08	0.75	6.89
-g3	3.10	0.04	2.81	0.06	0.07	0.07	0.68	6.82
-g4	3.14	0.02	2.62	0.10	0.21	0.07	0.79	6.95
-g5	3.12	0.04	2.71	0.09	0.12	0.08	0.73	6.89
-g6	3.09	0.09	2.70	0.15	0.03	0.05	0.78	6.89
-g7	3.16	0.06	2.49	0.16	0.24	0.01	0.84	6.96
-g8	3.41	0.01	2.23	0.33	0.11	0.03	0.70	6.83
-g9	3.10	0.04	2.83	0.06	0.06	0.05	0.64	6.78
-g10	3.09	0.02	2.79	0.08	0.07	0.09	0.75	6.90
-g11	3.11	0.02	2.78	0.09	0.08	0.04	0.74	6.86
-g12	3.16	0.03	2.58	0.24	0.14	0.02	0.71	6.89
-g13	3.39	0.01	2.24	0.32	0.13	0.03	0.78	6.88
-g14	3.59	0.01	2.03	0.27	0.28	0.00	0.40	6.59
-g15	3.57	0.01	2.06	0.30	0.24	0.00	0.43	6.61
M13-g1	3.11	0.04	2.75	0.10	0.07	0.05	0.75	6.88
-g2	3.10	0.04	2.76	0.07	0.09	0.06	0.81	6.92
-g3	3.08	0.02	2.82	0.08	0.07	0.06	0.77	6.90
-g4	3.10	0.04	2.75	0.09	0.08	0.05	0.80	6.91
-g5	3.12	0.03	2.72	0.10	0.11	0.02	0.79	6.89
-g6	3.13	0.04	2.69	0.12	0.10	0.03	0.78	6.89
-g7	3.09	0.04	2.79	0.07	0.07	0.07	0.77	6.89
-g8	3.13	0.03	2.68	0.12	0.09	0.03	0.82	6.91
-g9	3.14	0.03	2.69	0.12	0.09	0.08	0.76	6.91
-g10	3.12	0.04	2.76	0.08	0.07	0.06	0.75	6.87
-g11	3.06	0.04	2.81	0.08	0.08	0.06	0.80	6.93

*Total geochemical contents of analytical spots including Cr₂O₃ (<0.04 wt.%), CaO (<0.15 wt.%), MnO (<0.06 wt.%), and NiO (<0.05 wt.%).

Fig. 6. Si–Al plot of detrital muscovites from the Carboniferous sedimentary rocks.

Fig. 7. Rb–Sr isotopic composition of detrital muscovites, detrital biotites and whole-rocks of the Carboniferous sedimentary rocks.

of 0.72, model Rb–Sr ages were calculated for individual grains (Table 4). The distribution pattern of these modal ages likely suggests that most grains formed between 400 Ma and 480 Ma (Fig. 8). Three phengitic muscovite grains yield Rb–Sr model ages of 386 Ma, 415 Ma, and 457 Ma, implying Devonian and/or pre-Devonian high-pressure metamorphism(s).

From the Rb–Sr isotopic data set of sample M13 two different groups of detrital biotite can be distinguished (Fig. 7). Four biotite grains have high $^{87}\text{Rb}/^{86}\text{Sr}$ ratios between 72 and 91 and high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios between 0.7864 and 0.8199, while the other four biotite grains yield lower $^{87}\text{Rb}/^{86}\text{Sr}$ (14 to 33) and lower $^{87}\text{Sr}/^{86}\text{Sr}$ ratios

Fig. 8. Histogram showing Rb–Sr model ages of detrital muscovites from Carboniferous sedimentary rocks. Calculation of model ages was done assuming an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.72.

(0.7262 to 0.7434). All biotite grains give surprisingly young Rb–Sr model ages (<100 Ma; Table 4) by using an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.72. This phenomenon indicates that the Rb–Sr isotopic system of detrital biotite was obviously disturbed during diagenesis of the sedimentary rocks and/or during later metamorphism.

DISCUSSION

The tectonic setting and provenance of the low-grade Beihuaiyang metamorphic zone exposed along the northern foothills of the Dabie Mountains has been controversially discussed. The metasediments of this zone have been considered as flysch formation that was deposited in a back-arc or fore-arc basin along the active margin of the southern North China block (e.g., Şengör *et al.*, 1988; Dong *et al.*, 1993). Alternatively, the sedimentary sequence was interpreted as a passive margin deposit along the northern margin of the South China Block (e.g., Okay *et al.*, 1993; Zhou *et al.*, 2001; Zheng *et al.*, 2005). Detrital zircon ages from the Foziling group of the Beihuaiyang low-grade metamorphic zone, which comprises Paleozoic sedimentary rocks (Chen *et al.*, 2003a) and from other Carboniferous sedimentary rocks (Li *et al.*, 2004), which both belong to this low-grade metamorphic zone, evidently demonstrate that the metasediments contain populations of Early Paleozoic detrital zircons of North China affinity as well as Late Proterozoic detrital zircons of Yangtze affinity. It was concluded that the sedimentary material originated from these two different cratonic sources. It was further concluded that the sediments were deposited on the active southern margin of the North China block (Chen *et al.*, 2003a; Li *et al.*, 2004). This interpretation was mainly based on the fact that Neoproterozoic magmatism (~700–800 Ma) is widely

Table 4. Single-grain Rb–Sr analytical data of detrital micas

Sample	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	error (2 σ)	Model age** (Ma)
M13	biotite					
Bi-g1	62.39	7.092	25.54	0.74220	0.00003	50
Bi-g2	62.39	12.73	14.20	0.72625	0.00004	48
Bi-g3	107.4	16.01	19.44	0.73325	0.00002	31
Bi-g4	55.03	4.85	32.90	0.74337	0.00003	61
Bi-g5	56.17	2.28	72.04	0.81990	0.00032	98
Bi-g6	127.5	4.40	84.61	0.79916	0.00080	66
Bi-g7	131.3	4.77	80.23	0.79038	0.00024	62
Bi-g8	78.57	2.52	90.75	0.78644	0.00056	52
M13	muscovite					
Mus-g1	11.17	1.73	18.90	0.81869	0.00009	367
Mus-g2	7.84	4.11	5.540	0.75182	0.00009	404
Mus-g3	27.41	9.24	8.636	0.77475	0.00010	446
Mus-g4	16.88	3.71	13.28	0.79557	0.00008	400
Mus-g5	8.68	16.74	1.505	0.73658	0.00014	777
Mus-g6	14.83	6.93	6.226	0.76167	0.00008	470
Mus-g8	14.98	4.07	10.71	0.77767	0.00007	378
Mus-g9	11.16	2.01	16.22	0.81168	0.00012	397
Mus-g10	25.32	6.60	11.19	0.79005	0.00005	440
Mus-g11	23.54	4.51	15.25	0.81094	0.00003	419
Mus-g12	13.81	3.07	13.15	0.79798	0.00010	417
Mus-g13	30.13	3.80	23.26	0.86329	0.00072	433
Mus-g14	15.10	4.57	9.641	0.78481	0.00015	472
Mus-g15	41.29	7.13	16.96	0.82644	0.00007	441
Mus-g16	51.46	8.83	17.06	0.82899	0.00007	449
Mus-g17	30.04	6.09	14.41	0.80512	0.00012	415
Mus-g18	47.29	20.22	6.812	0.77245	0.00080	541
Mus-g19	23.65	5.02	13.78	0.82000	0.00160	509
Mus-g20	32.85	5.62	17.10	0.82371	0.00016	426
Mus-g21	40.61	6.37	18.69	0.83978	0.00007	450
Mus-g22	14.39	3.10	13.59	0.80904	0.00006	460
Mus-g23	30.57	7.80	11.43	0.79629	0.00016	469
Mus-g24	14.94	2.71	16.14	0.82597	0.00017	461
M70	muscovite					
Mus-g1	40.01	8.57	13.61	0.78977	0.00019	360
Mus-g2	40.14	7.40	15.85	0.80287	0.00017	368
Mus-g4	63.20	19.35	9.523	0.77650	0.00012	417
Mus-g5	62.09	19.61	9.231	0.78068	0.00013	462
Mus-g8*	77.76	7.65	30.01	0.91548	0.00026	457
Mus-g9	15.93	1.59	29.50	0.86135	0.00024	337
Mus-g12	39.85	6.64	17.56	0.81908	0.00021	396
Mus-g13*	39.08	4.31	26.70	0.87770	0.00013	415
Mus-g15*	34.05	21.18	4.672	0.74562	0.00017	386

Contents of Rb and Sr were calculated from an estimated weight of mineral grains.

*Phengite (Si number > 3.3).

**Age values are calculated using an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.72.

observed in the Yangtze block but absent in the North China block (NCB). On the other hand, Paleozoic magmatism was found mostly along the southern margin of the NCB and/or the northern Qinling terrane.

The main reason for different interpretations of the origin and provenance of the low-grade metamorphic zone is apparently due to contrasting tectonic models proposed

for the Qinling–Dabie orogenic belt. This orogenic belt together with the Kunlun and Qilian orogenic belts to the west forms an important tectonic terrane in China. Several models have been proposed in the literature that are based on different time constraints for the amalgamation of the North and South China (Yangtze) blocks (e.g., Mattauer *et al.*, 1985; Hsü *et al.*, 1987; Zhang, 1988;

Huang and Wu, 1992; Yin and Nie, 1993; Zhang *et al.*, 1995a; Meng and Zhang, 1999, 2000). Pre-Devonian or Early Silurian collision of the North and South China blocks was inferred from evidence of Carboniferous strike-slip faulting along the Shandan suture between the North and South Qinling terranes (Mattauer *et al.*, 1985) and from Early Devonian crustal shortening and metamorphism recorded in granulitic rocks exposed in the Tongbai terrane (Kröner *et al.*, 1993; Zhai *et al.*, 1998). In contrast, Şengör (1985) and Hsü *et al.* (1987) favored a Late Triassic collision of the North and South China blocks. Numerous Late Triassic metamorphic ages were obtained in the last decade from ultrahigh-pressure metamorphic rocks in the Tongbai–Dabie–Sulu terranes that strongly suggest an Early Mesozoic collision event (e.g., Li, S.-G. *et al.*, 1993, 1999, 2000; Okay *et al.*, 1993; Ames *et al.*, 1993) and paleomagnetic data corroborates a Late Triassic to Middle Jurassic amalgamation of the North and South China blocks (e.g., McElhinny *et al.*, 1981; Zhao and Coe, 1987; Enkin *et al.*, 1992).

Recognition of the Mianlue suture along the South Qinling southern margin (Zhang *et al.*, 1995a) led to the proposal of a two-stage collision model, in which the Qinling orogenic belt experienced multiple and prolonged rifting, drifting and collisional processes (Zhang *et al.*, 1996; Meng and Zhang, 1999, 2000). Ophiolitic complexes which mark the Mianlue suture differ in age and composition from rocks found along the Shangdan suture exposed between the North and South Qinling terranes (Zhang *et al.*, 1995b). According to the two-stage collision model, the Shangdan suture resulted from the middle Paleozoic collision of the North China block (including North Qinling) and the South Qinling terrane of Yangtze affinity, while the Mianlue suture traces the Late Triassic collision of the South Qinling terrane and the South China (Yangtze) block (Fig. 9).

Analyzed detrital muscovite grains from the Carboniferous sedimentary rocks (samples M13 and M70) define a regression line corresponding to an age of about 420 Ma (Fig. 7) and most of the single grains yield radiometric dates in the range 480 Ma and 380 Ma (Fig. 8). The pooled Rb–Sr age defined by the muscovites is similar to reported metamorphic ages between 406 and 426 Ma obtained from greenschist-facies metamorphic rocks exposed in the North Qinling terrane by Rb–Sr and ^{40}Ar – ^{39}Ar dating methods (Sun *et al.*, 2002a). Previous studies have shown that the late Paleozoic low-grade metamorphic sedimentary rocks contain abundant detrital zircons of Neoproterozoic to early Paleozoic age (about 800 Ma to 450 Ma; Chen *et al.*, 2003a; Li *et al.*, 2004). Surprisingly, almost all the detrital muscovites in the Carboniferous sediments record merely Paleozoic thermal events. Potential reason for this might be that the Rb–Sr mica system of the source rocks acted as an open system dur-

ing the Paleozoic thermal event, while the U–Pb zircon system remained close owing to its higher isotopic closure temperature. This age relationship therefore can imply that the detrital muscovites mainly or completely originated from an early to middle Paleozoic metamorphic-magmatic source within the North Qinling terrane which was an active plate margin of the North China block at that time (e.g., Kröner *et al.*, 1993; Meng and Zhang, 1999, 2000). This thesis is supported by detrital zircon ages obtained from Paleozoic sedimentary rocks of the Beihuiyang low-grade metamorphic zone in the northern Dabie Mountains (Chen *et al.*, 2003a; Li *et al.*, 2004). Abundant Early to Middle Paleozoic and Late Proterozoic detrital zircons were found in these rocks. Although recent studies have shown that the North and South China (Yangtze) blocks likely underwent similar thermal events in the early Precambrian, especially in late Archean and early Proterozoic (e.g., Zheng *et al.*, 2006; Zhang *et al.*, 2006), they have had different thermal histories during Late Proterozoic and Early Paleozoic times. During the Late Proterozoic, the evolution of the Yangtze block was associated with magmatic-metamorphic events especially along the northern and western margins (e.g., Chen *et al.*, 2003a, b; Rowley *et al.*, 1997; Xue *et al.*, 1997; Hacker *et al.*, 1998). The southern margin of the North China block, in turn, was characterized by Early Paleozoic magmatism and metamorphism (e.g., Kröner *et al.*, 1993; Zhai *et al.*, 1998; Meng and Zhang, 1999, 2000). Hence, it has been argued that the sedimentary rocks of the low-grade metamorphic zone originated from the North Qinling and South Qinling terranes, which record different crustal evolution and belong to different geological provinces (Chen *et al.*, 2003a). The Paleozoic detrital muscovites provide further evidence to support an origin from an active continental arc situated along the southern margin of the North China block. This arc was located in the northern part of the Qinling–Dabie orogenic belt (Fig. 9).

Detrital muscovites of phengitic composition are found in sedimentary rocks of the Huyoufang (C_2) and Yangxiaozi (C_2) Formations. The single-grain Rb–Sr analysis shows that phengites likely formed during the Early to Middle Paleozoic, implying high-pressure metamorphic rocks were exposed in the source area probably between the North and South Qinling terranes along the Shangdan suture. Accordingly, these two terranes collided in the Devonian after the closure of the proto-Tethyan Qinling ocean (Meng and Zhang, 1999, 2000; Sun *et al.*, 2002a). High-pressure and ultrahigh-pressure rocks of early Paleozoic age can be found in the Kunlun and Qilian orogenic belts of central-western China (e.g., Song *et al.*, 2003, 2007; Yang *et al.*, 2002). However, Paleozoic high-pressure metamorphic rocks were rarely reported in the Qinling–Dabie orogenic belt. Eclogites found in the Dabie

Fig. 9. Schematic diagram showing tectonic evolution of the Qinling–Dabie orogenic belt (modified after Meng and Zhang, 1999, 2000) and origin of the low-grade Late Paleozoic metamorphic zone.

ultrahigh-pressure metamorphic terrane mostly give Early Mesozoic ages, except for those exposed in the western Dabie region that were dated at about 310 Ma (Sun *et al.*, 2002b). Therefore, we propose that the Middle Paleozoic detrital phengites found in the Carboniferous sedimentary sequences originated from high-pressure metamorphic rocks of the southern margin of the North China block (or the North Qinling terrane), that formed during the closure of the Proto-Tethyan Qinling ocean and subsequent collision of the North and South Qinling terranes prior to the Carboniferous (Fig. 9; Meng and Zhang, 1999, 2000). The high-pressure rocks were exhumed after the Paleozoic collision and were completely eroded during the sedimentation of the Carboniferous sequences.

Detrital zircons extracted from the Carboniferous

sediments suggest the presence of Archean to Paleoproterozoic and Late Proterozoic to Paleozoic source regions during their deposition (Li *et al.*, 2004). The Sr isotope systematics of the biotites in the Carboniferous sediments are consistent with the presence of different source material. The Rb–Sr isotopic system of detrital biotites from the Carboniferous sedimentary rocks was significantly disturbed probably during diagenesis and/or later thermal imprint and therefore, formation ages of the biotite group with high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios can not be exactly determined. They might originate from old basement of the North China or Yangtze block. The other biotite group with low $^{87}\text{Sr}/^{86}\text{Sr}$ ratios demands a less radiogenic Sr or young material source and could be derived from juvenile crust exposed along the active conti-

nenal margin of the North China block during the early Paleozoic. Geochemical signatures of the less mobile trace elements La, Th, Zr, Ti and Sc also imply that the metasediments contain a significant contribution of arc-related magmatic rocks (Figs. 3 and 4). Considering the difference in Rb–Sr closure temperature between biotite and muscovite (~450–500°C for muscovite and ~350°C for biotite; e.g., Mezger, 1990; Villa, 1997; Jenkin *et al.*, 1995, 2001), metamorphic temperatures of the low-grade sedimentary rocks can be indirectly constrained to be between 350°C and 450°C. This temperature range is only valid if fluids did not disturb the Rb–Sr isotopic system of detrital biotites during diagenesis.

Whole-rock Sm–Nd isotopic composition of the Carboniferous sedimentary rocks provides additional support for an active margin setting. Basement rocks of the North China block commonly have low ϵ_{Nd} values (<–25) and old Nd model ages (>2.5 Ga; Wu *et al.*, 2005 and references therein). Compared to old basement rocks exposed in the North China block and the North Qinling terrane, the low-grade Carboniferous sedimentary rocks give relatively high $\epsilon_{\text{Nd}}(t)$ values and much younger Nd model ages between 2.1 Ga to 1.6 Ga (T_{DM2}). This characteristic requires juvenile crustal material, such as Paleozoic arc-related magmatic rocks, as one of the material sources, if Paleoproterozoic to Archean basement rocks of the North China block and the North Qinling terrane provided major sedimentary material. Early to Middle Paleozoic arc-related magmatic rocks have been found in the North Qinling terrane. They were formed during the closure of the Proto–Tethyan Qinling ocean prior to the Carboniferous (e.g., Xue *et al.*, 1993, 1997). Alternatively, these rocks might have formed later during the closure of the Paleo–Tethyan Qinling ocean prior to Late Triassic (e.g., Meng and Zhang, 1999, 2000; Fig. 9). Due to the complete lack of late Paleozoic detrital zircons in the low-grade sedimentary rocks (Chen *et al.*, 2003a; Li *et al.*, 2004), we conclude that the juvenile material component mainly came from an Early to Middle Paleozoic active continental margin situated at the North Qinling terrane.

CONCLUSIONS

This study contributes to the understanding of the tectonic setting and provenance of the Beihuaiyang low-grade zone exposed in the northern Dabie Mountains. Detrital zircon ages of the low-grade sedimentary rocks from this zone imply that the sedimentary material originated from mixed sources of the North China and Yangtze blocks and that the sediments were deposited along an active continental margin (Chen *et al.*, 2003a; Li *et al.*, 2004). Carboniferous sediments occur as part of the low-grade metamorphic sequence and contain detrital biotite and muscovite, partly phengite. Single grain Rb–

Sr age data suggest that both detrital muscovites and phengites formed during the Early to Middle Paleozoic. This provides evidence for Paleozoic thermal and high-pressure metamorphic events in the source region. Detrital phengites of Paleozoic ages most likely originated from Paleozoic subduction and subsequent collision processes along the North Qinling zone of the Qinling–Dabie orogenic belt. Detrital muscovites preserve information of the Early to Middle Paleozoic thermal history probably related to the closure of Proto–Tethyan Qinling ocean and formation of the North Qinling tectonic zone along the southern margin of the North China block. In conjunction with detrital zircon ages, our Rb–Sr isotopic age data on detrital muscovites further demonstrate an active continental margin setting during the deposition of the Paleozoic low-grade sediments. We finally conclude that age information from detrital micas especially muscovite, obtained by the single-grain Rb–Sr technique provides a useful tool for recognizing the origin of low-grade metamorphic rocks and for deciphering the provenance of geological terranes.

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