Provenance and geotectonic setting of the Palaeoproterozoic Zhongtiao Group and implications for assembly of the North China Craton: whole-rock geochemistry and detrital zircon data

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Abstract: Geochemical data reveal the contrasting geochemical characteristics of the metasediments in the Jiepailiang and Bizigou formations of the Palaeoproterozoic Zhongtiao Group, North China Craton. High Zr/Sc and SiO2/Al2O3 values and especially the evolved and uniform nature of tPeak(t) values plus detrital zircon U–Pb ages and Hf isotopic signatures for the former are consistent with derivation from an evolved felsic source with sedimentary recycling signs. However, lower values of SiO2/Al2O3 and Zr/Sc, and higher contents of Fe2O3* and MgO for the latter indicate input of more mafic components. These geochemical characteristics, combined with the wide range of tPeak(t) values, suggest that these rocks were derived in part from old continental material, dominated by felsic rocks of magmatic origin, and in part from a continental island arc, which accounts for the variable mixture of mafic components. These results suggest that the Zhongtiao Group was deposited after c. 2110 Ma, in a back-arc basin, behind an eastward-directed subduction system. Subsequent deformation and metamorphism reflect closure of the oceanic basin between the Eastern and Western blocks of the North China Craton, along the Trans-North China Orogen, contributing to amalgamation of the supercontinental Columbia.

Supplementary material: Data are available at http://www.geolsoc.org.uk/SUP18478.

Integration of geology, geophysics, geochemistry, isotope geochemistry and geochronology has greatly contributed to our understanding of the evolution of the North China Craton (Zhao et al. 2001, 2005, 2006; Zhang et al. 2007, 2008, 2010; Wilde 2002, 2005, 2008). In the past decade, one of the major achievements in understanding the evolution of the North China Craton is the recognition of the Trans-North China Orogen along which the discrete Eastern and Western blocks that developed independently were stitched together (Fig. 1). Nevertheless, the timing of the amalgamation and the polarity of subduction during ocean closure is still debated (Zhao et al. 2001, 2005; Kusky & Li 2003; Faure et al. 2007; Kusky & Santosh 2009; Santosh 2010). The position of the Zhongtiao Mountains within the configuration of the North China Craton is particularly contentious. Some models favour the eastward-directed subduction of an old ocean, with collision occurring at about 1.85 Ga and with the Zhongtiao Mountains belonging to the Trans-North China Orogen (Fig. 1; Zhao et al. 2001, 2005, 2007, 2008, 2010; Wilde et al. 2002, 2005; Kröner et al. 2005, 2006; Zhang et al. 2009). Other models argue for westward-directed subduction and a final collision at either 2.5 Ga (Kusky & Li 2003; Kusky et al. 2007; Kusky & Santosh 2009) or 1.9–1.8 Ga (Faure et al. 2007; Santosh 2010), with the Zhongtiao Mountains belonging to the Western Block (Kusky & Li 2003; Kusky et al. 2007; Kusky & Santosh 2009). The Zhongtiao Group is a key tectonic marker unit in the Zhongtiao Mountains, composed mainly of metasedimentary rocks and local economic copper deposits with minor mafic volcanic and tuffaceous rocks (Sun & Hu 1993; Bai et al. 1997), but its tectonic setting has been a subject of contention (Sun & Hu 1993; Bai et al. 1997; Kusky & Li 2003; Kusky et al. 2007). As such, these rocks may provide the answers to some of these controversies.

Numerous investigations have demonstrated that the chemical composition of sedimentary rocks may reflect that of their source rocks, although the relationships may be complicated (McLennan et al. 1993, 2003; Murphy & Nance 2002; Li et al. 2008a). Zircon is a mechanically robust mineral that usually survives multiple events of erosion, transport and metamorphism. The U–Pb and Lu–Hf isotopic analysis of detrital zircons has become an important tool for constraining both provenance and maximum age of deposition in sedimentary rocks (Xia et al. 2006, 2008; Li et al. 2008a, 2009). Such data help to recognize palaeotectonic linkages and determine the geotectonic setting of sedimentary basins. Given that each method has advantages and disadvantages (McLennan et al. 2003; Li et al. 2008a), there is a general consensus that a combination of whole-rock geochemistry and the analysis of detrital zircon U–Pb and Hf isotopes allows a more complete image to appear of the source terrain of the sedimentary units and tectonomagmatic evolution of sedimentary basins and their siliciclastic deposits than if these cases were evaluated in isolation (McLennan et al. 2003; Li et al. 2005, 2008a, 2009; Xia et al. 2008).

In this paper, we present major and trace element geochemistry, whole-rock Sm–Nd isotope, and detrital zircon U–Pb and
Fig. 1. (a) Tectonic subdivision of the North China Craton and location of the Zhongtiao Mountains (after Zhao et al. 2005). (b, c) Precambrian geology of the Zhongtiao Mountains (after Bai et al. 1997), and sample locations. FPC, Fuping Complex; WTC, Wutai Complex; HSC, Hengshan Complex; LLA, Lüliang Arc.
Hf isotope data from the metasedimentary rocks of the Zhongtiao Group within the Zhongtiao Mountains. The main focus of this study is on the source variation, provenance and maximum age of deposition of the Zhongtiao Group metasediments. Furthermore, the results provide further insight into the tectonic context of the Zhongtiao Mountains during the Early Precambrian.

**Geological setting**

The North China Craton, the largest and oldest craton in China, occupies an area of more than $1.5 \times 10^6$ km$^2$, bounded by the Central Asian Orogenic Belt to the north, the Qinling–Dabie Orogenic Belt to the south, and the Su–Lu Orogenic Belt to the east (Fig. 1a). It has been subdivided into three Archaean to Palaeoproterozoic microcontinental blocks, named the Eastern, Yinshan and Ordos blocks (the latter two forming the Western Block), and three Palaeoproterozoic linear structural belts, called the Trans-North China Orogen, also known as the Central Orogenic Belt (Kusky & Li 2003; Kusky & Santosh 2009; Santosh 2010), Khondalite Belt and Jiao-Liao-Ji Belt (Zhao et al. 2001, 2005). With the Eastern Block to the east, the Yinshan Block to the NW and the Ordos Block to the SW, the North China Craton comprises three tectonic provinces dissected by the Trans-North China Orogen and the Khondalite Belt (Fig. 1a). A comprehensive summary of these blocks and tectonic provinces has been given by Zhao et al. (2005), and thus is not repeated here. The north–south-trending Trans-North China Orogen is generally considered as a trace of the final assembly of the North China Craton and contains late Archaean to Palaeoproterozoic granitoid (tonalite–trondhjemite–granodiorite; TTG) gneisses, green-schist-facies mafic rocks and paragneisses, amphibolites, high-pressure granulite and retrograded eclogite (Zhao et al. 2001, 2005, 2010; Kröner et al. 2005; Wilde et al. 2005; Li et al. 2008a). Geochemical data suggest that most of these rocks formed in a subduction zone (Liu et al. 2002, 2004; Li et al. 2008a). Available geochronological data including U–Pb zircon and electron microprobe analysis monazite ages indicate that these rocks along the Trans-North China Orogen experienced a regional metamorphism at c. 1.85 Ga (Zhao et al. 2002a, 2010; Liu et al. 2006).

The NNE–SSW-trending Zhongtiao Mountains are situated in the Trans-North China Orogen (Fig. 1). The Precambrian geology of the Zhongtiao Mountains can be described in terms of five tectonostratigraphic units, separated by unconformities and tectonic contact (Sun & Hu 1993; Bai et al. 1997). The five units are as follows: (I) the Late Archaean to Palaeoproterozoic Sushui Complex, the Palaeoproterozoic (II) Jiangxian Group, (III) Zhongtiao Group and (IV) Danshanshi Group, and (V) the Mesoproterozoic Xiyanghe and Ruyang groups (Fig. 1b and c).

The Zhongtiao Group, which is the focus of this paper, occurs within the northern and central parts of the mountain range (Fig. 1b) and contains a wide variety of rocks, most of which have undergone at least three phases of deformation and metamorphism in the lower greenschist to lower amphibolite facies (Bai et al. 1997). The group can be divided into lower and upper subgroups, separated by an erosional unconformity (Sun & Hu 1993). Based on the characteristics of lithofacies, these two subgroups can be further divided into the following eight formations (from oldest to youngest): the Jiepailiang, Longyu, Yuyuanxia, Bizigou, Yujiaxiang, Wenyu, Wujiaoping, and Chenjiashan formations, as shown in Figure 2 (Sun & Hu 1993; Bai et al. 1997). Using the thermal ionization mass spectrometry (TIMS) method, Sun & Hu (1993) obtained a U–Pb zircon concordia upper intercept age of 2059 ± 5 Ma for felsic tuff in the Bizigou Formation.

**Samples**

For this study, 18 samples were collected from the Zhongtiao Group, and their locations are given in Figures 1c and 2. Of these, three samples from the Jiepailiang Formation are yellow–brown medium-grained granoblastic feldspathic quartzite, with a mineral assemblage of quartz (c. 78%) + K-feldspar (c. 10%) + plagioclase (c. 8%) + biotite (c. 3%) + muscovite (<1%). The other 15 samples, three feldspathic quartzite and 12 schist samples, were obtained from the Bizigou Formation. These massive feldspathic quartzite samples are marked by pale brown and fine- to medium-grained granoblastic texture, and consist predominantly of quartz, plagioclase and K-feldspar, with minor amounts of biotite and muscovite. Although there is no major difference in mineral assemblage signatures for the feldspathic quartzite samples between the Bizigou Formation and the Jiepailiang Formation, the former tends to be slightly more enriched in plagioclase. Schists collected from the Bizigou Formation include various sericite schists, and sericite quartz schists. The rocks generally display porphyritic fine- to medium-grained lepidoblastic texture, with porphyroblasts that commonly show diablastic and helicitic textures. The main diagnostic metamorphic minerals are biotite, staurotite and garnet. The matrix consists principally of sericite, chlorite, quartz and plagioclase.

All samples were examined in thin section with the optical microscope and were analysed for major and trace elements. All but one were analysed for Sm–Nd isotopes. One sample of the Jiepailiang Formation was selected for detrital zircon U–Pb and Hf (laser ablation inductively coupled plasma mass spectrometry; LA-ICP-MS) isotope analyses.

**Analytical procedures**

*Whole-rock major and trace elements, and Sm–Nd isotopes*

Major and trace elements were analysed by X-ray fluorescence (XRF) (Thermo ARL Advant XP+) on fused glass discs at the Key Laboratory of Orogenic Belts and Crustal Evolution, Ministry of Education, Peking University, and by ICP-MS (Perkin Elmer Sciex Elan 6100DRC) after acid digestion of samples in Teflon bombs at the National Key Laboratory of Continental Dynamics, Northwest University, Xi’an, respectively. Detailed analytical techniques were described by Li et al. (2009).

Nd isotopic analyses were performed by TIMS using a multi-collector Isoprobe-T system at the Analyzing Center of Beijing Institute of Nuclear Engineering. Details of the analytical techniques, procedures and data normalization were given by Li et al. (2009). Briefly, an aliquot of about 50–100 mg of powder was weighed into a Teflon bomb, spiked with a $^{148}$Sm/$^{150}$Nd tracer, and digested with HF–HNO$_3$ on a hot plate for 7 days. After digestion, two-stage cation exchange column procedures were used for the separation of REE and other elements, and subsequently for the separation of Sm and Nd.

*Detrital zircon U–Pb dating and Lu–Hf isotopes*

Zircons were extracted for cathodoluminescence (CL) imaging and isotope analyses. The CL images were collected using a Hitachi S3000-N SEM (with a Gatan Chroma Luminescence
attachment) at the Institute of Geology, Chinese Academy of Geological Sciences, Beijing. Zircon U–Pb dating was carried out at the State Key Laboratory of Continental Dynamics, Northwest University, Xi’an. A GeoLas 200 M laser ablation system equipped with a 193 nm ArF excimer laser was used in connection with an Agilent 7500a ICP-MS system. The detailed analytical protocol follows that of Yuan et al. (2004). Data reduction was performed using GLITTER 4.4 software. Pb contents were evaluated according to the method of Andersen (2002). Age calculations and probability diagrams were constructed using the ISOPLOT/Ex program of Ludwig (2003) and AGEDISPLAY program of Sircombe (2004), respectively. The results are reported with 1σ error.

After U–Pb dating, \textit{in situ} Hf isotope analyses were made with the Neptune multicollector (MC)-ICP-MS system (equipped with a 193 nm laser) at the Institute of Geology and Geophysics, Chinese Academy of Science. Analyses were generally carried out on the site of the already-generated pits to match Hf results with the corresponding U–Pb age data. Instrumental conditions and analytical procedures followed the method outlined by Wu et al. (2006). The external reproducibility for the analytical procedure was evaluated by repeated analysis of the international reference zircons 91500 and TEMORA, which yielded average
$^{176}\text{Hf}/^{177}\text{Hf}$ values of 0.282308 $\pm$ 44 (2σ, n = 10) and 0.282683 $\pm$ 32 (2σ, n = 3), respectively. These values are identical, within error, to the recently published $^{176}\text{Hf}/^{177}\text{Hf}$ values of 0.282307 $\pm$ 31 (2σ, n = 44) and 0.282680 $\pm$ 15 (2σ, n = 15) for 91500 and TEMORA, respectively (Wu et al. 2006).

**Results**

**Whole-rock geochemistry**

Major element analyses of samples from the Zhongtiao Group demonstrate that the Jiepailiang and Bizigou formations have contrasting geochemical characteristics. Samples from the Jiepailiang Formation show a restricted compositional range ($\text{SiO}_2$ contents of 79.0–79.4 wt%), characterized by high $\text{K}_2\text{O}$ (>6 wt%) and low $\text{Al}_2\text{O}_3$ contents (<11 wt%). In contrast, samples from the Bizigou Formation have a wider range of major element contents, with $\text{SiO}_2$ varying from 47.5 to 78.5 wt% and $\text{TiO}_2$ from 0.2 to 1.54 wt%. These variations primarily reflect geographical variability in the sample locations (Fig. 1c), indicating that samples from the south (05SJ08-1, 05SJ08-2, 05SJ08-3, 05ZT60-1, 05ZT60-4, and 05ZT61-1) are enriched in $\text{SiO}_2$ and depleted in $\text{Al}_2\text{O}_3$, $\text{Fe}_2\text{O}_3^*$, $\text{MgO}$ and $\text{TiO}_2$ compared with those from the north. The higher $\text{SiO}_2$ contents and lower $\text{Al}_2\text{O}_3$ contents in the south can be attributed to the greater proportion of quartz grains, whereas the lower $\text{Fe}_2\text{O}_3^*$, $\text{MgO}$ and $\text{TiO}_2$ contents are a result of smaller amounts of mafic material.

On the geochemical classification diagram proposed by Herron (1988), the Jiepailiang Formation samples plot in the arkose field, whereas the Bizigou Formation samples plot as Fe-shale, shale, wacke and arkose (Fig. 3). The samples within the Fe-shale field tend to have higher $\text{Fe}_2\text{O}_3^*$ contents, attributable to their high chlorite content, whereas samples within the arkose field have higher $\text{SiO}_2/\text{Al}_2\text{O}_3$ values (Fig. 3). A narrow range of $\text{SiO}_2/\text{Al}_2\text{O}_3$ values (from 2.9 to 6.0) for the Bizigou Formation samples indicates a low degree of sediment recycling, whereas the values in samples from the Jiepailiang Formation are generally higher than 7.5, implying a considerable degree of recycling (Roser et al. 1996).

As with the major elements, there are also main differences in trace elements between the Jiepailiang and Bizigou formations. Excluding samples 05SJ08-1 and 05ZT60-1, the Bizigou Formation rocks contain higher contents of Th and ferromagnesian elements (Co, Ni, Cr, Sc and V) relative to the rocks from the Jiepailiang Formation. High field strength element (HFSE) contents show slightly higher values of $\text{Zr}$ and lower values of $\text{Nb}$ in the Jiepailiang Formation than the Bizigou Formation. The total REE contents are lower in the Jiepailiang Formation rocks than in the Bizigou Formation rocks. Also, the former is characterized by relatively lower (La/$\text{Yb}_n$) and higher negative Eu anomalies relative to the latter. The values for total REE in all samples display a weakly positive correlation with $\text{Al}_2\text{O}_3$ ($r = 0.49$), suggesting that REE may be hosted in other phases in addition to clay minerals.

Thorium and scandium, which are relatively incompatible and compatible elements during igneous processes, respectively, are considered as reliable indicators of sediment provenance because of their low solubility during sedimentary processes (McLennan 1989; McLennan et al. 1993, 2003). On a Th/Sc–Zr/Sc plot (Fig. 4), all samples from the Bizigou Formation scatter about the compositional variation line, interpreted as due to a minimal influence of sedimentary sorting and recycling (McLennan et al. 1993, 2003), suggestive of the relationship expected for provenance-dependent trace element variation. For the Jiepailiang Formation samples, pronounced enrichment is seen in Zr/Sc ratios, typical of zircon accumulation associated with recycling and sorting of sediments.

**Sm–Nd isotopic data**

Based on the U–Pb zircon age in felsic tuff of the Bizigou Formation (Sun & Hu 1993), initial $\delta^{147}\text{Sm}/\delta^{144}\text{Nd}$ values for the samples are calculated on the basis of the estimated stratigraphic age of 2.1 Ga. All samples have $\delta^{147}\text{Sm}/\delta^{144}\text{Nd}$ values ranging from 0.0980 to 0.1523, with $\delta^{147}\text{Sm}/\delta^{144}\text{Nd}$ values varying from

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**Fig. 3.** Geochemical classification of terrigenous sandstones and shales using a log(SiO2/Al2O3)–log(Fe2O3*/K2O) diagram (after Herron 1988).

**Fig. 4.** Zr/Sc–Th/Sc diagram (McLennan et al. 1993) for metasedimentary rocks of the Zhongtiao Group. Asterisks mark the average compositions for Proterozoic rocks: granite, TTG, felsic volcanic rock, andesite, basalt, and Archaean komatiite (from Condie 1993). Grey squares represent the average compositions of upper continental crust (UCC; McLennan 2001) and normal mid-ocean ridge basalt (N-MORB; Hofmann 1988). Symbols are as in Figure 3.
-29.6 to -13.7. Samples from the Jiepailiang Formation display a restricted isotope range, with negative $\varepsilon_{\text{Nd}}(t)$ values (-3.89 to -2.79; Fig. 5). In contrast, samples from the Bizigou Formation show a wider variation in initial $\varepsilon_{\text{Nd}}(t)$ values (-6.45 to -0.27) (Fig. 5). Apart from sample 05ZY04-4, samples from the north have higher initial $\varepsilon_{\text{Nd}}(t)$ values than those from the south, as exemplified by samples 05SJ08-2, 05SJ08-5, 05ZT60-4 and 05ZT61-1. The differences between the Nd isotope patterns are probably due to variations in the source composition.

**U–Pb and Lu–Hf isotopes in detrital zircon**

Zircon CL images, and U–Pb and Lu–Hf isotope results for the sample from the Jiepailiang Formation are presented in Figure 6. The morphology of zircon grains is highly variable, but they are generally subhedral or rounded in shape, with lengths of 100–200 µm; the zircons are dominantly yellow, rose and colourless. Most analysed zircons have high Th/U ratios (>0.30) and show clear oscillatory zoning in CL images. These features suggest an origin from igneous source rocks (Fig. 6a). Of the 41 analysed zircon grains, 38 analyses have discordance lower than 10% and their $^{207}\text{Pb}/^{206}\text{Pb}$ age is selected for geological interpretation. They display a multimodal age distribution between 2132 ± 34 Ma and 2784 ± 19 Ma marked by a prominent peak at c. 2533 Ma, a subsidiary peak at 2630 Ma with a broad shoulder extending to about 2800 Ma, and a minor peak at 2132 Ma (Fig. 6b). The youngest grain is subrounded, and has a concordant $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2132 ± 34 Ma.

Forty Hf isotope data were generated in dated detrital zircons. In the $\varepsilon_{\text{Hf}}(t)$–age diagram (Fig. 6c), the Archaean to Early Palaeoproterozoic grains plot chiefly between the evolution lines for CHUR and depleted mantle, with only one zircon showing a negative $\varepsilon_{\text{Hf}}(t)$. For the majority of zircons with positive $\varepsilon_{\text{Hf}}(t)$ values, their ‘crustal’ model ages ($T_{\text{DM}}^C$); its calculation is based on the assumption that the zircon’s parental magma was produced from a volume of average continental crust, $^{176}\text{Lu}/^{177}\text{Hf} = 0.015$, which was originally derived from depleted mantle) are less than 200 Ma older than their crystallization ages, indicating that the magmas from which they crystallized were derived largely from juvenile mantle sources. Some grains with $\varepsilon_{\text{Hf}}(t)$ values close to or below zero (Fig. 6c) have $T_{\text{DM}}^C$ values of about 3.0 Ga, indicating reworking of 3.0 Ga crust or sources contaminated with 3.0 Ga crust. Also of note is that one Late Palaeoproterozoic grain (4.1), with an age of 2132 ± 34 Ma, has a negative $\varepsilon_{\text{Hf}}(t)$ value of ~3, suggesting that this zircon crystallized in magmas derived from old crust.

**Discussion and implications**

**Depositional age**

The conglomerate that defines at the base of the Zhongtiao Group just above the Jiangxian Group is interpreted to represent an unconformable depositional contact and thus the maximum depositional age of the former could be constrained by the upper age limit of the Jiangxian Group. The sensitive high-resolution ion microprobe (SHRIMP) zircon age of 2115 ± 1 Ma (Sun & Hu 1993) obtained from the Jiangxian Group tuffs is therefore considered a robust maximum age for the deposition of the lower subgroup of the Zhongtiao Group. The youngest analysed zircon with interpreted detrital characteristics yields a concordant $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2132 ± 34 Ma, which is also synchronous with the magmatic events recorded in the Yejishan Group volcanic rocks from the Lüliang region (Geng et al. 2003), the Dawaliang granite and the pink phase of the Wanjianghui granite from the Wutai Complex (Wilde et al. 2005), and the Nanying granite from the Fuping Complex (Guan et al. 2002; Zhao et al. 2002a).

The dataset points to deposition of the Jiepailiang Formation after c. 2110 Ma. This maximum depositional age is slightly older than the U–Pb age of 2059 ± 5 Ma obtained for zircon in felsic tuff of the Bizigou Formation (Sun & Hu 1993).
The ages of detrital zircons from the analysed sample reveal a preponderance of Archaean ages from 2505 to 2784 Ma, but only one Palaeoproterozoic grain. The prominent age peak at 2533 Ma indicates a significant input of Neoarchaean igneous rocks, outcrops of which have been reported in the Trans-North China Orogen and Eastern Block of the North China Craton (Guan et al. 2002; Zhao et al. 2002a, 2006; Kröner et al. 2005; Wilde et al. 2005; Geng et al. 2006). In addition, an interesting population is that at c. 2630 Ma (Fig. 6b), which has been sparsely reported in the Wutai and Fuping Complexes (Guan et al. 2002; Li et al. 2008a). It is interesting to note that the population of c. 2630 Ma is present in the sediments of some regions of the Trans-North China Orogen whose source area is interpreted to be the Trans-North China Orogen itself (Li et al. 2008a,b, 2009). The lack of zircons older than 3.0 Ga indicates that the provenance region of the sediments was relatively far from the potential source of Palaeo- and Eoarchaean zircons located in the Anshan and Eastern Hebei areas in the Eastern Block (Song et al. 1996; Liu et al. 2008). Therefore, the source region of the Jiepailiang Formation is deduced to be the proximal basement of the Trans-North China Orogen, formed essentially by Neoarchaean components (Fig. 6). Moreover, the $T_{DM}^c$ continental model ages from the Jiepailiang Formation are generally greater than 2.6 Ga, in contrast to 2.6 Ga as the best estimate for the timing of major material extraction from the mantle for the Western Block (Xia et al. 2006, 2008, 2009), precluding the possibility that the Western Block is the most important source. Additionally, the similarity in zircon age population to the underlying Jiangxian Group (Fig. 6b) suggests a common provenance for the Jiangxian Group and Jiepailiang Formation, pointing to a first-cycle or recycled dominantly Neoarchaean component. Recycling of the underlying Jiangxian Group can be deduced, as conglomerates occur at the base of the Jiepailiang Formation, and is also suggested by the geochemical signatures, such as Zr/Sc and SiO$_2$/Al$_2$O$_3$ values.

There are no U–Pb detrital zircon age data for the Bizigou Formation metasediments. The Sm–Nd isotope system is another powerful tool in identifying provenance (Murphy & Nance 2002; Li et al. 2005, 2008a). The wide range of $\varepsilon_{Nd}(t)$ values indicates derivation from more than one source. As mentioned above, the Bizigou Formation shows different geochemical and Sm–Nd isotope characteristics in its northern and southern parts. The more radiogenic Nd isotopic composition for the northern part can be explained by input from marginally younger detritus than in the southern part and in the Jiepailiang Formation. The similar isotopic signatures of the volcanic rocks of the Lüliang and Yejishan groups, as described by Geng et al. (2003), and the northern part of the Bizigou Formation (Fig. 5) highlights the suitability of the Lüliang and Yejishan volcanic rocks as candidate source rocks of the Bizigou Formation. In contrast, the southern samples, which have relatively evolved Nd isotopic signatures, have a range of Nd isotope values similar to those of the basement Trans-North China Orogen and the Eastern Block of the North China Craton (Wu et al. 2005). The isotopic characteristics of these samples are not derived from juvenile rocks related to the Lüliang and Yejishan volcanic rocks, but point to a significant contribution from older continental material. Therefore, the Bizigou metasediments could have been derived from a mixture of ancient and juvenile sources. Similarly, a Th/Sc–Zr/Sc plot (Fig. 4) reveals two dominant source areas: a continental source with Th/Sc values greater than unity and a mafic component, resulting in such a compositional variation of these samples.
Geotectonic implications

The deposition of the lower subgroup of the Zhongtiao Group predated the c. 1.8 Ga Trans-North China orogeny. Geochemical and detrital zircon data for the metasediments from the Jiangxian Group underlying the Zhongtiao Group (Li et al. 2008b, 2009) suggest deposition in a Palaeoproterozoic arc system. As noted above, a change in provenance is indicated by the contrasting geochemical and Nd isotopic signatures of the Jiepailiang and Bizigou formations. Compositional homogeneity is a characteristic of the Jiepailiang Formation, which is also notable for its predominantly evolved Nd isotopic signatures and the prevalence of Neoproterozoic detrital zircons, implying derivation from continental-derived materials and/or recycled sedimentary rocks. Based on the sedimentary characteristics, Bai et al. (1997) interpreted the Jiepailiang Group as having been deposited in a fluvial depositional system above the Jiangxian Group. The unconformity between the Jiangxian and Zhongtiao groups attributed to uplift was probably caused by the extrusion of volcanic rocks and intrusion of granitoids around 2.1 Ga (Sun & Hu 1993; Kröner et al. 2005, 2006; Zhao et al. 2006, 2007). The fining-upward succession of the Jiepailiang Group was deposited in response to an increase in accommodation space leading to transgression, signifying that regional crustal extension occurred at this time. Recently, Kröner et al. (2005, 2006) and Zhao et al. (2006, 2007) emphasized that in the Palaeoproterozoic (about 2200–1950 Ma), granitoids and mafic dykes developed within both the Trans-North China Orogen and the Eastern Block, and that they represent an inboard expression of subduction-related back-arc extension.

The data, including Sm–Nd isotope data, for the Bizigou Formation suggest a contribution of c. 2.1 Ga juvenile material, which was probably derived from the Palaeoproterozoic Lüliang Arc (Faure et al. 2007; Zhao et al. 2008; Liu et al. 2009). The two sources implied for the Bizigou sediments are conceivably linked to a convergent margin setting, and the highest value of εNd(t) (−0.27) indicates dilution by large amounts of material derived directly from a continental source, or material derived indirectly from continent-contaminated magmatic-arc rocks, or some combination of the two. Thus, the isotopic features probably reflect not only the influence of Archaean continental-derived materials, but also the denudation of an arc built upon an old continental crust. Based on geochemical data, Geng et al. (2003) and Liu et al. (2009) suggested that the Palaeoproterozoic volcanic rocks of the Lüliang and Yejishan groups in the Lüliang arc experienced varying degrees of continental contamination, signifying the existence of a Palaeoproterozoic active continental margin between the Western and Eastern blocks (Zhao et al. 2008; Liu et al. 2009). In this case, subduction would have played a crucial role in the formation of a favourable basin environment for the deposition of the Bizigou Formation in a back-arc location around 2.1 Ga. Consequently, we consider the Bizigou Formation sediments in the northern part to be the relatively proximal facies of the Lüliang arc, whereas those in the southern part are coeval distal deposits (Fig. 7).

Following these arguments, we infer that the Zhongtiao Group was deposited in a back-arc basin within an active continental margin setting, with the Lüliang arc to the NW and the Eastern Block to the east (Fig. 7). The proposed westward-directed subduction model (Kusky & Li 2003; Faure et al. 2007; Kusky et al. 2007; Kusky & Santosh 2009; Santosh 2010) for the North China Craton in contradiction with the data presented in this study.

A maximum age of deposition is 2130 ± 34 Ma, slightly older than the U–Pb age of 2059 ± 5 Ma obtained for zircon in felsic tuff of the Bizigou Formation (Sun & Hu 1993), which is related to the Palaeoproterozoic active margin along the Trans-North China Orogen (Fig. 1). It is notable that a series of Palaeoproterozoic volcano-sedimentary units are widespread in the Trans-North China Orogen, including the Hutuo Group in the Wutai Mountain, the Lüliang and Yejishan groups in the Lüliang Mountain, and the Jiangxian and Zhongtiao groups in the Zhongtiao Mountains, and have been strongly deformed and metamorphosed by later tectonic events (c. 1.85 Ga) that led to the final unification of the North China Craton. The age range roughly coincides with the global collision event at 2.1–1.8 Ga being recognized as the timing of the amalgamation of the Palaeo-Mesoproterozoic supercontinental Columbia (Wilde et al. 2002; Zhao et al. 2002b; Zhai et al. 2005; Kusky et al. 2007; Kusky & Santosh 2009; Santosh 2010). In this case, the geodynamic aspects related to the final assembly of the various blocks within the North China Craton have been placed into the context of the Columbia supercontinental amalgamation, although the position of the North China Craton within the configuration of the Columbia is controversial (Zhao et al. 2002b; Kusky & Santosh 2009).

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Fig. 7. A schematic illustration of the Zhongtiao Group deposition and its position relative to tectonic elements that may have provided detritus. The Zhongtiao Group is interpreted to have been deposited in a back-arc basin relative to the Palaeoproterozoic Lüliang Arc. TEB, Trans-North China Orogen–Eastern Block boundary.
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