Crustal evolution of the North Qinling terrain of the Qinling Orogen, China: Evidence from detrital zircon U–Pb ages and Hf isotopic composition

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ABSTRACT

The North Qinling terrain reveals a different geological history from the North China block to the north and the South Qinling micro-continental block to the south. The timing of events and geochemical features of the North Qinling terrain are essential for understanding the evolution of the Qinling orogenic belt that joins the North and South China blocks. This study presents detrital zircon ages and Hf isotopic compositions from the Guandaokou Group, a cover sequence of the North China block, and from the Kuanping Group, an upper basement sequence of the North Qinling terrain. The youngest detrital zircon U–Pb ages constrain the initiation of sedimentation in the Guandaokou Group to 1.85 Ga and the maximum depositional age of the Kuanping Group to ~640 Ma. Zircon U–Pb ages and Hf data testify to a major phase of magmatism in the North Qinling terrain at ~1000–900 Ma. The magmatic rocks were largely produced from reworking of early Paleoproterozoic (~2.5–2.0 Ga) crust with minor contribution of late Paleoproterozoic (~1.7 Ga) juvenile material. This age record differs in time from the two important thermal events of ~1.85 Ga and ~2.5 Ga, widely manifested in the North China block. The North Qinling terrain can thus be regarded as a separate micro-continent with a pre-Neoproterozoic evolution different from that of the North China block. The final assembly of the North Qinling terrain to the North China block took place after about 640 Ma.

1. Introduction

The Qinling orogenic belt, being part of the central orogenic belt in China, was amalgamated with the North China block (NCB) to the north along the Lo-Luan tectonic zone (e.g., R.C.S. Henan, 1989; Zhao et al., 2009). This belt was sutured to the South China block (SCB) during the middle to late Triassic along the Mian-Lue tectonic zone (~240–225 Ma; Li et al., 1993, 2000; Chavagnac and Jahn, 1996; Rowley et al., 1997; Hacker et al., 1998; Webb et al., 1999; Chavagnac et al., 2001; Liu et al., 2008; Li et al., 2009, 2010). The Shang-Dan tectonic zone is an inner suture, which separates the Qinling orogenic belt into the North Qinling terrain (NQ) and the South Qinling terrain (SQ). Over the last decade, a characteristic Neoproterozoic magmatic event was recorded by zircons in magmatic and low-grade metamorphic rocks of the South Qinling terrain and the South China block (e.g., Ling et al., 2003, 2007; Chen et al., 2006; Zhu et al., 2008, 2009; Ling et al., 2007, 2010). However, whether the North Qinling terrain was connected with the North China block or the South China block (Yangtze Block) remains a matter of controversy (Xue et al., 1996a,b; Zhang et al., 2001). Recently, Yang et al. (2010) argued that the North Qinling terrain was dissimilar to the North China block and the South China block because it displays a unique late Mesoproterozoic to early Neoproterozoic magmatic event. In a number of studies, the North Qinling terrain is regarded as a micro-continent with a distinct geological evolution prior to the final amalgamation with the North China block (e.g., O’Yang and Zhang, 1996; Dong et al., 2003).

Zircons contain high concentrations of the element Hf (generally 1–2%) resulting in low Lu/Hf ratios of typically <0.001, much lower than the bulk Lu/Hf ratio of the continental crust. Hf is more incompatible than Lu during mantle melting and hence, the melt acquires a lower Lu–Hf ratio compared to the residual mantle. Therefore, crust and mantle show different Hf isotopic evolution trends with time and the 176Hf/177Hf ratio of a zircon is an excellent tracer of the source material and the time of crust/mantle differentiation (Kemp et al., 2000, 2002). The Hf isotopic composition of zircons has been successfully used as an indicator for sedimentary provenance and interaction between crust and mantle (e.g., Kemp et al., 1999, 2000; Griffin et al., 2000, 2002; Kemp et al., 2005; Zheng et al., 2006a,b). Many previous studies have demonstrated that the Proterozoic was an important episode for the crustal evolution of the Chinese blocks.
especially for the South China block (Yangtze and Cathaysia blocks; Chen and Jahn, 1998; Ling et al., 2002). U–Pb analysis of zircon grains from sediments and basement rocks suggest four stages of crustal evolution of the Yangtze block, namely at >3.0 Ga, ~2.95 Ga, ~1.95 Ga and 820–750 Ma (Zhang et al., 2006; Zheng et al., 2006a). But, previous studies have also shown that the Sm–Nd model ages (TDM) of different rock types cluster around three peaks at 2.05 Ga, 1.40 Ga, and 1.05 Ga that were interpreted as representing three crustal formation stages (Wei et al., 1999).

This study presents new detrital zircon U–Pb and Hf isotopic data from the low-grade metamorphic rocks of the northern part of the Qinling orogenic belt, and provides a discussion on the source characteristics, the crustal evolution and the tectonic relationship between the North China block and the North Qinling terrain during the Precambrian.

2. Geological background

The Qinling orogen constitutes the western part of the Qinling–Dabie orogenic belt in central China. It was formed in a two-stage collision process between the North China and South China blocks during the early–middle Paleozoic (e.g., Meng and Zhang, 1999; Zhang et al., 2001; Sun et al., 2002; Faure et al., 2008) and early Mesozoic (e.g., Li et al., 1993, 2000; Ames et al., 1993; Meng and Zhang, 2000; Li et al., 2007b; Faure et al., 2008; Jiang et al., 2010). The Shang-Dan and the Mian-Lue suture zones formed during these collisions. The Shang-Dan suture zone separates the Qinling orogen into a northern and a southern terrain, which are referred to as the North Qinling and the South Qinling, respectively (Fig. 1). Geologically, the North Qinling terrain is composed of Mesozoic–to Paleoproterozoic gneiss; e.g., the Qinling and Kuanping Groups, Neoproterozoic meta-sedimentary and meta-volcanic rocks, e.g., the Danfeng and Erlangping Groups, and Paleozoic low-grade meta-sedimentary rocks, whereas the South Qinling terrain consists mainly of Neoproterozoic meta-sedimentary and meta-volcanic rocks, e.g., the Wudang and Yaolinghe Groups.

The Qinling Group is considered to be the oldest basement unit exposed in the North Qinling terrain. It is composed of gneisses, amphibolites and marbles (e.g., Ratschbacher et al., 2003; Dong et al., 2008). U–Pb zircon ages from gneisses range from 2.2 to 2.3 Ga (e.g., Zhang et al., 1994c), whereas amphiboles yielded a Sm–Nd isochron age of ~2.0 Ga (Zhang et al., 1994b). New U–Pb zircon analyses from gneisses located in southeastern Shaanxi and western Henan indicate that the Qinling Group formed mainly during the late Mesoproterozoic to early Neoproterozoic (Yang et al., 2010). The Erlangping and Danfeng Groups are composed of meta-sedimentary and meta-volcanic rocks that formed during the Neoproterozoic to early Paleozoic (Zhang et al., 1994a; Lerch et al., 1995; Xue et al., 1996a,b). Geochemical composition indicates that the volcanic rocks range in composition from basalt to andesite, to dacite and that these rocks erupted in an intraoceanic arc (Zhang et al., 1994b; Xue et al., 1996b). The upper sequence of the Kuanping Group, consisting chiefly of low amphibolite- to greenschist-facies marbles and two-mica quartz schists (Li et al., 1995), is interpreted as part of the metamorphosed south-facing passive margin of the North China block (Wang et al., 2000) or, as an accretionary wedge (Ratschbacher et al., 2003). Element geochemistry suggests that the protoliths of greenschist- to amphibolite-facies rocks of the lower sequence of the Kuanping Group were tholeiitic basaltic with N-MORB or T-MORB geochemical characteristics (Liu and Zhou, 1995; Zhang et al., 1997). Sm–Nd isochron ages of these meta-basalts range from 0.94 to 1.2 Ga (Zhang et al., 1994c; Dong et al., 2003, 2008). The meta-volcanic rocks of the Kuanping Group are associated with meta-gabbro and serpentinitized peridotite that are considered to represent a Grenvillian-age ophiolite. Such interpretation would imply an initial rift along the southern margin of the North China block (Wei et al., 1999; Meng and Zhang, 1999). A pre-Mesoproterozoic age has been suggested for the formation of the Kuanping Group (e.g., Wei et al., 1999; Zhang et al., 2001 and references therein).

3. Analytical technique

Zircon grains were isolated from crushed rocks by standard mineral separation techniques and were handpicked for analysis under a binocular microscope. Zircon U–Pb age dating was accomplished by the mean of LA-ICP-MS (laser-ablation inductively coupled plasma mass spectrometer) at the CAS Key Laboratory of Crust–Mantle Materials and Environments, University of Science and Technology of China in Hefei. The laser-ablation system was a GeoLas 200 M equipped with a 193 nm ArF excimer laser. The diameter of the laser-ablation pit was approximately 40 µm and the average power output was about 4 W. Signal and background measuring durations were about 70 s and 40 s, respectively. Zircon 91500 was used as an external calibration standard for age calculation, and NIST610 was analyzed twice for every 10 analyses for concentration calculations of U, Th, and Pb. Further analytical details are given in Liu et al. (2007).

U–Pb isotopic ratios were calculated using the Glitter Ver4.0 software and U–Pb age calculation was performed using the software program Isoplot (Ludwig, 2003). All errors are quoted as 2σ.

Zircon Hf analytical procedure has been described in Wu et al. (2006) and Hou et al. (2007). All analyses were performed using a Neptune MC-ICP-MS located at Chinese Academy of Geological Science (CAGS). This mass spectrometer is equipped with double-focusing and multi-collectors. A GeoLas 200 M laser-ablation system (Microlas, Germany) was used equipped with an ArF excimer 193 nm laser. In this study, a 40 µm laser spot size was selected during the ablation with a repetition rate of 8 Hz. Measured 176Hf/177Hf ratios were not corrected for isobaric interference of 176Lu on 176Hf due to the extremely low 176Lu/177Hf in zircon (normally <0.002). 175Lu/176Hf = 0.02655 was used for elemental fractionation correction. Isobaric interference of 176Yb on 176Hf was corrected using the mean fractionation index proposed by lizuka et al. (2005). The applied value of 176Yb/177Yb = 0.5886 (Chu et al., 2002; Vervoort et al., 2004). A 176Hf/177Hf ratio of 0.282007 ± 7 (2σ, n = 36) was obtained for zircon GJ1, which is identical with values obtained by the solution method (Morel et al., 2008; Hou et al., 2007; Slama et al., 2008). Analytical data of this study were corrected using 176Hf/177Hf ratio of 0.281994 ± 15 of zircon GJ1 (MSWD = 2.2; n = 12).

4. Analytical results

Mica quartz-schist samples belonging to the middle-upper Kuanping Group were collected from western Henan Province, where the sedimentary sequences are well exposed and fresh samples can be easily obtained. In order to allow a comparison with crystalline rocks of the North China block, sedimentary rocks from the Guandaokou Group exposed along the southern margin of the North China block were also collected. Sample localities and information about the rock types is given in Table 1. Analytical results of zircon U–Pb dating and Hf isotopic composition are given as the supplementary data in the journal website (Table S1 and Table S2). Zircon grains from sandstones of the lower part of the Guandaokou Group are well rounded, implying a long transport of the grains before deposition or multiple sedimentary recycling. As seen from cathodoluminescence (CL) images (Fig. 2), some zircons show oscillatory growth zoning consistent with a primary magmatic origin, while others display typical fri-tree-zoned, sector and planar internal texture. Generally, the inhomogeneous CL intensity of zircons is interpreted as the result of a complex origin. Forty-seven detrital zircons from sample GSH0806 and GSH0808 were selected for U–Pb and Hf isotope analyses. The two main peak age values of these zircons are ~1.85 Ga and ~2.50 Ga (Fig. 3). Zircons from schist samples of the middle-upper Kuanping Group are euhedral to subhedral, implying a rapid weathering cycle and
short transportation of materials. The CL images show that most grains have preserved magmatic oscillatory zonation. Some grains display characteristics of a metamorphic origin without oscillatory zoning (Fig. 2), indicating a metamorphic event. A total of one hundred and twenty-seven detrital zircons from samples 08HN46, 08HN49 and 08HN60 were analyzed for U–Pb and Hf isotopic composition. Concordia diagrams for the detrital zircons from these rocks are shown in Fig. 4. Zircons with U–Pb ages ranging from Neoarchean (~2.5–2.4 Ga) to early Neoproterozoic (~1.1–1.0 Ga and ~950–810 Ma) can be distinguished. Minor zircons of Mesoproterozoic (~1.7–1.4 Ga) and Paleoproterozoic (~2.5–2.0 Ga) age are also identified in these diagrams.

Forty-eight detrital zircons from the Guandaokou Group give εHf(t) values ranging from −13.4 to 7.0 (Fig. 5). More than half of the grains have εHf(t) values >0, indicating that the detrital zircons crystallized from magmas that originated from juvenile crustal material or directly from a depleted mantle source and reworked ancient crustal material. Two-stage Hf model age values (TDM2) of the detrital zircons range from ca. 3.3–2.2 Ga, some are even older than 4.0 Ga, implying pre-existing basement material with a prolonged crustal evolution.

εHf(t) values of seventy-nine detrital zircon grains from the Kuanping Group range from −26.5 to 10.9 (Fig. 5). About 80% of these grains have negative εHf(t) values, meaning that most detrital zircons crystallized from the magmas derived by melting of crustal material. The corresponding Hf model ages (TDM2) range from 3.8 Ga to 1.5 Ga. Similar to the sandstone samples from the Guandaokou Group, some detrital zircons from the Kuanping Group also yield Hf model ages older than 4.0 Ga.

5. Discussion

5.1. Deposition age of the sedimentary sequences

The Guandaokou Group is usually considered as a Mesoproterozoic sequence (R.G.S. Henan, 1989; Zhao et al., 1998; Zhai et al., 2007; Kusky et al., 2007a,b) and the formation time probably corresponds to

<table>
<thead>
<tr>
<th>Sample</th>
<th>Rock group</th>
<th>Lithology</th>
<th>Texture</th>
<th>Major mineralogy</th>
<th>Locality</th>
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<td>GSH0806</td>
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<td>Qz</td>
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<td>Sandstone</td>
<td>Fine-grained</td>
<td>Qz + Sc</td>
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</tr>
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<td>Quartz schist</td>
<td>Laminated and oriented</td>
<td>Qz + Ms + Bi</td>
<td>N33°44′04″E111°42′59″</td>
</tr>
<tr>
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<td>Kuanping</td>
<td>Quartz schist</td>
<td>Laminated and oriented</td>
<td>Qz + Ms + Bi</td>
<td>N33°44′45″E111°43′28″</td>
</tr>
<tr>
<td>08HN60</td>
<td>Kuanping</td>
<td>Mica quartz schist</td>
<td>Laminated and oriented</td>
<td>Ms + Bi + Qz</td>
<td>N33°51′11″E111°12′51″</td>
</tr>
</tbody>
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Mineral: Qz = quartz, Sc = sericite, Cc = calcite, Ms = muscovite, Bi = biotite.
that of the Changcheng Group in the North China block (e.g., Zhao et al., 2001b; Fig. 6). Sandstones of the lower part of the sequence overlie the volcanic-sedimentary sequence of the Xiong'er Group distributed in northwestern Henan Province (e.g., R.G.S. Henan, 1989; Zhao et al., 2001a, 2009). These rocks are covered by marine-facies sandstone, stromatolitic dolomite and limestone of the upper Guandaokou Group.

Fig. 2. Cathodoluminescence (CL) images of typical zircon populations. (a) rounded zircons from sandstones of the Guandaokou Group (samples GSH0806 and GSH0808). Late overprint zones characterized by high CL intensity can be observed in some grains; (b) euhedral or subhedral grains from the schists of the Kuaping Group (samples 08HN46, 08HN49, and 08HN60). Most grains display CL oscillatory zoning typical for magmatic origin.

Fig. 3. Zircon U–Pb concordia diagrams for sandstone samples of the Guandaokou Group.
which, in turn, is overlain by the Sinian to Triassic section (R.G.S. Henan, 1989). Most of the detrital zircons from the lower part of the Guandaokou Group yield concordant $^{207}$Pb/$^{206}$Pb ages between 1.85 Ga and 2.5 Ga, except for a few grains, which are older than 3.0 Ga. These grains are highly rounded (Fig. 2), with various internal texture. Most grains with oscillatory zoning have high Th/U ratios ($>0.4$), characteristic of magmatic zircon. Because sedimentary rocks of the Guandaokou Group have only undergone a merely low-grade metamorphic overprint, the U–Pb system of the most zircon grains should remain closed during late metamorphic event(s). Hence, the youngest detrital zircon ages of 1.85 Ga (MSWD=0.91, n=9) can constrain the maximum depositional age of the Guandaokou Group. However, according to field observations, volcanic rocks and their intrusive counterparts in the underlying Xiong'er Group were emplaced at ~1.78 Ga (Zhao et al., 2001a, 2002b, 2009; Peng et al., 2007, 2008; Hou et al., 2008a,b; He et al., 2009), hence, the deposition time of the lower Guandaokou Group can be better constrained to the late Mesoproterozoic.

Earlier studies have suggested that the Kuanping Group, especially amphibolites and other meta-mafic rocks of the lower part, formed during the Paleo- to Mesoproterozoic (e.g., Zhang et al., 1994a,b,c). Recently, He et al. (2007) reported a U–Pb zircon age of 1.75 Ga for the amphibolites of the middle part of the Kuanping Group, Gansu Province, by using the LA-ICP-MS zircon dating technique. However, in the present study, most of the investigated detrital zircons are euhedral or subhedral with magmatic zoning (Fig. 2) and Th/U ratios $>0.3$ and the U–Pb systematics of these grains constrain the maximum depositional age of the quartz schists from the middle part of the Kuanping Group at ~640 Ma (n = 7, Fig. 7). Two detrital zircon grains even yield younger $^{206}$Pb/$^{238}$U concordant ages of ca. 510 Ma and ca. 540 Ma. Meanwhile, Yan et al. (2008) presented a SHRIMP U–Pb age of 611±13 Ma for
meta-mafic volcanic rocks of the lower part of the Kuanping Group, Shaanxi Province. Paleontological evidence also supports the conclusion that the Kuanping Group is much younger than previously suggested (Wang et al., 2009).

5.2. Provenance of the sedimentary sequences

Material sources of sedimentary rocks are mainly derived from three major sources, that are high-grade metamorphic rocks of deeply eroded cratonic basement, young volcanic or plutonic rocks from accretionary basins along active continental margins, and recycled rock complexes of old crustal sections (Chen et al., 2009). Detrital minerals in sedimentary rocks (e.g., zircon, garnet, apatite and muscovite) have been used to distinguish their sources and the history of ancient continental margins in regions adjacent to the Qinling orogen, e.g., in the North China block, Yangtze Block and the Dabie orogen (e.g., Chen et al., 2009; Sun et al., 2009; Hu et al., 2009; Wang et al., 2010a,b; Yan et al., 2010). Furthermore, whole-rock Nd (e.g., Barovich and Foden, 2000; Krogstad et al., 2003; Wade et al., 2005) and zircon Hf isotope analyses (e.g., Iizuka et al., 2005; Kemp et al., 2006; Hawkesworth and Kemp, 2006a,b) have been broadly applied in such studies.

Sandstones of the Guandaokou Group are exposed along the southern margin of the North China block. The U–Pb age spectrum outlined for detrital zircons (Fig. 7) shows that the sediments obtained material mainly from Neoarchean (~2.5 Ga) and middle Paleoproterozoic (~1.85 Ga) sources. Evidence for significant magmatic–tectonic events at about 2.5 Ga can be found throughout the North China block. This tectonothermal episode was characterized by the formation of granulite belts, magmatism and metamorphism (e.g.,
Zhao et al., 2002a; Rogers and Santos, 2009; Santosh et al., 2006, 2007a,b, 2009a,b, 2010), indicating that various micro-blocks amalgamated to form a coherent craton (e.g., Zhai, 2000; Geng et al., 2006; Zhai, 2010). Shortly after ~1.85 Ga the North China block underwent an extensional tectonic regime, characterized by anorogenic magmatism, rift-magmatism or volcanism, and retrograde metamorphism (e.g., Zhao et al., 2001b, 2005; Zhao, 2009; Guo et al., 2002). Volcanic rocks of the Xiong'er Group and dyke swarms that formed at ~1.8 Ga mark the end of this tectonic phase in the North China block (e.g., Zhai, 2010; Zhao et al., 2002a, 2004, 2009; Peng et al., 2007, 2008). As an important finding, detrital zircons from sedimentary rocks of the Zhaerai and Huade Groups along the northern margin of the North China block (Li et al., 2007a; Hu et al., 2009), the Penglai Group in the eastern part (Li et al., 2007c; Zhou et al., 2008), the Changcheng (Wan et al., 2003), Gaofan, Hutuo, Dongjiao Groups in the central part (Wan et al., 2010), provide the same age peaks as the detrital zircons from the Guandaokou Group, all corresponding with the two major geological events of the North China block. The sedimentary sources of this group evidently originated from the basement rocks of the North China block.

The detrital zircon populations from schists of the middle-upper Kuanping Group exposed in the northernmost Qinling orogen, reveal dominant age clusters at ~2.5 Ga and ~1000–900 Ma (Fig. 7), indicating that the material was derived from late Neoproterozoic and early Neoproterozoic sources. As both the North China and South China blocks contain late Archean basement rocks or detritus, it remains unclear from which the Neoproterozoic detrital zircons in the Kuanping Group were derived. But, with the exception of some diabase dikes (~1000 Ma; Liu et al., 2006), Neoproterozoic rocks are scarce along the southern margin of the North China block, indicating that the North China block was tectonically inactive during this time period (Zhai, 2010). In contrast, in the South China block, including the South Qinling micro-continental block, large-scale Neoproterozoic tectono-magmatic activity is evident (e.g., Li et al., 2002, 2003a,b; Zheng et al., 2004; Chen et al., 2006; Ling et al., 2003, 2007; Yu et al., 2008; Sun et al., 2009; Zhu et al., 2009; Wang et al., 2010a,b). Besides the outcrops of the Grenvillian rocks (~1000 Ma) exposed along the western margin of the South China block, e.g., the Huiqiongou granitic gneiss and contemporaneous deposits (Li et al., 2002) and the Laoyu pluton (~400 Ma, e.g., O’Yang and Zhang, 1996; Zhang et al., 2004; Chen et al., 2004b, 2006, 2007), several Paleoproterozoic detrital zircon grains of about ~2.5 Ga to ~1.85 Ga from the Kuanping Group samples also show negative εHf(t) values of ~8.9 to ~1.9 and Hf model ages of about 3.0 Ga to 2.7 Ga, indicating the reworking of Archean crust (Wan et al., 2005a; Zhai et al., 2005). This conclusion is consistent with the evidence provided by Nd isotopic analysis in Wu et al. (2005). The oldest zircons found in the two groups in this study have U–Pb ages of about 3.3 Ga to 3.0 Ga, εHf(t) values of ~13.4 to ~3.2, and Hf model ages of about 4.5 Ga to 3.8 Ga and these isotopic features are similar to those of the oldest Archean rocks presently exposed in the North China block (Liu et al., 1992; Song et al., 1996; Wan et al., 2005b; Wu et al., 2008).

Half of Neoproterozoic and Paleoproterozoic zircon grains of the Guandaokou Group is characterized by positive εHf(t) values of up to ~7, corresponding to Hf model ages (~1.28 Ga to 2.5 Ga). Several Paleoproterozoic detrital zircon grains of about ~2.5 Ga to 2.0 Ga from the Kuanping Group also yield positive εHf(t) values of up to ~2.3 and Hf model ages (~1.28–2.6 Ga). These values are consistent with derivation from variably dePLETED mantle sources.

The U–Pb and Hf zircon data from the Kuanping sedimentary sequence also help to unravel the late Precambrian crustal evolution of the North Qinling terrain. Detrital zircon U–Pb ages and in-situ zircon Lu–Hf isotope data show that the major magmatic activity in the North Qinling terrain occurred around ~1000–900 Ma (Fig. 5) and this magmatism was largely produced by reworking of late Paleoproterozoic crust with minor contribution of late Paleoproterozoic juvenile material.

The oldest basement rocks exposed in the North Qinling terrain range from 2.2 to 2.3 Ga (U–Pb zircon ages, Zhang et al., 1994c), whereas amphibolites have yielded a Sm–Nd isochron age of ~2.0 Ga (Zhang et al., 1994b). Previous studies have demonstrated that the North Qinling terrain is distinguished from the South Qinling terrain and the South China block by the absence of Archean basement rocks (e.g., O’Yang and Zhang, 1996; Zhang et al., 2001; Lu et al., 2006). But, the oldest zircon ages from the Kuanping Group presented here show the existence of recycled Archean material in the North Qinling terrain.

Recent studies indicate a dominant phase of Neoproterozoic magmatism in the Qinling Group of the North Qinling terrain. Abundant granitoid rocks formed between about 980 Ma and 930 Ma, e.g., from west to east, the Lianghekou granite (Chen et al., 2004a, 2007), the Laoyu pluton (Lu et al., 2005), the Cai’ao granite (Zhang et al., 2004), the Niujiaoshan granite (Wang et al., 2002, 2005), the Dehe monzogranite (Chen et al., 2004b) and the Zhai gen monzogranite (Chen et al., 2004b) and the Zhai gen monzogranite (Chen et al., 2006). These plutons are regarded as syn-collisional or post-collisional intrusives following the about 1.3–1.0 Ga Grenvillian orogenic period (e.g., Zhang et al., 2004; Chen et al., 2004b, 2006, 2007). In addition, a Sm–Nd whole-rock isochron age of 1.03 Ga, obtained from the Songshugou ophiolite, also represents the Grenvillian-aged event in the North Qinling terrain (Dong et al., 2008). Thus, it is reasonable to suggest that the early Neoproterozoic source for the sedimentary rocks from the middle-upper Kuanping Group has close affinity with the North Qinling terrain, rather than the North China block and the South China block.

5.3. Crustal evolution of the North Qinling terrain

HF isotope composition of detrital zircons is a very powerful tool to decipher reworking and growth of continental crust (Wu et al., 2007 and references therein). As shown below, together with detrital zircon U–Pb ages, they help us to constrain the crustal evolution of the North China block and the North Qinling terrain during the Precambrian. Analyses of Hf isotopic composition in Neoproterozoic detrital zircons (ca. 2.5 Ga) in sedimentary samples from the Guandaokou and Kuanping Groups reveal that a sub-group of the grains have negative εHf(t) values of ~6.3 to ~0.2 and Hf model ages of about ~3.4 Ga to ~3.0 Ga, and the Paleoproterozoic detrital zircon grains (ca. 2.2 Ga to ~1.85 Ga) from the Guandaokou Group samples also show negative εHf(t) values of ~8.9 to ~1.9 and Hf model ages of about 3.0 Ga to 2.7 Ga, indicating the reworking of Archean crust (Wan et al., 2005a; Zhai et al., 2005). This conclusion is consistent with the evidence provided by Nd isotopic analysis in Wu et al. (2005). The oldest zircons found in the two groups in this study have U–Pb ages of about 3.3 Ga to 3.0 Ga, εHf(t) values of ~13.4 to ~3.2, and Hf model ages of about 4.5 Ga to 3.8 Ga and these isotopic features are similar to those of the oldest Archean rocks presently exposed in the North China block (Liu et al., 1992; Song et al., 1996; Wan et al., 2005b; Wu et al., 2008).

The detrital zircons from the southern Qinling orogen and the North Qinling terrain are characterized by positive εHf(t) values of up to ~7, corresponding to Hf model ages (~1.28 Ga to 2.5 Ga). Several Paleoproterozoic detrital zircon grains of about 2.5 Ga to 2.0 Ga from the Kuanping Group also yield positive εHf(t) values of up to ~2.3 and Hf model ages (~1.28–2.6 Ga). These values are consistent with derivation from variably depleted mantle sources.

The U–Pb and Hf zircon data from the Kuanping sedimentary sequence also help to unravel the late Precambrian crustal evolution of the North Qinling terrain. Detrital zircon U–Pb ages and in-situ zircon Lu–Hf isotope data show that the major magmatic activity in the North Qinling terrain occurred around ~1000–900 Ma (Fig. 5) and this magmatism was largely produced by reworking of early Paleoproterozoic crust with minor contribution of late Paleoproterozoic juvenile material.

The oldest basement rocks exposed in the North Qinling terrain range from 2.2 to 2.3 Ga (U–Pb zircon ages, Zhang et al., 1994c), whereas amphibolites have yielded a Sm–Nd isochron age of ~2.0 Ga (Zhang et al., 1994b). Previous studies have demonstrated that the North Qinling terrain is distinguished from the South Qinling terrain and the South China block by the absence of Archean basement rocks (e.g., O’Yang and Zhang, 1996; Zhang et al., 2001; Lu et al., 2006). But, the oldest zircon ages from the Kuanping Group presented here show the existence of recycled Archean material in the North Qinling terrain.

Early Neoproterozoic to Mesoproterozoic detrital zircons of the Kuanping Group from the North Qinling terrain yield negative εHf(t)
values (most < −10), corresponding with Hf model ages from 2.5 Ga to 2.8 Ga (Fig. 8). Noticeably, two magmatic zircons with U–Pb ages of 615 Ma and 1083 Ma have Hf isotopic compositions that suggest the parental magmas were derived from old sources of 3.2 Ga to 3.4 Ga. Therefore, it could be concluded that Archean basement rocks beneath the North Qinling terrain were reworked during Neoproterozoic and Mesoproterozoic times to contribute to the detrital zircon population.

The majority of zircons grains from the Kuanping Group define a narrow age cluster at ca. 1000–900 Ma (Figs. 4 and 7). These grains have negative εHf(t) values ranging from −10.8 to −1.6 (Fig. 5), corresponding to Hf model ages (TDM2) of 2.5–2.0 Ga. The large age difference between Hf model ages and zircon crystallization ages can be readily explained by reworking of early Paleoproterozoic crust. Some detrital zircons of primary magmatic origin have relatively high or positive εHf(t) values (−0.3 to +5.3), with Hf model ages ranging from ca. 1.85 to 1.55 Ga. A remarkable positive εHf(t) value of +10.9 was obtained for a zircon grain from sample 08HN60. This zircon has an indistinct magmatic structure and a Th/U ratio of 0.68 (Fig. 2). The corresponding Hf model age is 1.73 Ga, which is equal to its crystallization ages. Accordingly, when the Hf model ages closely approaches the U–Pb age of the detrital zircon, geological processes that led to the accretion of new juvenile crust are likely to have occurred (e.g., Wu et al., 2007). Hence, these grains reflect derivation from magma that contains juvenile material derived from the mantle during the late Paleoproterozoic.

The majority of Neoproterozoic detrital zircons of the Kuanping Group have negative εHf(t) values in the range −12.5 to −4.8, corresponding to TDM2 Hf model ages of 2.5–2.0 Ga, and the minority have relatively high εHf(t) values ranging from −1.7 to −0.3, corresponding to TDM2 Hf model ages of ca. 1.7 Ga, indicating that both ancient crust and juvenile igneous material had contributed to the magma sources.

Summarizing, it can be concluded that the major magmatic activity in the North Qinling terrain occurred around 1000–900 Ma (Fig. 7). This magmatism was largely produced by reworking of early Paleoproterozoic crust with minor contributions of late Paleoproterozoic juvenile material. The U–Pb ages and Hf data of detrital zircons presented in this study demonstrate that no juvenile material contributed to the magma sources of the about 1000–900 Ma magmatic rocks for the Kuanping Group.

5.4. Implication for Precambrian evolution of the southern North China block

The detrital zircons of igneous origin in meta-sediments of the Guandaokou and the Kuanping Groups provide two U–Pb age peaks, one around ~2.5–2.4 Ga and another around ~1.85 Ga (Fig. 5). This age distribution is reminiscent to that of the North China block, with peaks at 2.6–2.45 Ga and 1.95–1.75 Ga. These age peaks constrain the most important tectonothermal events in the evolution of the craton and they are considered to be related to Precambrian supercontinents (Zha et al., 2001b, 2002a; Zhai et al., 2000,2005; Rogers and Santosh, 2009; Santosh et al., 2006, 2007ab, 2009ab, 2010).

However, U–Pb ages of about 1000–900 Ma obtained from detrital zircons of the Kuanping Group indicate a 100-million year period of magmatic activity along the northern margin of the North Qinling terrain during the early Neoproterozoic. There is abundant evidence for Neoproterozoic (~980–930 Ma) granitic magmatism in the Qinling Group (e.g., Lianghekou granite, Laoyu pluton, Cai’ao granite, Niujiaoshan granite, Dehe monzogranite, Zhai et al., 2000,2002, 2005; Zhang et al., 2004; Chen et al., 2004a,b, 2006, 2007; Lu et al., 2005, 2006; Yang et al., 2010). The remaining zircon data from the Kuanping Group is best explained in terms of reworking of early Paleoproterozoic crustal material (~2.5–2.0 Ga), different from that of the North China block (Fig. 8).

Accordingly, it can be concluded that the North Qinling terrain and the North China block are characterized by different geological histories. It seems that during the Precambrian, the North Qinling terrain was indeed a separate micro-continent (Y’ang and Zhang, 1996; Ding et al., 2003). The conclusion that the North Qinling and the North China block collided after 640 Ma can be drawn from the dating results of the youngest detrital zircons from the middle Kuanping Group. The Sinian sequences, composed of shallow-marine carbonates and silicilastic deposits, are widely distributed along the southern margin of the North China block (Zhai et al., 2003), and can be compared with coeval strata (~640 Ma) from the sedimentary facies of the upper Kuanping Group and the Taowan Group (Fig. 6). This sedimentary record testifies that the North Qinling terrain and the North China block were assembled no earlier than 640 Ma.

Meta-gabbros and serpentinized peridotites associated with the Kuanping Group have been interpreted as a Grenvillian-age ophiolite (Wei et al., 1999; Meng and Zhang, 1999). This would be in line with the subduction of oceanic lithosphere beneath the North Qinling terrain, and a period of major magmatism that actually has been established between 1000 Ma and 900 Ma indicated by zircon Hf analysis. Sedimentation of the middle Kuanping Group started after 640 Ma, demonstrating a temporal hiatus of ~260 Myr between terrrain assembly and the onset of sedimentation.

6. Conclusions

The youngest detrital zircon U–Pb ages constrain a maximum deposition age of ~1.85 Ga for the Guandaokou Group (lowest cover sequence along the southern margin of the North China block), and ~640 Ma for the Kuanping Group, the basement sequence along the northern margin of the North Qinling terrain. Peak U–Pb age values of detrital zircons around ~2.5–2.4 Ga and ~1000–900 Ma for the Kuanping Group suggest a mixed provenance with material derived from the North China block and the North Qinling terrain.

Major magmatic activity in the North Qinling terrain occurred around 1000–900 Ma and the magmatic rocks constitute a major component of reworking of the early Paleoproterozoic crust with minor contribution of late Paleoproterozoic juvenile material.

Detrital zircon U–Pb and Hf data from the sediments of the Guandaokou and Kuanping Groups accentuates the disparate magmatic and geochemical character of the North Qinling terrain and the
North China block. The final accretion and assembly of these blocks took place after about 640 Ma.

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