Partial melting of the South Qinling orogenic crust, China: evidence from Triassic migmatites and diorites of the Foping dome

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Abstract: The Qinling orogen was ultimately formed by suturing of the South Qinling and Yangtze blocks, but the exact timing of the final amalgamation of the two blocks has not been well established so far. Partial melting of the Qinling orogenic continental crust resulted in the generation of migmatites and such rocks may help to decipher the chronology of such event. In this paper we report U-Pb ages, trace element and Hf isotopic compositions of zircons from migmatites and diorite gneisses of the Foping dome, South Qinling. Zircons from migmatites form anhedral grains of variable sizes that are characterized by complex trace element compositions. Based on zircon U-Pb ages, the migmatites can be subdivided into two groups: Group 1 migmatites mainly retain Triassic zircons with U-Pb ages of 214-211 Ma and Hf model ages of ~1.46 Ga in core and rim domains; zircons from Group 2 migmatites record both Triassic (~210 Ma) and Neoproterozoic U-Pb ages, analogous to igneous rocks of the Wudang and Yaolinghe Groups exposed in South Qinling. Zircons from the diorite gneisses yield U-Pb ages of 216-210 Ma with Hf isotopic composition (T_{DM2} ages of ~1.46 Ga) similar to the migmatites. Evidence from whole-rock Nd isotopic analyses also points to a similar genesis between migmatites and diorite gneisses. It is proposed that Group 1 migmatites were derived by melting of Triassic diorites, while Group 2 migmatites were derived from Neoproterozoic igneous rocks, a major basement lithology of South Qinling. Partial melting of the orogenic crust took place at ~214-210 Ma, approximately consistent with the retrograde metamorphism of granulites exposed along the suture zone between the South Qinling and Yangtze blocks. We suggest that the collision of these two blocks occurred prior to ~215 Ma and that the Foping dome resulted from rapid collapse of an overthickened crust followed by partial melting enhanced by asthenospheric influx.

Key words: South Qinling; migmatite; diorite; U-Pb age; Hf isotope

1. Introduction

Migmatites provide direct evidence for partial melting of continental crust. Generally, partial melting can be achieved through the infiltration of external fluids or dehydration of hydrous minerals under sub-solidus condition. In an orogenic belt, partial melting may occur during thickening, exhumation or post-collisional extension of the continental crust. The formation of migmatites is generally accompanied by deformation of the crust and changes in crustal architecture. Therefore, studying the timing of migmatization can help to understand the tectonic evolution of an orogen (e.g., D'lemos et al., 1992; Brown, 1994, 2001; Sawyer, 1996; Brown and Solar, 1998, 1999; Vanderhaeghe, 2009; Brown et al., 2011; Sawyer et al., 2011).

The Qinling orogen is located in central China between the Qilian Mountains to the northwest and the Dabie orogenic belt to the southeast (Fig. 1A). This orogen can be subdivided into three approximately E-W trending terranes: southern margin of the North China block, North Qinling block, and South Qinling block (SQB). The Shang-Dan suture in the north records the Paleozoic northward subduction of the Shang-Dan ocean and the assemblage between the SQB and North Qinling block (e.g., Zhang et al., 2001; Ratschbacher et al., 2003; Cheng et al., 2011, 2012; Dong et al., 2011; Wu and Zheng, 2013; Wang et al., 2011a, 2013a, 2014). The Mian-Lue suture zone in the south marks the line of collision between the SQB and Yangtze (or South China) block during the Triassic, which led to the formation of the Qinling orogen (e.g., Meng and Zhang, 1999; Dong et al., 1999, 2004; Xu et al., 2000; Zhang et al., 2003, 2004a). However, the final closure of the Mian-Lue ocean basin and the formation of the Mian-Lue suture zone is not well constrained yet and its tectonic correlation with the Dabie-Sulu orogen is still a matter of debate.

In South Qinling, numerous Triassic granitoid plutons (240-200 Ma) have been identified (Fig. 1B). Their geochemical characteristics indicate subduction-related, syn- and post-collisional affinities (e.g., Li et al., 1996; Zhang et al., 2002a; Qin et al., 2007, 2008a, 2009; Dong et al., 2011; Li et al., 2013; Wang et al., 2013b), but the exact origin and tectonic setting of these granitoids is still being debated.

Previous geophysical studies indicate that the Foping dome, an E-W trending narrow zone within the SQB, is a key unit to understand the tectonic adjustment of the SQB (e.g., Cheng et al., 2003). In the Foping dome, migmatites occur, but they have not yet been studied in detail with respect to their formation age and geochemical characteristics. In this paper, we present U-Pb ages and Hf isotopic composition of zircons from migmatites of the Foping dome to constrain the time of migmatization and the nature of their protoliths. We also discuss the tectonic evolution of the SQB based on compositional criteria of Triassic granitoids.

2. Geological setting and sample description

The South Qinling block, bounded by the Shan-Dan and Mian-Lue sutures, is made up of Neoarchean to Proterozoic basement rocks and a Neoproterozoic (or Sinian in Chinese literature) to Triassic cover sequence (Zhang et al., 2000, 2001). The 2.6-2.7 Ga old Yudongzi Group exposed along the Mian-Lue suture and in the Bikou block represents the oldest basement of the SQB (Zhang et al., 2001; Wang et al., 2011b). Geochemical characteristics indicate that the Yudongzi Group differs from the Archean Taihua Group of the North China block and the Archean Kongling Group of the Yangtze block. Other major Precambrian basement rocks of the SQB include the Foping Group (U-Pb age of 2000 Ma, Zhang et al., 2004b), the Douling Group (Paleoproterozoic to Palaeozoic, Zhang et al., 2002b; Zhu, 2010; Hu et al., 2013), the Wudang Group (Paleoproterozoic to Neoproterozoic, Ling et al., 2007; Zhu et al., 2008), and the Neoproterozoic Yaolinghe Group (Cai et al., 2007; Ling et al., 2007; Zhu et al., 2014b). The overlying cover rocks mainly consist of clastic and carbonate rocks, ranging in age from Sinian to Triassic (Zhang et al., 2001). Triassic granitoids are the dominant igneous rocks in the SQB. They include, from west to east, the Mishuling, Guangtoushan, Huayang, Wulong, Laocheng, Yanzhiba, Dongjiangkou and Zhashui plutons. Previous studies have constrained their formation ages between 240 Ma and 200 Ma (e.g., Gong et al., 2009; Jiang et al., 2010; Qin, 2010; Yang et al., 2011, 2012b; Ping et al., 2013; Qin et al., 2013).

The Foping dome exposes gneisses that mainly formed during the Paleoproterozoic (2.5 - 2.0 Ga, Li et al., 2000b; Zhang et al., 2004b). In the dome area, a large Late Triassic granite batholith known as Wulong pluton (Fig. 1C) is exposed. The Wulong pluton has been identified to consist of three phases which are, from the centre to the margin of the pluton, porphyritic granite dated at ~207 Ma, mafic enclave-bearing monzonitic granite and granodiorite of ~218 Ma, and enclave-bearing quartz diorite and granodiorite of ~230 Ma (Qin et al., 2013). Granulites were also reported from the Foping dome (Yang et al., 1999) and the peak of granulite-facies metamorphism was constrained at ~220 Ma. This high-grade metamorphic event is attributed to the Late Triassic orogeny in the SQB (e.g., Li et al., 2000a; Zhang et al., 2002c; Liang et al., 2013).

Migmatites, diorite gneisses, and amphibolites can be observed in the center of the dome structure (Fig. 2). The migmatites are either composed of rock types that consist of clearly distinguishable leucosomes and associated melanosomes (Fig. 2A) or those consisting of diffuse areas of pre-existing and newly formed material (Fig. 2B). The leucosomes are coarsely crystallized and several millimeters to centimeters in width and the melanosomes often have a banded or foliated appearance (Fig. 2A). At several localities migmatites contain boudins of amphibolite (Fig. 2B). Migmatite samples 13-FP-30 and 13-FP-31 are mainly composed of plagioclase, K-feldspar, quartz, biotite and hornblende (Fig. 3A). Migmatite samples 13-FP-33A and 13-FP-33B, collected from Wenquan village, consist of quartz, feldspar, biotite and minor amphibole (Fig. 3B). Sample 13-FP-32 was collected from a migmatitic amphibolite and consists of ~35% hornblende and ~60% plagioclase.

Small bodies of diorite gneisses can be found in the Wulong pluton. Those rocks were collected from the vicinity of the Donghekou, Xichahe, Chenjiaba, and Simudi villages. They are mainly quartz diorite to granodiorite in composition. Sample 13-FP-13 collected from Donghekou village is a medium-grained quartz diorite gneiss composed of ~50% plagioclase, ~25% hornblende, ~10% biotite, and ~10% quartz. The gneissic texture is defined by the lineation of hornblende and biotite (Fig. 3C).

Diorite gneiss sample 13-FP-34 from Xichahe village is composed of ~35% K-feldspar, ~25% plagioclase, ~15% quartz, ~15% biotite, and minor hornblende, partially epidotized. Granodiorite gneiss samples 13-NS-59 and 13-NS-62 from Chenjiaba and Simudi villages are medium- to coarse-grained with major mineral assemblages of ~50% plagioclase, ~25% quartz, ~10% hornblende, ~10% biotite, and minor sphene and magnetite (Fig. 3D).

3. Analytical methods

Zircon grains were concentrated from ~5 kg rock samples by standard processing procedures of crushing, sieving, heavy liquid extraction and magnetic separation. About 150 grains for each sample were handpicked under a stereomicroscope, mounted in epoxy and polished. Internal textures of the zircon grains were examined by the cathodoluminescence (CL) technique. U-Pb isotopic dating was done by a LA-ICP-MS located at Key Laboratory of Crust-Mantle Materials and Environments, University of Science and Technology of China (USTC). Standard materials 91500 and NIST610 were used as external calibration for the U-Pb ages and element concentrations of rare earth elements (REE), U, Th and Pb calculation, respectively. A laser beam of 32 μm in diameter was adopted for analysis. More details on the laser-ablation technique are given in Liu et al. (2007). U-Pb ages and element contents were processed by ICPMSDataCal software (Liu et al., 2008, 2010) and calculation of U-Pb ages was performed by the Isoplot program (Ludwig, 2003). Whole-rock Sm and Nd isotope analysis was determined by the isotopic dilution technique using ^{149}Sm and ^{150}Nd tracer solutions. 150 mg of sample material was dissolved in a mixture of HClO_4 and HF acid solution at 120 $^{\circ}\text{C}$ for 7 days. Subsequently, the solution was dried and re-dissolved in HCl acid solution. Sm and Nd isotopic ratios were measured on a Finnigan MAT-262 spectrometer at the Radiogenic Isotope Geochemistry Laboratory of the USTC. Repeated analysis on Nd isotope reference solution (La Jolla) gives a mean $^{143}\text{Nd}/^{144}\text{Nd}$ value of 0.511869 ± 0.000006 (2σ). Analytical precisions are stated as 2 sigma standard errors and details of the analytical

technique are described in Chen et al. (2000, 2007).

Hf isotope analyses of zircon grains were performed on a Neptune MC-ICP-MS at the Institute of Geology and Geophysics, Chinese Academy of Science in Beijing. Standard zircons GJ-1 ($^{176}\text{Hf}/^{177}\text{Hf}=0.282020$) and MUD ($^{176}\text{Hf}/^{177}\text{Hf}=0.282500$) were chosen for external calibration and the ablation diameter was *ca.* 60 μm . Details of the instrument parameters, analytical procedures and interference correction are given in Xu et al. (2004) and Wu et al. (2006).

4. Analytical results

Zircon grains from five migmatite samples (13-FP-30, 13-FP-31, 13-FP-32, 13-FP-33A, 13-FP-33B) and four diorite gneiss samples (13-FP-13, 13-FP-34, 13-NS-59, 13-NS-62) were selected for combined in situ analyses of rare earth elements and U-Pb isotopic composition. Samples 13-FP-33A and 13-FP-33B were collected from the same locality. Sample 13-FP-33B is composed of light-colored leucosome-rich material, whereas sample 13-FP-33A predominantly consists of melanosomic material. Analytical results are given as supplementary data (Table S1 and Table S2) on the website of the journal.

Zircon grains from migmatite 13-FP-30 are colorless, transparent and subhedral to anhedral in shape with the lengths of long axis ranging from 100 to 400 μm . Most grains display dark cores and light rims in CL images (Figs. 4a-c). Twenty-six spots were analyzed and yield relatively low Th (44-122 ppm) and U (59-170 ppm) contents with Th/U ratios varying from 0.55 to 0.99. The U-Pb apparent ages of the twenty-six analytical spots vary from 204 to 224 Ma (Fig. 5a), yielding a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 214 ± 2 Ma (MSWD= 0.83). Core and rim domains give the same $^{206}\text{Pb}/^{238}\text{U}$ ages within analytical uncertainties. In the chondrite-normalized REE diagram, all zircon grains portray positive Ce- and negative Eu-anomalies and enrichment in heavy REEs (Fig. 5a').

Zircon grains from migmatite 13-FP-31 have similar features similar to those of

sample 13-FP-30. They are colorless, transparent, and irregular in shape. Grain sizes range from 100 to 450 μm and some grains have dark cores and light rims in CL images (Figs. 4d-e). Thirty-six spot analyses give low Th (8-293 ppm) and variable U (22-1040 ppm) contents and a large range of Th/U ratios (0.05-1.21). Thirty-four spots yield apparent U-Pb isotopic ages ranging from 198 to 226 Ma (Fig. 5b) with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 211 ± 2 Ma (MSWD= 2.3). The other two spots yield similar $^{206}\text{Pb}/^{238}\text{U}$ ages of 791 and 773 Ma. Most zircon grains of sample 13-FP-31 have chondrite-normalized REE patterns characterized by positive Ce- and negative Eu-anomalies and enrichment in heavy REEs (Fig. 5b').

Migmatite sample 13-FP-32 contains colorless zircon grains with rounded ovoid shapes. The CL images reveal internal textures similar to those observed in the migmatite samples mentioned above (Figs. 4f-h). Twenty-six analyses give low Th (45-124 ppm) and U (57-140 ppm) contents and Th/U ratios varying from 0.65 to 1.24. Apparent U-Pb ages vary from 199 to 224 Ma (Fig. 5c), with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 211 ± 2 Ma (MSWD= 1.01). All zircon grains have similar REE features including positive Ce- and negative Eu-anomalies in the chondrite-normalized diagram (Fig. 5c').

Zircon grains from migmatite 13-FP-33A have irregular shapes and variable lengths (60-450 μm) and show complex internal textures in CL images (Figs. 4i-l). Nineteen out of twenty-six spots give low Th (20-141 ppm) and variable U (61-1093 ppm) contents with Th/U ratios ranging from 0.07 to 0.43. U-Pb apparent ages range from 200 Ma to 231 Ma (Fig. 5d) with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 209 ± 3 Ma (MSWD= 2.6). The other seven spots have Th (20-177 ppm) and U (40-239 ppm) contents with high Th/U ratios of 0.39-0.74. They yield discordant age data with $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 446 to 742 Ma (Fig. 5d). Regression through all data points yields a discordia line with an upper intercept age of 1109 ± 91 Ma.

Zircon grains from the leucosomes rich part of the migmatite (13-FP-33B) have more euhedral habitus and smaller size compared to those from the other migmatite samples (Figs. 4m-p). They show distinct oscillatory zoning in CL images and

variable Th/U ratios ranging from 0.04 to 0.7. Fourteen spots give a complex chronologic record. Seven grains have Neoproterozoic ages with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 806 ± 28 Ma. Three analytical spots give $^{206}\text{Pb}/^{238}\text{U}$ ages of 641 Ma to 535 Ma and the remaining four spots vary in age from 266 to 218 Ma (Fig. 5). All analytical spots of samples 13-FP-33A and 13-FP-33B have positive Ce-anomalies but slightly negative Eu-anomalies in chondrite-normalized diagrams (Figs. 5d'-e').

Compared to the migmatite samples, the diorite gneisses generally contain euhedral prismatic zircons with uniform grain sizes between 100 to 250 μm . In CL images, most zircons from the gneisses reveal typical igneous-looking textures, including the presence of well-preserved oscillatory zoning (Fig. 6). Twenty-four analytical spots from sample 13-FP-13 have low Th (57-188 ppm) and moderate U (131-392 ppm) contents and Th/U ratios of 0.42-0.60. Their apparent U-Pb ages range from 205 to 225 Ma (Fig. 7a), giving a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 214 ± 2 Ma (MSWD= 1.07). Twenty-four zircon grains were analysed from sample 13-FP-34. They contain 85-206 ppm Th and 147-405 ppm U with high Th/U ratios of 0.57-0.86. Their U-Pb apparent ages range from 208 to 236 Ma (Fig. 7b), yielding a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 216 ± 2 Ma (MSWD= 2.1). Twenty-three analyzed zircon grains from sample 13-NS-59 have Th contents of 109-288 ppm and U contents of 241-632 ppm, with Th/U ratios of 0.36-0.66. Apparent U-Pb ages of 203 to 231 Ma (Fig. 7c) and a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 213 ± 3 Ma (MSWD= 3.3) were obtained from this sample. Twenty-two spots were measured on zircons from sample 13-NS-62 and give variable Th (104-728 ppm) and U (197-898 ppm) contents with Th/U ratios between 0.49 and 0.81. Their apparent ages vary from 203 to 231 Ma (Fig. 7d) with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 213 ± 3 Ma (MSWD = 0.99). In chondrite-normalized diagrams, all analyzed zircon grains are characterized by negative Eu-anomalies and most grains show variable degrees of positive Ce-anomalies (Figs. 7a'-d').

Hf isotope composition was obtained from zircon grains of three migmatite samples (13-FP-30, 13-FP-32, 13-FP-33A) and one diorite gneiss sample (13-FP-34).

Analytical spots are shown in Figures 4 and 6 and the results are available as supplementary data (Table S3) on the journal's website. Twenty-six analyses were performed on zircon grains from sample 13-FP-30. Their $^{176}\text{Hf}/^{177}\text{Hf}$ ratios range from 0.282482 to 0.282598 and initial ϵ_{Hf} values from -1.7 to -5.6, corresponding to two-stage Hf model ages (T_{DM2}) of 1.36 to 1.61 Ga (Figs. 8a, 9). $^{176}\text{Hf}/^{177}\text{Hf}$ values of twenty-six analytical spots on sample 13-FP-32 vary from 0.282497 to 0.282597 and initial ϵ_{Hf} values from -1.5 to -5.4 with T_{DM2} values of 1.35 to 1.58 Ga (Figs. 8b, 9). Seven analyses from older (pre-Triassic) zircon domains of sample 13-FP-33A yield $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of 0.282486 to 0.282605 and initial ϵ_{Hf} values from -0.7 to 8.0 with T_{DM2} values from 1.10 to 1.48 Ga, while the remaining fifteen analyses of this sample have $^{176}\text{Hf}/^{177}\text{Hf}$ ratios ranging from 0.282585 to 0.282723 and initial ϵ_{Hf} values between -2.1 and 2.7 with T_{DM2} values of 1.08 to 1.38 Ga (Figs. 8c, 9). Twenty-three analyses from zircon grains of sample 13-FP-34 give $^{176}\text{Hf}/^{177}\text{Hf}$ ratios ranging from 0.282502 to 0.282605 and initial ϵ_{Hf} values from -0.9 to -4.8, corresponding to T_{DM2} values of 1.33 to 1.56 Ga (Figs. 8d, 9).

Whole-rock Sm-Nd isotopic data of four diorite gneiss samples are given in Table 1. The samples have relatively uniform $^{147}\text{Sm}/^{144}\text{Nd}$ ratios between 0.1116 and 0.1194. When calculating back to the Triassic zircon ages, initial ϵ_{Nd} values vary from -4.3 to -5.3 (Fig. 10) and two-stage Nd model ages range from 1.35 to 1.42 Ga, which is similar to the range of the zircon two-stage Hf model ages.

5. Discussion

Based on the zircon age record, migmatites from the Foping dome can be subdivided into two groups: Group I migmatites mainly recording Triassic age (samples 13-FP-30, 13-FP-31 and 13-FP-32) and Group II migmatites (samples 13-FP-33A and 13-FP-33B) documenting both Neoproterozoic and Triassic ages.

The trace element composition and the U-Pb ages of the zircons from the Foping migmatites can provide information concerning the nature of the protolith. High Th/U

ratios of >0.4 and uniform chondrite-normalized REE patterns of zircon grains from Group I migmatites may point to an igneous protolith being similar to the Triassic diorites. This is substantiated by the fact that major mineral and Hf isotopic composition between migmatites and diorite gneisses are very similar. Zircons from these migmatites samples show strong enrichment in heavy REEs (steep patterns) suggesting that such grains did not re-crystallize under high-grade granulite-facies metamorphic condition (Rubatto, 2002). Mean core and rim ages from zircons of Group I migmatites are almost identical within errors.

Zircon Hf isotope data of the migmatites and diorite gneisses can provide information on the nature of the protolith and on the time of crust-mantle differentiation. However, cautions must be taken when using Hf model ages of complex igneous systems, such which are characterized by multiple compositions or source components (e.g., Wu et al., 2007). U-Pb ages clearly indicate a Triassic migmatization age of the Foping rocks. Hf model ages of zircons (~ 1.6 - 1.1 Ga) and whole-rock Nd model ages (~ 1.4 Ga) of Group I migmatites likely suggest that the protoliths of these migmatites were derived from Mesoproterozoic crustal rocks. However, according to previous dating results such rocks are not frequent in the South Qinling unit. Precambrian rocks of the South Qinling unit are mainly late Archean to Paleoproterozoic and Neoproterozoic in age. Except some volcano-sedimentary sequences of the Kunyang and Huili Groups along the southwestern margin of the Yangtze block, late Paleoproterozoic and Mesoproterozoic magmatic activity or crustal growth in the Yangtze block was only reported from within the Sichuan and Yunnan provinces (e.g., Li et al., 2002; Greentree and Li, 2008; Yin et al., 2011, 2012; Yang et al., 2012a; Fan et al., 2013). This magmatism was possibly associated with the formation of the supercontinent Columbia (e.g., Zhao et al., 2004; Ernst et al., 2008). The occurrence of Mesoproterozoic magmatism at the northern margin of the Yangtze block needs further investigation. The Qinling Group in North Qinling records some Mesoproterozoic thermal events in paragneisses (e.g., Lu et al., 2006; Yang et al., 2010; Bader et al., 2013) but from a geochemical perspective, these

paragneisses are not a likely source of the Foping migmatites. In the initial ϵ_{Hf} value versus U-Pb age diagram (Fig. 9), ϵ_{Hf} values of zircons from the Foping migmatites are plotted together with those from Triassic granitoids and basement rocks exposed in the SQB. It can be observed that zircons from migmatites and granitoids are characterized by large variation in Hf isotopic composition. Both rock types tend to form a mixing array pointing to a mixture between mantle, or juvenile crust and ancient basement rocks of the Yangtze block. Such a mixing scenario would also explain the variable initial ϵ_{Hf} values and Mesoproterozoic model ages of the Foping migmatites and diorite gneisses. Similarly, the initial ϵ_{Nd} values of the diorite gneisses from the Foping dome overlap with those reported from the nearby Triassic Wulong pluton (Qin, 2010; Wang et al., 2011c) (Fig. 10), supporting such interpretation.

Zircon grains from Group II migmatites preserve both Triassic and Neoproterozoic U-Pb ages. Evidence of Neoproterozoic igneous activity is found in the Wudang and Yaolinghe Groups of the SQB and Neoproterozoic mafic plutons were also reported close to the Foping dome (e.g., Ling et al., 2002, 2007; Zhu et al., 2008, 2014b). The Neoproterozoic magmatic rocks have Mesoproterozoic Hf model ages (Ling et al., 2007, 2010; Zhu et al., 2009, 2014a; Hu et al., 2016). Therefore, such rocks are potential source candidates for the migmatites. The Neoproterozoic zircon grains retain juvenile initial ϵ_{Hf} signatures (Fig. 9), probably indicating a mantle-derived origin for the protoliths of Group II migmatites. Igneous rocks of Neoproterozoic age (~800-700 Ma) are widely distributed along the northern margin of the Yangtze block. Their presence is related to the formation or breakup of Rodinia and the same applies for most protoliths of Triassic ultrahigh-pressure rocks in the Dabie-Sulu orogen (e.g., Zheng, 2008; Zhang et al., 2009; Liou et al., 2012; Zhang et al., 2014). It seems that igneous rocks of the Wudang and Yaolinghe Groups in the SQB also belong to this Neoproterozoic assemblage. They exhibit geochemical features of bimodal volcanism although their tectonic setting is still not yet well defined (Ling et al., 2002, 2007; Zhu et al., 2008, 2014a, b).

In previous work, it was suggested that possible zircon growth mechanisms in

high-grade metamorphic rock include subsolidus metamorphic reaction between zirconium-bearing accessory minerals and silicates, precipitation from metamorphic fluids, and crystallization from the melt during crustal melting (e.g., Vavra et al., 1996; Schaltegger et al., 1999; Andersson et al., 2002; Rubatto, 2002; Rubatto and Hermann, 2003). During this process, any pre-metamorphic (or pre-migmatitic) zircon can experience various degree of recrystallization related to reaction with metamorphic fluid or melt. The mechanisms generally include solid-state recrystallization, replacement recrystallization, and dissolution- recrystallization of preexisting zircons (e.g., Schaltegger et al., 1999; Hoskin and Black, 2000; Geisler et al., 2007; Rubatto et al., 2008, 2001; Xia et al., 2009; Chen et al., 2010). Solid-state recrystallization generally occurs under dry conditions (i.e. lack of a fluid phase). Recrystallized zircons often have euhedral shape but do not maintain their original oscillatory zoning pattern. This mechanism can disturb the zircon U-Pb system resulting in strongly discordant metamorphic ages. Trace elements and Hf isotope composition of the zircon grains, however, are nearly identical to those in the precursor rocks. Replacement-recrystallization takes place in the presence of a fluid phase. Zircons produced by such process have euhedral morphology and patched zoning. The U-Pb ages are discordant and Th/U ratios are lower than in the pre-metamorphic zircon grains. The Hf isotope ratios are almost identical to that of the original grains. Dissolution-recrystallization also occurs under fluid or melt present conditions. Metamorphic zircon grains are often anhedral and recrystallization domains show spongy texture but this texture can seal as the result of equilibration (Geisler et al., 2007); their U-Pb ages can be nearly concordant and close to the discordia. The Th/U ratios and REE content are lower than in the pre-metamorphic zircons. The Hf isotope ratios depend on whether the system was open or not (Geisler et al., 2007; Xia et al., 2009; Chen et al., 2010).

The metamorphic zircon domains from Group I migmatites yield similar concordant ages. Besides, their REE distribution pattern shows strong enrichment in heavy REEs, which is typical for an igneous origin. When plotted in a diagram of

(Sm/La)_N versus La-content (Fig. 11A), most Group I zircon grains show a magmatic affinity. Average Th/U ratios of the cores and rims of Group I zircons are higher than 0.4 (Fig. 11B), except two analytical spots with very high U-contents of 864 ppm and 1004 ppm. Total REE contents of the cores are normally higher than those of the rims (Fig. 11C). ¹⁷⁶Hf/¹⁷⁷Hf ratios of the cores and rims from Group I migmatites (samples 13-FP-30 and 13-FP-31) are relatively uniform compared to those of Group II migmatites (Fig. 11D). All these features indicate that the zircons formed through the mechanism of dissolution-recrystallization where chemical and isotopic equilibration was achieved. The Ti-in-zircon thermometer (Ferry and Watson, 2007) shows that the crystallization temperatures of Group I migmatites mainly cluster between 750 and 850 °C and this high temperature can cause fluid-absent incongruent melting of meta-andesitic rock (e.g., Sawyer et al., 2011). The Ti-in-zircon temperatures of Group II migmatites range from 650 to 700 °C and could indicate a fluid-present partial melting event at relatively shallow crustal depths.

The zircon dating results on the Foping migmatites clearly demonstrate the existence of a partial melting event of the SQB crust during the Late Triassic. A question arises about the tectonic event associated with this thermal regime. Recent geophysical surveys have shown that South Qinling, including the Foping and Ningshan area, is underlain by a hotter and thinner underlying lithosphere compared with North Qinling and the Yangtze block. This has been interpreted as a result of isostatic adjustment of the lithosphere after the Triassic continental collision (Cheng et al., 2003). The exact timing of the closure of the Mian-Lue ocean and the final collision of the SQB and the Yangtze block is not yet well constrained. Geochronological data from mafic and volcanic rocks along the Mian-Lue suture zone suggest that the Paleo-Tethys ocean between the North and South China blocks did not close until Triassic (e.g., Li et al., 1996, 2003; Xu et al., 1997, 2000; Lai et al., 1998, 2002, 2003; Dong et al., 1999, 2004; Zhang et al., 2003; Qin et al., 2008b; Lai and Qin, 2010). Although ultrahigh-pressure metamorphic rocks have not been reported in the SQB, outcrops of high-pressure granulites are located along the

Mian-Lue suture zone that can be used to further unravel the thermal evolution of the orogen (Wei et al., 1998; Yang et al., 1999; Li et al., 2000a; Zhang et al., 2002c; Liang et al., 2013). Granulite-facies metamorphism dated at ~220 Ma (Yang et al., 1999) and late amphibolite-facies metamorphism dated at 214 Ma (Liang et al., 2013) was related to crustal thickening caused by collision and subsequently post-collisional exhumation, respectively.

Late Triassic granitoids are widely exposed in the SQB. Previous studies on the formation and composition of these rocks have led to diverse interpretations. Qin et al. (2008a, 2013) have proposed that the Triassic granitoids (e.g., Wulong, Qinlingliang, Guangtoushan and Laojunshan plutons) formed in a post-collisional environment at ~230-210 Ma. Wang et al., (2007, 2011c) came to the same conclusion based on studies of the c. 220-210 Ma old Qinlingliang, Laojunshan and Shehewan granites and related lamprophyres. However, several authors have argued that final closure of the Mian-Lue ocean took place later than 211 Ma (Jiang et al., 2010) or at 207-201 Ma (Dong et al., 2012). Based on Li et al. (2015), the Triassic granitoids are subduction-related and the final amalgamation of the SQB and Yangtze block occurred at ~200 Ma.

The timing of partial melting of orogenic crust in the Foping dome can provide further clues on the temporal evolution of the orogen. A large number of the above-mentioned Late Triassic granitic plutons show geochemical characteristics of “continental adakites”. This suggests that a thick crust was established in the South Qinling block when these rocks emplaced. A thick crust can be established during subduction, like in central Andes, or during continental collision (e.g., Vanderhaeghe and Duchêne, 2010; de Sigoyer et al., 2014). However, the geochemical characteristics of subduction and collision related magmas are different. Concerning subduction zones, calc-alkaline melts can be produced in the mantle wedge by dehydration reactions and, if young and hot oceanic crust is subducted, adakites can be generated in the oceanic crust itself. Both types of magma record evidence for the incorporation of depleted mantle material or for mixing between depleted mantle and

continental crust. Such “mantle signatures” have not yet reported in the late Triassic plutons of the South Qinling block. These magmas (including the “continental adakites”) show enriched Sr and Nd isotope characteristic which suggest a major contribution of crustal material in their original magma source. Some of the “continental adakites” display features of mantle metasomatism as high $Mg^\#$ and Cr and Ni contents.

Besides, the timing of migmatization in the Foping dome is temporally identical with the retrograde metamorphism of the granulites exposed along the Mian-Lue suture zone (Liang et al., 2013). This suggests that the South Qinling crust had entered the post-collision stage and the lower crust was undergoing thickening and delamination during 220 to 210 Ma. The delaminated lower crust could have caused upwelling of asthenosphere, which is also confirmed by the positive $\epsilon_{Hf}(t)$ of the Triassic plutons in South Qinling (e.g., Ping et al., 2013). The heat from the asthenospheric mantle plus the heat provided by radioactive decay in the continental crust (England and Thompson, 1986, Vanderhaeghe et al., 2003) could have increased the temperature at the base of lower crust giving rise to anatexis melting and formation of Group I migmatites (Fig. 12A). The successive delamination and melt migration can accelerate lower crust thinning of a narrow orogen in a few million years (Teyssier and Whitney, 2002; Rey et al., 2009). Rapid adiabatic rise of magmas would transfer the heat in higher crustal levels (Thompson et al., 1997; Huerta et al., 1998). Such process could have provided the heat source for water-induced partial melting of the lower crust the formation of Group II migmatites at shallower crustal depths (Fig. 12B). This rapid process cause partial melting of lower crust at deep to lower depths. During this event, granulite-facies rocks were exhumed and, as a consequence of these processes, the Foping dome was formed.

6. Conclusions

Based on the zircon age record, migmatites from the Foping dome can be divided into two groups: Group I migmatites record Triassic ages of 214-211 Ma whereas

Group II migmatites preserve both Neoproterozoic and Triassic ages. These differences indicate the occurrence of at least two different geological components in this part of the South Qinling orogenic crust. Our data also imply different Late Triassic partial melting behavior of the orogenic crust. Combined with the evidence from Hf isotopes of zircon and whole-rock Nd isotopes of migmatite and gneissic diorite, the protoliths of Group I migmatites were Triassic diorites, while Group II migmatites probably originated from Neoproterozoic mantle-derived igneous rocks or juvenile crust, analogous with volcanic rocks of the Wudang and Yaolinghe Groups of South Qinling.

Partial melting of the orogenic crust in the Foping dome occurred nearly at the same time as retrograde metamorphism of granulites along the Mian-Lue suture zone, implying that the suturing and collision between South Qinling and the Yangtze block occurred prior to 215 Ma. Igneous rocks which were formed during an earlier stage of plate convergence as well as Neoproterozoic basement rocks of South Qinling underwent strong reworking during the post-collisional extensional stage which finally led to the formation of the Foping gneiss dome.

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References

- Andersson, J., Moller, C., Johansson, L., 2002. Zircon geochronology of migmatite gneisses along the Mylonite Zone (S Sweden): a major Sveconorwegian terrane boundary in the Baltic Shield. *Precambrian Research* 114, 121-147.
- Bader, T., Ratschbacher, L., Franz, L., Yang, Z., Hofmann, M., Linnemann, U., Yuan, H., 2013. The heart of China revisited, I. Proterozoic tectonics of the Qin mountains in the core of supercontinent Rodinia. *Tectonics* 32, 661-687.
- Brown, M., 1994. The generation, segregation, ascent and emplacement of granite magma: the migmatite-to-crustally-derived granite connection in thicken orogens. *Earth-Science Reviews* 36, 83-130.
- Brown, M., 2001. Crust melting and granite magmatism: key issues. *Physics and Chemistry of the Earth, Part A: Solid Earth and Geodesy* 26, 201-212.
- Brown, M., Korhnen, F.J., Siddoway, C.S., 2011. Organizing melt flow through the crust. *Elements* 7, 261-266.
- Brown, M., Solar, G.S., 1998. Granite ascent and emplacement during contractional deformation in convergent orogens. *Journal of Structural Geology* 20, 1365-1393.
- Brown, M., Solar, G.S., 1999. The mechanism of ascent and emplacement of granite magma during transpression: a syntectonic granite paradigm. *Tectonophysics* 312, 1-33.
- Cai, Z., Xiong, X., Luo, H., Wu, D., Sun, S., Rao, B., Wang, S., 2007. Forming age of the volcanic rocks of the Yaolinghe Group from Wudang block, southern Qinling mountain: constraint from grain-zircon U-Pb dating. *Acta Geologica Sinica* 81, 620-625 (in Chinese with English abstract).
- Chen, F., Hegner, E., Todt, W., 2000. Zircon ages and Nd isotopic and chemical compositions of orthogneisses from the Black Forest, Germany: evidence for a Cambrian magmatic arc. *International Journal of Earth Sciences* 2000, 791-802.
- Chen, F., Li, X.-H., Wang, X.-L., Li, Q.-L., Siebel, W., 2007. Zircon age and Nd-Hf isotopic composition of the Yunnan Tethyan belt, southwestern China. *International Journal of Earth Sciences* 96, 1179-1194.
- Chen, R.-X., Zheng, Y.-F., Xie, L., 2010. Metamorphic growth and recrystallization of zircon: Distinction by simultaneous in-situ analyses of trace elements, U-Th-Pb and Lu-Hf isotopes in zircons from eclogite-facies rocks in the Sulu orogen. *Lithos* 114, 132-154.
- Cheng, H., Zhang, C., Vervoort, J.D., Li, X., Li, Q., Wu, Y., Zheng, S., 2012. Timing of eclogite facies metamorphism in the North Qinling by U-Pb and Lu-Hf geochronology. *Lithos* 136-139, 46-59.
- Cheng, H., Zhang, C., Vervoort, J.D., Li, X., Li, Q., Zheng, S., Cao, D., 2011.

- Geochronology of the transition of eclogite to amphibolite facies metamorphism in the North Qinling orogen of central China. *Lithos* 125, 969-983.
- Cheng, S., Zhang, G., Li, L., 2003. Lithospheric electrical structure of the Qinling orogen and its geodynamic implication. *Chinese Journal of Geophysics* 46, 390-397 (in Chinese with English abstract).
- D'lemos, R.S., Brown, M., Strachan, R.A., 1992. Granite magma generation, ascent and emplacement within a transpressional orogen. *Journal of the Geological Society* 149, 487-790.
- de Sigoyer, J., Vanderhaeghe, O., Duchêne, S., Billerot, A., 2014. Generation and emplacement of Triassic granitoids within the Songpan Ganze accretionary-orogenic wedge in a context of slab retreat accommodated by tear faulting, Eastern Tibetan plateau, China. *Journal of Asian Earth Sciences* 88, 192-216.
- Dong, Y., Liu, X., Zhang, G., Chen, Q., Zhang, X., Li, W., Yang, C., 2012. Triassic diorites and granitoids in the Foping area: Constraints on the conversion from subduction to collision in the Qinling orogen, China. *Journal of Asian Earth Sciences* 47, 123-142.
- Dong, Y., Zhang, G., Lai, S.-C., Zhou, D., Zhu, B., 1999. An ophiolitic tectonic melange first discovered in Huashan area, south margin of Qinling orogenic belt, and its tectonic implications. *Science in China (Series D)* 42, 292-301.
- Dong, Y., Zhang, G., Neubauer, F., Liu, X., Genser, J., Hauzenberger, C., 2011. Tectonic evolution of the Qinling orogen, China: Review and synthesis. *Journal of Asian Earth Sciences* 41, 213-237.
- Dong, Y., Zhang, G., Zhao, X., Yao, A., Liu, X., 2004. Geochemistry of the subduction-related magmatic rocks in the Dahong Mountains, northern Hubei Province: constraint on the existence and subduction of the eastern Mianlue oceanic basin. *Science in China (Series D)* 47, 366-377.
- England, P.C., Thompson, A.B., 1986. Some thermal and tectonic models for crustal melting in continental collision zones. *Geological Society Special Publication* 19, 83-94.
- Ernst, R.E., Wingate, M.T.D., Buchan, K.L., Li, Z.X., 2008. Global record of 1600-700 Ma Large Igneous Provinces (LIPs): Implications for the reconstruction of the proposed Nuna (Columbia) and Rodinia supercontinents. *Precambrian Research* 160, 159-178.
- Fan, H.-P., Zhu, W.-G., Li, Z.-X., Zhong, H., Bai, Z.-J., He, D.-F., Chen, C.-J., Cao, C.-Y., 2013. Ca. 1.5Ga mafic magmatism in South China during the break-up of the supercontinent Nuna/Columbia: The Zhuqing Fe-Ti-V oxide ore-bearing mafic intrusions in western Yangtze Block. *Lithos* 168-169, 85-98.
- Ferry, J.M., Watson, E.B., 2007. New thermodynamic models and revised calibrations

- for the Ti-in-zircon and Zr-in-rutile thermometers. *Contributions to Mineralogy and Petrology* 154, 429-437.
- Gao, S., Ling, W., Qiu, Y., Lian, Z., Hartmann, G., Simon, K., 1999. Contrasting geochemical and Sm-Nd isotopic compositions of Archean metasediments from the Kongling high-grade terrain of the Yangtze craton: Evidence for cratonic evolution and redistribution of REE during crustal anatexis. *Geochimica et Cosmochimica Acta* 63, 2071-2088.
- Geisler, T., Schaltegger, U., Tomaschek, F., 2007. Re-equilibration of zircon in aqueous fluids and melts. *Elements* 3, 43-50.
- Gong, H., Zhu, L., Sun, B., Li, B., Guo, B., Wang, J., 2009. Zircon U-Pb and Hf isotope composition of the Dongjiangkou granitic pluton and its mafic enclaves in the South Qinling terrain. *Acta Petrologica Sinica* 25, 3029-3042.
- Greentree, M.R., Li, Z.-X., 2008. The oldest known rocks in south-western China: SHRIMP U-Pb magmatic crystallisation age and detrital provenance analysis of the Paleoproterozoic Dahongshan Group. *Journal of Asian Earth Sciences* 33, 289-302.
- Hoskin, P.W.O., 2005. Trace-element composition of hydrothermal zircon and the alteration of Hadean zircon from the Jack Hills, Australia. *Geochimica et Cosmochimica Acta* 69, 637-648.
- Hoskin, P.W.O., Black, L.P., 2000. Metamorphic zircon formation by solid-state recrystallization of protolith igneous zircon. *Journal of Metamorphic Geology* 18, 423-439.
- Hu, F., Liu, S., Santosh, M., Deng, Z., Wang, W., Zhang, W., Yan, M., 2016. Chronology and tectonic implications of Neoproterozoic blocks in the South Qinling Orogenic Belt, Central China. *Gondwana Research* 30, 24-47.
- Hu, J., Liu, X., Chen, L., Qu, W., Li, H., Geng, J., 2013. A ~2.5 Ga magmatic event at the northern margin of the Yangtze craton: Evidence from U-Pb dating and Hf isotope analysis of zircons from the Douling Complex in the South Qinling orogen. *Chinese Science Bulletin* 58, 3564-3579.
- Huerta, A.D., Royden, L.H., Hodges, K.V., 1998. The thermal structure of collisional orogens as a response to accretion, erosion, and radiogenic heating. *Journal of Geophysical Research* 103, 15287-15302.
- Jiang, Y.-H., Jin, G.-D., Liao, S.-Y., Zhou, Q., Zhao, P., 2010. Geochemical and Sr-Nd-Hf isotopic constraints on the origin of Late Triassic granitoids from the Qinling orogen, central China: Implications for a continental arc to continent-continent collision. *Lithos* 117, 183-197.
- Lai, S., Qin, J., 2010. U-Pb dating and Hf isotopic composition of the diabase dike swarm from Sanchazi area, Mianlue suture: chronology evidence for the Paleo-Tethys oceanic crust subduction. *Journal of Earth Sciences and Environment* 32, 27-33 (in Chinese with English abstract).

- Lai, S., Zhang, G., Pei, X., 2002. Geochemistry of the Pipasi ophiolite in the Mianlue suture zone South Qinling, and its tectonic significance. *Geological Bulletin of China* 21, 465-470 (in Chinese with English abstract).
- Lai, S., Zhang, G., Pei, X., Yang, H., 2003. Geochemistry of the ophiolite and oceanic island basalt in the Kangxian-Pipasi-Nanping tectonic melange zone, south Qinling and their tectonic significance. *Science in China (Series D)* 33, 10-18.
- Lai, S., Zhang, G., Yang, Y., Chen, J., 1998. Geochemistry of the ophiolite and island volcanic rock in the Mianxian-Lueyang suture zone, southern Qinling and their tectonic significances. *Geochimica* 27, 283-293 (in Chinese with English abstract).
- Li, H., Zhang, C., Yao, C., Xiang, Z., 2013. U-Pb zircon age and Hf isotope compositions of Mesoproterozoic sedimentary strata on the western margin of the Yangtze massif. *Science in China (Series D)* 56, 628-639.
- Li, N., Chen, Y.-J., Santosh, M., Pirajno, F., 2015. Compositional polarity of Triassic granitoids in the Qinling Orogen, China: Implication for termination of the northernmost paleo-Tethys. *Gondwana Research* 27, 244-257.
- Li, S., Hou, Z., Yang, Y., Sun, W., Zhang, G., Li, Q., 2003. Timing and geochemistry characters of the Sanchazi magmatic arc in Mianlue tectonic zone, South Qinling. *Science in China (Series D)* 33, 1163-1173.
- Li, S., Sun, W., Zhang, G., Chen, J., Yang, Y., 1996. Chronology and geochemistry of metavolcaic rocks from Heigouxia Valley in the Mian-Lue tectonic zone, South Qinling: evidence for a Paleozoic oceanic basin and its close time. *Science in China (Series D)* 26, 223-260.
- Li, S., Zhang, G., Li, Y., Yang, Y., 2000a. Discovery of granulite in the Mianxian-Lueyang suture zone, Mianxian area and its tectonic significance. *Acta Petrologica Sinica* 16, 220-226.
- Li, Y., Wang, G., Wang, C., Chang, H., 2000b. Zircon U-Pb isotope geochronology of the Longcaoping crystal complex in South Qinling. *Acta Mineralogica Sinica* 20, 50-54.
- Li, Z., Li, X., Zhou, H., Kinny, P.D., 2002. Grenvillian continental collision in south China: New SHRIMP U-Pb zircon results and implications for the configuration of Rodinia. *Geology* 30, 163-166.
- Liang, S., Liu, L., Zhang, C., Yang, Y., Yang, W., Kang, L., Cao, Y., 2013. Metamorphism and zircon U-Pb age of high-pressure mafic granulite in Mian-Lue suture zone, South Qinling orogen. *Acta Petrologica Sinica* 29, 1657-1674.
- Ling, W., Cheng, J., Wang, X., Zhou, H., 2002. Geochemical features of the Neoproterozoic igneous rocks from the Wudang region and their implications for the Jinling tectonic evolution along the South Qinling orogenic belt. *Acta Petrologica Sinica* 18, 25-36.

- Ling, W., Duan, R., Liu, X., Cheng, J., Mao, X., Peng, L., Liu, Z., Yang, H., Ren, B., 2010. U-Pb dating of detrital zircons from the Wudang Group in the South Qinling and its geological significance Chinese Science Bulletin 55, 1153-1161.
- Ling, W., Ren, B., Duan, R., Liu, X., Mao, X., Peng, L., Liu, Z., Cheng, J., Yang, H., 2007. Zircon U-Pb isotope ages and geological implication of mafic rocks of the Wudang and Yaolinghe Groups in southern Qinling. Chinese Science Bulletin 52, 1445-1456.
- Liou, J.G., Zhang, R., Liu, F., Zhang, Z., Ernst, W.G., 2012. Mineralogy, petrology, U-Pb geochronology, and geologic evolution of the Dabie-Sulu classic ultrahigh-pressure metamorphic terrane, East-Central China. American Mineralogist 97, 1533-1543.
- Liu, X., Gao, S., Diwu, C.-R., Yuan, H., Hu, Z., 2007. Simultaneous in-site determination of U-Pb age and trace elements in zircon by LA-ICP-MS in 20 μ m spot size. Chinese Science Bulletin 52, 1257-1264.
- Liu, Y., Hu, Z., Gao, S., Gunther, D., Xu, J., Gao, C., Chen, H., 2008. In situ analysis of major and trace elements of anhydrous minerals by LA-ICP-MS without applying an internal standard. Chemical Geology 257, 34-43.
- Liu, Y., Hu, Z., Zong, K., Gao, C., Gao, S., Xu, J., Chen, H., 2010. Reappraisal and refinement of zircon U-Pb isotope and trace element analyses by LA-ICP-MS. Chinese Science Bulletin 55, 1535-1546.
- Lu, S., Chen, Z., Xiang, Z., Li, H., Li, H., Song, B., 2006. U-Pb ages of detrital zircons from the para-metamorphic rocks of the Qinling Group and their geological significance. Earth Science Frontiers 13, 303-310.
- Ludwig, K., 2003. Isoplot/Ex, Version 3: A Geochronological Toolkit for MicrosoftExcel: Berkeley. Geochronology Center Berkeley, California.
- Meng, Q.-R., Zhang, G.-W., 1999. Timing of collision of the North and South China blocks: Controversy and reconciliation. Geology 27, 123.
- Meng, X., Wang, X., He, C., Li, J., Yang, Y., Lv, X., 2013. LA-ICP-MS zircon U-Pb age, geochemistry and Hf isotope of the granitoids from Huayang pluton in South Qinling orogen: Constraints on the genesis of Wulong plutons. Geological Bulletin of China 32, 1704-1719.
- Ping, X., Zheng, J., Zhao, J., Tang, H., Griffin, W.L., 2013. Heterogeneous sources of the Triassic granitoid plutons in the southern Qinling orogen: An E-W tectonic division in central China. Tectonics 32, 396-416.
- Qin, J.-F., Lai, S.-C., Diwu, C.-R., Ju, Y.-J., Li, Y.-F., 2009. Magma mixing origin for the post-collisional adakitic monzogranite of the Triassic Yangba pluton, Northwestern margin of the South China block: geochemistry, Sr-Nd isotopic, zircon U-Pb dating and Hf isotopic evidences. Contributions to Mineralogy and Petrology 159, 389-409.

- Qin, J.-F., Lai, S.-C., Li, Y.-F., 2013. Multi-stage granitic magmatism during exhumation of subducted continental lithosphere: Evidence from the Wulong pluton, South Qinling. *Gondwana Research* 24, 1108-1126.
- Qin, J., 2010. Petrogenesis and geodynamic implications of the Late-Triassic granitoids from the Qinling orogenic belt. Northwest University, Xian, China, pp. 1-266 (in Chinese with English abstract).
- Qin, J., Lai, S., Li, Y., 2008a. Slab Breakoff Model for the Triassic Post-Collisional Adakitic Granitoids in the Qinling Orogen, Central China: Zircon U-Pb Ages, Geochemistry, and Sr-Nd-Pb Isotopic Constraints. *International Geology Review* 50, 1080-1104.
- Qin, J., Lai, S., Wang, J., Li, Y., 2007. High-Mg[#] Adakitic Tonalite from the Xichahe Area, South Qinling Orogenic Belt (Central China): Petrogenesis and Geological Implications. *International Geology Review* 49, 1145-1158.
- Qin, J., Lai, S., Zhang, G., Diwu, C.-R., Li, Y., 2008b. Zircon LA-ICP-MS U-Pb dating of the Longkang ignimbrite in the Jiuzhaigou area, Sichun, China: Evidence of the weatern extension of the Mianlue suture. *Geological Bulletin of China* 27, 345-350 (in Chinese with English abstract).
- Ratschbacher, L., Hacker, B.R., Calvert, A., Webb, L.E., Grimmer, J.C., McWilliams, M.O., Ireland, T., Dong, S., Hu, J., 2003. Tectonics of the Qinling (Central China): tectonostratigraphy, geochronology, and deformation history. *Tectonophysics* 366, 1-53.
- Rey, P.F., Teyssier, C., Whitney, D.L., 2009. Extension rates, crustal melting, and core complex dynamics. *Geology* 37, 391-394.
- Rey, P.F., Teyssier, C., Whitney, D.L., 2010. The limit of channel flow in orogenic plateaux. *Lithosphere* 2, 328-332.
- Rubatto, D., 2002. Zircon trace element geochemistry: partitioning with garnet and the link between U-Pb ages and metamorphism. *Chemical Geology* 184, 123-138.
- Rubatto, D., Hermann, J., 2003. Zircon formation during fluid circulation in eclogites (Monviso, Western Alps): implications for Zr and Hf budget in subduction zones. *Geochimica et Cosmochimica Acta* 67, 2173-2187.
- Rubatto, D., Muntener, O., Barnhoorn, A., Gregory, C., 2008. Dissolution-reprecipitation of zircon at low-temperature, high-pressure conditions (Lanzo Massif, Italy). *American Mineralogist* 93, 1519-1529.
- Rubatto, D., Williams, I.S., Buick, I.S., 2001. Zircon and monazite response to prograde metamorphism in the Reynolds Range, central Australia. *Contributions to Mineralogy and Petrology* 140, 458-468.
- Sawyer, E.W., 1996. Melt segregation and magma flow in migmatites: implications for the generation of granite magmas. *Geological Society of America Special*

- Papers 315, 85-94.
- Sawyer, E.W., Cesare, B., Brown, M., 2011. When the continental crust melts. *Elements* 7, 229-234.
- Schaltegger, U., Fanning, C.M., Gunther, D., Maurin, J.C., Schulmann, K., Gebauer, D., 1999. Growth, annealing and recrystallization of zircon and preservation of monazite in high-grade metamorphism: conventional and in-situ U-Pb isotope, cathodoluminescence and microchemical evidence. *Contributions to Mineralogy and Petrology* 134, 186-201.
- Sun, S.-S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: Saunders, A.D., Norry, M.J. (eds.) *Magmatism in the ocean basins*. Special Publication Geological Society 42, 313-345.
- Teyssier, C., Whitney, D.L., 2002. Gneiss domes and orogeny. *Geology* 30, 1139-1142.
- Thompson, A.B., Schulmann, K., Jezek, J., 1997. Extrusion tectonics and elevation of lower crustal metamorphic rocks in convergent orogens. *Geology* 25, 491-494.
- Vanderhaeghe, O., 2009. Migmatites, granites and orogeny: Flow modes of partially-molten rocks and magmas associated with melt/solid segregation in orogenic belts. *Tectonophysics* 477, 119-134.
- Vanderhaeghe, O., Duchêne, S., 2010. Crustal-scale mass transfer, geotherm and topography at convergent plate boundaries. *Terra Nova* 22, 315-323.
- Vanderhaeghe, O., Medvedev, S., Fullsack, P., Beaumont, C., Jamieson, R.A., 2003. Evolution of orogenic wedges and continental plateaux: insights from crustal thermal-mechanical models overlying subducting mantle lithosphere. *Geophysical Journal International* 153, 27-51.
- Vavra, G., Gebauer, D., Schmid, R., Compston, W., 1996. Multiple zircon growth and recrystallization during polyphase Late Carboniferous to Triassic metamorphism in granulites of the Ivrea Zone (Southern Alps): an ion microprobe (SHRIMP) study. *Contributions to Mineralogy and Petrology* 122, 337-358.
- Wang, H., Wu, Y.-B., Gao, S., Liu, X.-C., Liu, Q., Qin, Z.-W., Xie, S.-W., Zhou, L., Yang, S.-H., 2013a. Continental origin of eclogites in the North Qinling terrane and its tectonic implications. *Precambrian Research* 230, 13-30.
- Wang, H., Wu, Y.-B., Gao, S., Zheng, J.-P., Liu, Q., Liu, X.-C., Qin, Z.-W., Yang, S.-H., Gong, H.-J., 2014. Deep subduction of continental crust in accretionary orogen: Evidence from U-Pb dating on diamond-bearing zircons from the Qinling orogen, central China. *Lithos* 190-191, 420-429.
- Wang, H., Wu, Y.B., Gao, S., Liu, X.C., Gong, H.J., Li, Q.L., Li, X.H., Yuan, H.L., 2011a. Eclogite origin and timings in the North Qinling terrane, and their bearing

- on the amalgamation of the South and North China Blocks. *Journal of Metamorphic Geology* 29, 1019-1031.
- Wang, H., Xu, X., Chen, J., Yan, Z., Li, T., Zhu, T., 2011b. Constraints from zircon U-Pb chronology of Yudongzi Group magnetite-quartzite in the Lueyang area, Southern Qinling, China. *Acta Geologica Sinica* 85, 1284-1290 (in Chinese with English abstract).
- Wang, J., 2002. Geological features of Foping basal complex, Qinling orogenic belt. *Northwestern Geology* 35, 1-8 (in Chinese with English abstract).
- Wang, X., Wang, T., Castro, A., Pedreira, R., Lu, X., Xiao, Q., 2011c. Triassic granitoids of the Qinling orogen, central China: Genetic relationship of enclaves and rapakivi-textured rocks. *Lithos* 126, 369-387.
- Wang, X., Wang, T., Jahn, B.-m., Hu, N., Chen, W., 2007. Tectonic significance of Late Triassic post-collisional lamprophyre dykes from the Qingling Mountain (China). *Geological Magazine* 144, 837-848.
- Wang, X., Wang, T., Zhang, C., 2013b. Neoproterozoic, Paleozoic, and Mesozoic granitoid magmatism in the Qinling Orogen, China: Constraints on orogenic process. *Journal of Asian Earth Sciences* 72, 129-151.
- Wei, C., Yang, C., Zhang, S., Li, R., 1998. Discovery of granulite from the Foping area in southern Qinling Mountains and its geological significance. *Chinese Science Bulletin* 43, 982-985.
- Wu, F.-Y., Li, X., Zheng, Y.-F., Gao, S., 2007. Lu-Hf isotopic systematics and their applications in petrology. *Acta Petrologica Sinica* 23, 185-220 (in Chinese with English abstract).
- Wu, F.-Y., Yang, Y.-H., Xie, L.-W., Yang, J.-H., Xu, P., 2006. Hf isotopic compositions of the standard zircons and baddeleyites used in U-Pb geochronology. *Chemical Geology* 234, 105-126.
- Wu, Y.-B., Zheng, Y.-F., 2013. Tectonic evolution of a composite collision orogen: An overview on the Qinling-Tongbai-Hong'an-Dabie-Sulu orogenic belt in central China. *Gondwana Research* 23, 1402-1428.
- Xia, Q.-X., Zheng, Y.-F., Yuan, H., Wu, F.-Y., 2009. Contrasting Lu-Hf and U-Th-Pb isotope systematics between metamorphic growth and recrystallization of zircon from eclogite-facies metagranites in the Dabie orogen, China. *Lithos* 112, 477-496.
- Xu, J., Yu, X., Li, X., Han, Y., Sheng, J., Zhang, B., 1997. The discovery of the high depleted N-MORB-type volcanic rocks: new evidence for Paleo ocean of Mian-Lue. *Chinese Science Bulletin* 42, 2414-2418.
- Xu, J., Yu, X., Li, X., Zhang, B., Han, Y., 2000. Geochemistry of the Anzishan ophiolitic complex in the Mian-Lue belt of Qinling Orogen: evidence and implication of the Palaeo-ocean crust. *Acta Geologica Sinica* 74, 39-50 (in Chinese).

- with English abstract).
- Xu, P., Wu, F.-Y., Xie, L., Yang, Y., 2004. Hf isotopic compositions of the standard zircons for U-Pb dating. *Chinese Science Bulletin* 49, 1642-1648.
- Yang, C., Wei, C., Zhang, S., Li, H., Wan, Y., Li, R., 1999. U-Pb dating of granulite facies rocks from the Foping area in the southern Qinling mountains. *Geological Review* 45, 173-179 (in Chinese with English abstract).
- Yang, H., Liu, F., Du, L., Liu, P., Wang, F., 2012a. Zircon U-Pb dating for metavolcanites in the Laochanghe Formation of the Dahongshan Group in southwestern Yangtze Block, and its geological significance. *Acta Petrologica Sinica* 28, 2994-3014 (in Chinese with English abstract).
- Yang, L., Chen, F., Yang, Y., Li, S., Zhu, X., 2010. Zircon U-Pb ages of the Qillling Group in Danfeng area : Recording Mesoproterozoic and Neoproterozoic magmatism and Early Paleozoic metamorphism in the North Qinling terrain. *Acta Petrologica Sinica* 26, 1589-1603 (in Chinese with English abstract).
- Yang, P., Liu, S., Li, Q., Wang, Z., Wang, R., Wang, W., 2012b. Geochemistry and zircon U-Pb-Hf isotopic systematics of the Ningshan granitoid batholith, middle segment of the south Qinling belt, Central China: Constraints on petrogenesis and geodynamic processes. *Journal of Asian Earth Sciences* 61, 166-186.
- Yang, P., Liu, S., Li, Q., Zhang, F., Wang, Z., Wang, D., Wang, R., Yan, Q., Yan, Z., 2011. Ages of the Laocheng granitoids and crustal growth in the South Qinling tectonic domain, Central China: zircon U-Pb and Lu-Hf isotopic constraints. *Acta Geologica Sinica (English Edition)* 85, 854-869.
- Yin, F., Sun, Z., Ren, G., Wang, D., 2012. Geological record of Paleo- and Mesoproterozoic orogenesis in the weatern and margin of upper Yangtze Block. *Acta Geologica Sinica* 86, 1917-1932 (in Chinese with English abstract).
- Yin, F., Sun, Z., Zhang, Z., 2011. Mesoproterozoic stratigraphic-structure framework in Huili-Dongchuan area. *Geological Review* 57, 770-778.
- Zhang, B., Gao, S., Zhang, H., Han, Y., 2002a. *Geochemistry of Qinling Orogen*. Science Press, Beijing (in Chinese with English abstract).
- Zhang, G., Cheng, S., Guo, A., Dong, Y., Lai, S.-C., Yao, A., 2004a. Mianlue paleo-suture on the southern margin of the Central Orogenic System in Qingling-Dabie : with a discussion of the assembly of the main part of the continent of China. *Geological Bulletin of China* 23, 846-853 (in Chinese with English abstract).
- Zhang, G., Dong, Y., Lai, S.-C., Guo, A., Meng, Q., Liu, S., Cheng, S., Yao, A., Zhang, Z., Pei, X., Li, S., 2003. Mianlue tectonic zone and Mianlue suture zone on southern margin of Qinling-Dabie orogenic belt. *Science in China (Series D)* 33, 1121-1135.

- Zhang, G., Yu, Z., Dong, Y., Yao, A., 2000. On Precambrian framework and evolution of the Qinling belt. *Acta Petrologica Sinica* 16, 11-21 (in Chinese with English abstract).
- Zhang, G., Zhang, B., Yuan, X., Qiao, Q., 2001. Qinling orogenic belt and continental dynamics. Science Press, Beijing, China.
- Zhang, H., Han, Z.-Z., Xu, H., Siebel, W., Chen, F., 2014. Zircon U-Pb ages and geochemical composition of gneisses from the Mesozoic foreland basin in the Yellow Sea, China. *International Geology Review* 56, 1984-1999.
- Zhang, R.Y., Liou, J.G., Ernst, W.G., 2009. The Dabie–Sulu continental collision zone: A comprehensive review. *Gondwana Research* 16, 1-26.
- Zhang, Z., Song, B., Tang, S., Zhang, S., Yang, Y., Wang, J., 2004b. Age and material composition of the Foping metamorphic crystalline complex in the Qinling Mountains: SHRIMP zircon U-Pb and whole rock Sm-Nd geochronology. *Geology in China* 31, 161-168 (in Chinese with English abstract).
- Zhang, Z., Zhang, G., Tang, S., 2002b. Metamorphic strata geochronology of South Qinling. Geoscience Press, Beijing, China (in Chinese with English abstract).
- Zhang, Z., Zhang, G., Tang, S., Xu, J., Yang, Y., Wang, J., 2002c. Age of Anzishan granulites in the Mianxian-Lueyang suture zone of Qinling orogen: with a discussion of the timing of final assembly of Yangtze and North China craton blocks. *Chinese Science Bulletin* 47, 1925-1930.
- Zhao, G., Sun, M., Wilde, S.A., Li, S., 2004. A Paleo-Mesoproterozoic supercontinent: assembly, growth and breakup. *Earth-Science Reviews* 67, 91-123.
- Zheng, Y.-F., 2008. A perspective view on ultrahigh-pressure metamorphism and continental collision in the Dabie-Sulu orogenic belt. *Chinese Science Bulletin* 53, 3081-3104.
- Zhu, L.-m., Zhang, G.-w., Chen, Y.-j., Ding, Z.-j., Guo, B., Wang, F., Lee, B., 2011. Zircon U-Pb ages and geochemistry of the Wenquan Mo-bearing granitoids in West Qinling, China: Constraints on the geodynamic setting for the newly discovered Wenquan Mo deposit. *Ore Geology Reviews* 39, 46-62.
- Zhu, X., 2010. Evolution and provenance of the basement in the Eastern Qinling orogen, China: evidence from geochemistry and zircon U-Pb geochronology. Graduate School, Chinese Academy of Science, Beijing, China, pp. 1-138 (in Chinese with English abstract).
- Zhu, X., Chen, F., Liu, B., Zhang, H., Zhai, M., 2014a. Geochemistry and zircon ages of mafic dikes in the South Qinling, central China: evidence for late Neoproterozoic continental rifting in the northern Yangtze block. *International Journal of Earth Sciences* 104, 27-44.
- Zhu, X., Chen, F., Nie, H., Siebel, W., Yang, Y., Xue, Y., Zhai, M., 2014b.

Neoproterozoic tectonic evolution of South Qinling, China: Evidence from zircon ages and geochemistry of the Yaolinghe volcanic rocks. *Precambrian Research* 245, 115-130.

Zhu, X., Chen, F., Wang, W., PHAM, T.H., Wang, F., Zhang, F., 2008. Zircon U-Pb ages of volcanic and sedimentary rocks of the Wudang Group in the Qinling orogenic belt within western Henan province. *Acta Geoscientica Sinica* 29, 817-829 (in Chinese with English abstract).

Zhu, X., Chen, F., Yang, L., HIEU, P.T., Miao, L., Zhang, F., 2009. Zircon Hf isotope composition and source characteristics of the Wudang Group in the Qinling orogenic belt, western Henan province. *Acta Petrologica Sinica* 25, 3017-3028 (in Chinese with English abstract).

Figure captions

Figure 1 (a) Sketch of the Qinling orogen; (b) tectonic division of the Qinling orogen and distribution of the Triassic granitoids (modified after Zhang et al., 2001); (c) simplified geological map of the Foping dome (modified after Wang, 2002), showing sample localities, symbol of yellow star for migmatite and black ones for diorite

Figure 2 Field occurrences of migmatites and diorite gneisses. (A, B) migmatite outcrops nearby Longcaoping and Wenquan villages, (C, D) diorite gneisses within the Wulong pluton. Red arrows show orientation of minerals

Figure 3 Representative thin section microphotographs of migmatites and diorite gneisses under polarizing light. (A) Migmatite sample 13-FP-30 with Q+Pl+Hb+Bi; (B) Migmatite sample 13-FP-33B with Q+Pl+Bi; (C) Diorite gneiss sample 13-FP-13 with Q+Pl+Hb+Bi; (D) Diorite gneiss sample 13-NS-62 with Q+Pl+Hb+Bi. Q- quartz, Pl- plagioclase, Hb- hornblende, Bi- biotite

Figure 4 Cathodoluminescence images of representative zircon grains of migmatite samples 13-FP-30 (a-c), 13-FP-31 (d-e), 13-FP-32 (f-h), 13-FP-33A (i-l), and 13-FP-33B (m-p). Small circle: spot for the U-Pb dating; larger circle: spot for Hf isotopic analysis

Figure 5 Zircon U-Pb concordia diagrams (a-e) and chondrite-normalized REE patterns (a'-e') of zircon grains from migmatite samples. Chondrite normalized values are from Sun and McDonough (1989)

Figure 6 Cathodoluminescence images of representative zircon grains from diorite gneiss samples 13-FP-13 (a-b), 13-FP-34 (c-d), 13-NS-59 (e-f), and 13-NS-62 (g-h). Small circles: spot for the U-Pb dating; large circles: spot for Hf isotopic analysis

Figure 7 Zircon U-Pb concordia diagrams (a-d) and chondrite-normalized REE patterns (a'-d') of zircon grains from gneissic diorite samples. Chondrite

normalized values are from Sun and McDonough (1989)

Figure 8 Histograms of two-stage Hf model ages of zircon grains from migmatites and diorite gneisses in the Foping dome, (a) sample 13-FP-30, (b) sample 13-FP-32, (c) sample 13-FP-33a, (d) sample 13-FP-34

Figure 9 Diagram of initial ϵ_{Hf} value versus U-Pb zircon age from migmatites and diorite gneisses of the Foping dome. Literature data: basement rocks of the Yangtze block, Wudang Group, and Neoproterozoic mafic rocks (Zhu et al., 2009; Hu et al., 2016); Triassic granitoids of South Qinling (Gong et al., 2009; Qin, 2010; Wang et al., 2011c; Yang et al., 2011; Zhu et al., 2011; Meng et al., 2013; Ping et al., 2013)

Figure 10 Diagram of initial ϵ_{Nd} value of whole-rock versus zircon U-Pb age for gneissic diorite samples in the Foping dome. Literature data of the Wulong granitoids and rapakivi granite from Qin (2010) and Wang et al. (2011c) and of the Kongling amphibolite from Gao et al. (1999)

Figure 11 Plots of trace element and Hf isotopic composition of zircons for migmatite samples (13-FP-30, 13-FP-31, and 13-FP-32) from the Foping dome. (A) $(\text{Sm}/\text{La})_{\text{N}}$ versus La content, fields for hydrothermal and magmatic zircons (grey color) are taken from Hoskin (2005); (B) Th/U ratio versus $^{206}\text{Pb}/^{238}\text{U}$ age of core and rim domains; (C) REE contents of core and rim domains; (D) $^{176}\text{Hf}/^{177}\text{Hf}$ ratios. Red and blue symbols in (B)-(D) represent core and rim domains, respectively

Figure 12 Sketch illustrations for genesis of migmatite in the Foping dome and Late Triassic tectonic setting in South Qinling. (A) Crustal thickening due to the amalgamation of the Yangtze and North Qinling blocks prior to ~215 Ma; (B) Orogenic collapse coupling with asthenospheric upwelling, partial melting and doming of the deep crustal section after ~215-210 Ma. Tectonic model after Rey et al. (2010)

(A) Prior to ~215 Ma, crustal thickening

(B) ~215 - 210 Ma, crustal extension and doming

Table 1 Whole-rock Nd isotopic composition of diorite gneisses in the Foping dome

Sample	Nd (ppm)	Sm (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	Error (2σ)	$\epsilon_{\text{Nd}}(\text{t})$	T_{DM2} (Ga)
13-FP-13	30.16	5.96	0.1194	0.512259	0.000009	-5.3	1.42
13-FP-34	19.92	3.71	0.1118	0.512280	0.000018	-4.6	1.38
13-NS-59	27.00	4.99	0.1118	0.512292	0.000009	-4.4	1.36
13-NS-62	37.98	7.01	0.1116	0.512299	0.000012	-4.3	1.35