Petrogenesis, zircon U–Pb age, and geochemistry of the A-type Mogou syenite, western Henan Province: Implications for Mesozoic tectono-magmatic evolution of the Qinling Orogen

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The Mogou syenite intruded into the Mesoproterozoic Xiong'er Group is the main lithostratigraphic unit, along the southern margin of the North China Craton (NCC). This paper reports zircon LA-ICP-MS data, whole-rock major and trace element compositions of late Triassic magmatic rocks in the Mogou syenite, in order to constrain the formation age of the Mogou syenite, research the origin and evolution of the magma and analyse the geodynamic setting of the Qinling Orogen (QO) in Late Triassic. These rocks consist of medium- to coarse-grained syenite and fine-grained quartz syenite. Zircon U–Pb dating yields a crystallization age of 226.5 ± 2.7 Ma. The syenites are characterized by high SiO₂ (63.49–72.17%), alkali (K₂O+Na₂O of 11.18–15.38%) and potassium (K₂O/Na₂O of 2.88–28.11), are peralkaline or metaluminous (molar A/CNK of 0.87–1.02) and belong to shoshonite series. The syenites have ΣREE of 33.01–191.30 ppm, LREE/HREE of 14–20, (La/Yb)_N of 11–24, with LREE-rich distribution pattern and obvious differentiation between HREE and LREE. Eu anomalies are positive for the medium- to coarse-grained syenite and weakly negative for the fine-grained quartz syenite. In addition, the syenites are enriched in large-ion lithophile elements (Ba, K, Sr, and Pb) but depleted in high strength field elements (Ti, Ta, Nb, Zr, and Hf), and have high differentiation indices of 91.69–97.06. These geochemical features indicate that the primary magma of the Mogou syenite most likely originated from a mantle source with minor crustal component, and underwent a fractional crystallization process during its emplacement. The late Triassic A-type Mogou syenite along the southern margin of the NCC was generated in the late stage of the syn-collision event of QO, recording a transition period from compression to extension at around 227 Ma.

1. Introduction

The Qinling Orogen (QO), which is sandwiched between the North China Craton (NCC) and the

Yangtze Craton (YC), can be divided into four segments (figure 1a): (1) southern margin of the NCC, (2) North Qinling Orogen (NQO), (3) South Qinling Orogen (SQO) and (4) northern margin of

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the YC, with Luanchuan Fault, Shangdan Suture and Mianlue Suture as boundaries, respectively (Zhang *et al.* 2001a). It is widely accepted that the Shangdan Suture represented the closure of Shangdan Ocean (figure 11b) and the following collision between SQO and NQO in early Devonian (figure 11c), while the Mianlue Suture represented the site of the consumption of Mianlue Ocean (figure 11e) and hence the collision of SQO and the northern margin of the YC during Triassic (figure 11f) (Zhang *et al.* 2004; Chen 2010; Dong *et al.* 2011). The QO is a composite continental orogenic belt, as it has experienced complex orogenic movements that led to extremely active magmatism (figure 11) (Zhang *et al.* 1996a). During late Triassic, abundant collision-type and island-arc granites occurred in the West Qinling Orogen (WQO), while numerous alkalic rocks, alkali granites and carbonatites occurred far from the subduction zone in the East Qinling Orogen (EQO) (Lu *et al.* 1999a). The Zhifang–Huangzhuang area of the EQO is a dominant place of the late Triassic alkalic rocks (figure 1).

Major pulses of granitoid magmatism that have been recognized in the EQO, started from late Permian to Triassic (260–200 Ma) (Lu 2006) and became stronger during Jurassic and early Cretaceous (200–135 Ma) (Huang *et al.* 1977; Wang *et al.* 2015). Because of the enormous influence of Jurassic and early Cretaceous igneous activities, to which the late Permian to Triassic movements were apparently related (Ren *et al.* 1999; Lu 2006; Deng *et al.* 2011; Lu *et al.* 2013; Deng *et al.* 2014a; Wang *et al.* 2014a, b), previous studies (Li 2005; Pang 2006; Mao *et al.* 2010; Wang *et al.* 2011) have focussed principally on Jurassic and early Cretaceous magmatism; however, this is not conducive to get a full understanding of the evolution of the QO. Additionally, the final collision and assemblage of the NCC and the YC took place during Triassic (Zhang *et al.* 2001a; Dong *et al.* 2011; Wan 2011) and there existed a series of Triassic alkalic rocks in the south margin of NCC (Zhang *et al.* 1996b; Lu *et al.* 2008; Liu *et al.* 2010) (figure 1a). Therefore, it is hypothesized here that research on the Triassic Mogou syenite will contribute to the understanding of the tectonic setting of the southern margin of the NCC and the QO.

The characteristics and origin of the Mogou syenite have been studied and debated by previous researches (BGMRHP 1990; Zeng 1990; Qiu *et al.* 1993; Ren *et al.* 1999; Liu *et al.* 2010; Liang *et al.* 2012; Lu *et al.* 2013). This pluton consists of aegirine-augite syenite, biotite syenite and quartz syenite (BGMRHP 1990; Zeng 1990; Liang *et al.* 2012), and is dominantly composed of orthoclase, microcline with biotite, amphibole, aegirine-augite and aegirine, accessory minerals (zircon, titanite,

apatite and rutile), and opaque minerals such as magnetite and quartz in quartz syenite (Zeng 1990; Ren *et al.* 1999; Lu *et al.* 2013). From the margins to the cores of the syenite suites, grain size varies from fine to medium-coarse, with mafic minerals slightly decreased, while felsic minerals increased (BGMRHP 1990; Zeng 1990). Isotope data for Sr–Nd–Pb, O and Lu–Hf proved a crust–mantle mix origin for the Mogou syenite (Zeng 1990; Qiu *et al.* 1993; Ren *et al.* 1999; Lu *et al.* 2013), with proportions of 21% crust and 79% mantle (Zeng 1990). As primary magma, enriched basaltic magma experienced fractional crystallization of olivine, plagioclase, and clinopyroxene and then assimilated with felsic magma, characterized by low-LREE content and negative Eu anomalies (Zeng 1990). After emplacement, the syenitic magma locally experienced mineral fractionation (Zeng 1990), and the evolution to quartz enrichment was controlled by fractional crystallization of alkali feldspar, plagioclase, and clinopyroxene (Qiu *et al.* 1993). Formed in collision background between the SQO and the YC within the overall QO, three probable tectonic models have been proposed for emplacement of the Mogou syenite: (1) transition period from compression to extension (Liu *et al.* 2010; Liang *et al.* 2012); (2) convergence at the leading margin, while extension in the adjacent trailing part (Ren *et al.* 1999); and (3) partial extension of the thickened crust (Lu *et al.* 2013). However, as the ages of the Mogou syenite and the associated tectonic activities are not known, the evolution of the different phases of the Mogou syenite remains unconstrained. In addition, due to non-availability of geochemical data from the Mogou pluton, the petrogenesis of the Mogou syenites is not known.

In this paper, we report precise LA-ICP-MS zircon U–Pb ages of fine-grained quartz syenite, and whole rock major and trace element compositions of rocks from the Mogou syenite. These data are used to decipher the petrogenesis of the Mogou syenite and the tectonic evolution of the Qinling Orogen.

2. Geological setting

The research area is situated at the southern margin of the NCC, near the boundary between the Cenozoic Sonxian Fault Depression and the Xiong'ershan, and geographically located in the south part of Songxian County, Henan Province (figure 1).

The major lithostratigraphic units in this region are the Archean Taihua Group, the Jidanping Formation of the Mesoproterozoic Xiong'er Group, the Neogene Luoyang Formation and Quaternary strata. The Taihua Group is composed of amphibolite facies basement rocks, the protoliths of which

were trondhjemite, tonalite and granodiorite (TTG). The Jidanping Formation predominantly comprises andesite and rhyolite. The Luoyang Formation is mainly glutenite and claystone. The Quaternary strata consist of loess and gravel layers.

Dominant structures in the region are mainly NW, NE and nearly E–W trending faults (figure 1b). Most prominent one is the approximately E–W striking Machaoying Fault, 20 km south of the

Mogou syenite. In addition, the roughly E–W trending Dazhaung–Zhonghu Anticline is situated in the southern part of the study area, where alkaline rocks in the Zhifang–Huangzhuang area are distributed in the axial parts and the north limb of Dazhaung–Zhonghu Anticline.

Apart from individual small intermediate or acidic stocks or dykes (Wang *et al.* 2016b), igneous rocks in the region are virtually Mesozoic syenites,

Figure 1. Geological maps showing (a) distribution of granitoids along the southern margin of the North China Craton (modified from Lu 2000) and location of the study area; (b) distribution of syenites in Zhifang–Huangzhuang area, Songxian County, Henan Province (after Liang *et al.* 2012; BGMRHP 1990). (1) Quaternary System; (2) Neogene System; (3) Paleogene System; (4) Mesoproterozoic Xiong'er Group; (5) Archean Taihua Group; (6) Yanshanian granite; (7) Triassic syenite; (8) Mesoproterozoic quartz porphyry; (9) Mesoproterozoic diorite; (10) fault; (11) anticline; (12) sampling location; and (13) river and reservoir.

which intruded the Xiong'er Group (Zeng 1990). These syenites include the Mogou, Wusanggou, Longtou, Jiaogou and Lang'aogou (figure 1b). The Mogou syenite is exposed as an approximately elliptic stock trending NW, with an exposure area of about 15 km² (Lu *et al.* 2013).

3. Sample description and analytical methods

Three representative samples of fine-grained quartz syenite (samples MG1307-12, MG1307-21, and MG1307-22) and three samples of medium- to coarse-grained syenite (samples MG1307-11, MG1307-3, and MG1307-4) were collected from different sections of the Mogou syenite for geochemical analysis (figure 1b), and one of the fine-grained quartz syenite (sample MG1307-12) was selected for zircon U–Pb dating. The samples have euhedral–subhedral granular texture and massive structure (figure 2a, b), but differ in mineral assemblages. The fine-grained samples are fresh pink-light gray, comprising quartz (5–10%), K-feldspar (80–85%), amphibole (~8%) and accessory minerals (<2%) such as titanite, zircon and apatite. The medium- to coarse-grained samples are fresh pink and consist of K-feldspar (75–96%), amphibole (0–18%), biotite (2–3%) and auxiliary minerals (<2%) including

titanite, apatite and allanite. The orthoclase and microcline are primary species of K-feldspar, and while the former displays Carlsbad twinning (figure 2c), the latter is characterized by cross-hatched twinning (figure 2d).

Analysis of major and trace element concentrations of the Mogou syenite was undertaken at the Analytical Laboratory, Beijing Research Institute of Uranium Geology, China National Nuclear Corporation, using XRF on a PW2404 X-Ray fluorescence spectrometer, ICP-MS on an ELEMENT XR, respectively. Analytical precision and accuracy for major elements are generally better than 5%, but for trace element they vary between 5% ($\pm 5 \mu\text{g/g}$) and 10% ($\pm 10 \mu\text{g/g}$).

Zircon crystals were obtained by standard methods involving grinding, crushing, heavy liquid, and magnetic separation methods. The zircon grains were then separated under a binocular microscope according to size and shape, mounted together in epoxy disks, polished to obtain an even surface, cleaned, and gold-coated. The internal texture of zircons was observed by cathodoluminescence (CL) images prior to U–Pb analysis. Zircons were dated *in situ* by LA-ICP-MS at the Tianjin Institute of Geology and Mineral Resources, Ministry of Land and Resources, China Geological Survey. The laser-ablation system is a UP193-FX ArF from ESI and the ICP-MS used was a Neptune from Thermo

Figure 2. Field photographs and microphotographs of the Mogou syenite in the Zhifang–Huangzhuang area, Songxian County: (a) sample MG1307-4, medium- to coarse-grained texture; (b) sample MG1307-21, fine-grained texture; (c) sample MG1307-4 (cross-polarized light), orthoclase is characterized by Carlsbad twin; and (d) sample MG1307-21 (cross-polarized light), microcline is characterized by cross-hatched twin. Qz = quartz; Or = orthoclase; Mc = microcline; Am = amphibole.

Fisher. The laser beam spot during analysis was 35 μm in diameter. Zircon standard TEMORA was used as the external calibrant (Black *et al.* 2003; Jackson *et al.* 2004), whereas the standard silicate glass NIST612 was used to optimize the machine. The U–Pb data for dating were analysed using ICPMSDataCal (Liu *et al.* 2009b). Calculations of weighed mean ages and concordia plots were obtained by ISOPLOT (Ludwig 2003). Common Pb correction was carried out using the method of Anderson (2002). The detailed analytical procedures are described in Li *et al.* (2009).

4. Analytical results

4.1 Whole-rock major and trace element data

The major and trace element analyses for the syenite samples are listed in table 1. The syenites are intermediate-acidic (SiO_2 , 63.49–72.17%), rich in alkali ($\text{K}_2\text{O}+\text{Na}_2\text{O}$, 11.18–15.38%), potassium ($\text{K}_2\text{O}/\text{Na}_2\text{O}$, 3–28%) and iron ($\text{FeO}^{\text{T}}/\text{Mg}$, 11–78%). These rocks are generally peralkaline or metaluminous (A/CNK molar ranging from 0.87 to 1.02). The differentiation indices ($\text{DI}=\text{Qz}+\text{Or}+\text{Ab}+\text{Ne}+\text{Lc}+\text{Kp}$, the composition of six minerals is calculated by the CIPW norm) of 92–97 suggest that the Mogou syenite has experienced high-level crystal differentiation. In the SiO_2 vs. Nb/Y diagram (figure 3a), most of the samples fall in the trachyte field. In addition, the Ce/Yb vs. Ta/Yb diagram indicates their affinities with shoshonitic series (figure 3b). Both diagrams illustrate the high alkali character of the Mogou syenite. Moreover, the loss on ignition (LOI) is low ($\text{LOI}<1$) (table 1), which indicates no strong alteration of the Mogou syenite.

Samples of the Mogou syenite show high REE concentrations (ΣREE , 110.42–264.96 ppm; average, 190.63 ppm) except MG1307-3 (ΣREE , 33.01 ppm). The LREE/HREE ratio ranges from 14 to 20, with $(\text{La}/\text{Yb})_{\text{N}}$ (Boynton 1984) ratios ranging from 11 to 24, indicating fractionation between HREE and LREE and that LREE is relatively enriched. In addition, the data indicate relatively high LREE patterns with $(\text{La}/\text{Sm})_{\text{N}}$ of 5 to 12 and flat HREE patterns with $(\text{Gd}/\text{Yb})_{\text{N}}$ of 1 to 2. Moreover, the chondrite-normalized (Boynton 1984) REE distribution curve shows a rightward feature with positive or slightly negative Eu anomalies ($\text{Eu}/\text{Eu}^*=0.75\text{--}5.12$) and Ce anomalies ($\text{Ce}/\text{Ce}^*=0.87\text{--}1.54$) (figure 4a). In terms of trace elements, although there are some differences in the peaks and troughs in the spider diagram (figure 4b), most of samples show spikes in LILE (e.g., Ba, K, Sr, and Pb) and troughs in HFSE (Ti, Ta, Nb, Zr, and Hf).

4.2 Zircon U–Pb age

Most zircons from the Mogou syenite are colourless or buff, subhedral, stubby grains and the grain sizes vary in the range 20–200 μm . According to the CL images (figure 5c), most zircons show pronounced oscillatory zonings, and Th/U ratios range from 0.10 to 0.53 (except 0.07 and 0.08 of spots 7 and 8, respectively), which indicate magmatic zircon (Hoskin and Schaltegger 2003; Wu and Zheng 2004). Twenty-five determinations were performed on 25 different zircon crystals from the Mogou syenite and the analytical results of U–Pb dating are listed in table 2. Among them, $^{206}\text{Pb}/^{238}\text{U}$ ages from 16 spots are relatively younger or older or plot far from the $^{206}\text{Pb}/^{238}\text{U}\text{--}^{207}\text{Pb}/^{235}\text{U}$ concordant curve. Thus, those data are excluded from the weighed average age calculations (figure 5a). The remaining nine determinations show a coherent age group with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 226.5 ± 2.7 Ma (2σ , $\text{MSWD}=0.85$, confidence measure 95%) (figure 5b), which represents a reliable emplacement age of the Mogou syenite.

5. Discussion and conclusions

5.1 Constraints on the formation age of the Mogou syenite

The Triassic was a period of convergences and collisions among dispersed blocks in eastern Paleo-Tethys Ocean (Wan 2011; Deng *et al.* 2014b, c; Wang *et al.* 2016a). As a northern branch of the eastern Paleo-Tethys Ocean, the Mianlue ocean was closed after Middle Triassic (Zhang *et al.* 2001a), followed by the amalgamation of the SQO and the northern margin of the YC (Zhang *et al.* 2004; Deng *et al.* 2009). Qin *et al.* (2008a) reported a U–Pb age of 246 ± 3 Ma from andesitic ignimbrites representing the time of subduction in the WQO. Li *et al.* (1996) reported a Sm–Nd age of 242 ± 21 Ma from metavolcanic rocks, possibly representing residual ocean crust, which indicates the closure of Mianlue Ocean in the EQO and the beginning of continental collision. From these data, Wang *et al.* (2013b) constrained the timing of collision between the NCC and YC at ~ 245 Ma. In addition, some syn-collision ages for granitoids were reported, such as 247 Ma for the Dongjiangkou pluton (Liu *et al.* 2014), 232 Ma for Zhongchuan pluton (Zhu *et al.* 2013) and 229 Ma for Guanshan pluton (Zhang *et al.* 2006). Wang *et al.* (2013a, b) constrained the time of collision at 240–225 Ma, which is coeval with the metamorphic age of 245–219 Ma of the Dabie ultra-high pressure metamorphic belt (UHP), being contiguous with QO (Hacker *et al.* 1998; Zhang *et al.* 2001b; Zheng 2008). However, although a post-collision setting is conducive to voluminous

Table 1. Major (wt%) and trace elements (ppm) data of the Mogou syenite in the western Henan Province.

Samples	MG1307-12	MG1307-11	MG1307-21	MG1307-22	MG1307-3	MG1307-4	Samples	MG1307-12	MG1307-11	MG1307-21	MG1307-22	MG1307-3	MG1307-4
SiO ₂	72.17	64.99	65.99	65.75	63.86	63.49	Cs	3.11	4.93	2.25	2.42	4.35	7.8
TiO ₂	0.19	0.61	0.34	0.32	0.24	0.37	Ba	763	4329	1940	2082	5400	5476
Al ₂ O ₃	12.8	13.83	15.64	16.02	18.02	17.32	Hf	3.69	6.08	4.16	2.64	0.95	3.13
Fe ₂ O ₃ ^T	2.32	5.89	2.6	2.47	1.03	2.46	Ta	0.76	0.96	0.88	0.76	0.29	0.77
Fe ₂ O ₃	0.18	5.66	0.84	1.96	0.06	2.1	W	0.82	1.34	0.24	0.2	2.2	7.68
FeO	1.93	0.21	1.58	0.46	0.87	0.32	Re	<0.002	0.003	0.003	0.006	<0.002	0.004
MnO	0.02	0.18	0.04	0.04	0	0.01	Tl	1.88	1.4	1.73	1.83	1.82	1.76
MgO	0.07	0.08	0.22	0.2	0.1	0.07	Pb	74.1	311	27.6	22.8	13.8	27.5
CaO	0.18	0.37	0.83	0.77	0.12	0.2	Bi	2.73	2.45	0.64	0.35	0.43	0.05
Na ₂ O	1.31	0.42	3.46	3.49	1.31	1.15	Th	29.5	1.42	6.98	3.72	2.27	8.18
K ₂ O	9.87	11.89	9.98	10.15	14.07	13.56	U	2.85	6.19	1	0.63	0.43	1.03
P ₂ O ₅	0.02	0.25	0.06	0.04	0.02	0.11	Y	8.6	17.8	14.5	12.1	2.88	8.39
LOI	0.55	0.96	0.33	0.26	0.7	0.74	La	50	39.1	35.3	29.4	6.01	28.6
Total	99.27	99.44	99.32	99.45	99.37	99.45	Ce	68.2	99.6	73.6	63.2	17.6	48.6
A/CNK	0.97	0.97	0.87	0.88	1.02	1.02	Pr	7.18	7.68	8.56	7.55	1.26	5.6
DI	94.24	91.36	89.96	92.06	96.48	95.5	Nd	21.2	26.2	30.2	26.2	4.38	20.1
Li	1.27	2.84	2.34	2.32	0.726	2.41	Sm	2.67	4.3	4.51	3.89	0.734	3.13
Be	9.93	6.62	1.81	1.83	1.48	1.55	Eu	0.58	1.79	1.2	1.08	1.15	1.62
Sc	1.81	13.2	4.82	4.18	1.16	4.22	Gd	2.1	3.44	3.48	3.13	0.64	2.43
V	47.6	255	59.6	57.7	16.7	54.7	Tb	0.31	0.53	0.56	0.47	0.09	0.33
Cr	1.23	20.7	2.18	1.79	3.77	11.1	Dy	1.62	3.09	2.92	2.52	0.47	1.58
Co	0.85	12.2	2.33	1.72	0.72	3.54	Ho	0.32	0.59	0.53	0.45	0.08	0.27
Ni	1.8	14.8	1.26	1.23	1.45	4.29	Er	1.03	1.86	1.47	1.18	0.22	0.72
Cu	2.98	12.4	12.7	9.47	11.7	13.2	Tm	0.19	0.33	0.23	0.18	0.04	0.12
Zn	43.5	94.1	30.4	31.6	27.4	53.3	Yb	1.54	2.41	1.6	1.24	0.28	0.81
Ga	24.2	21	20.6	20.3	14	16.5	Lu	0.28	0.39	0.26	0.2	0.04	0.13
Rb	275	275	241	253	348	334	ΣREE	157.21	191.3	164.42	140.7	33.01	114.04
Sr	64	705	507	528	838	983	LREE	149.83	178.67	153.37	131.32	31.13	107.65
Zr	104	190	126	74	28.1	103	HREE	7.39	12.63	11.05	9.38	1.87	6.39
Nb	27.8	39.9	21.6	19	6.26	15.3	LREE/	20.28	14.15	13.88	14.01	16.62	16.85
Mo	0.31	0.83	0.65	0.63	0.5	1.26	HREE						
Cd	0.11	0.23	0.07	0.07	0.05	0.07	La _N /Yb _N	21.89	10.94	14.87	15.98	14.27	23.89
In	0.02	0.06	0.06	0.06	0.01	0.03	δEu	0.75	1.42	0.93	0.95	5.12	1.8
Sb	0.34	2.26	0.07	0.07	1.01	4.1	δCe	0.87	1.38	1.02	1.02	1.54	0.92

Figure 3. (a) SiO₂ vs. Nb/Y diagram (after Winchester and Floyd 1977) and (b) Ce/Yb vs. Ta/Yb diagram (after Pearce 1982) for samples from the Mogou syenite in the Zhifang–Huangzhuang area, Songxian County.

Figure 4. Chondrite-normalized rare-earth element patterns and primitive mantle-normalized trace element patterns for samples from the Mogou syenite in Zhifang–Huangzhuang area, Songxian County. The values for primitive mantle are from Sun and McDonough (1989). The values for chondrite are from Boynton (1984).

magmatism, a syn-collision tectonic environment associated with UHP is likely less favourable for the generation or emplacement of granitoids (Wang *et al.* 2013b). A few syn-collision granitoid magmatic rocks with ages of 245–225 Ma have been reported in the QO. Gong *et al.* (2009) reported U–Pb ages of 224.8 Ma for the Zhashui pluton and 224.1 Ma for the Caoping pluton; these ages represent the initial time of post-collision. Since 225 Ma, several post-collision granitoids have intruded until 196 Ma (Chen *et al.* 2009; Deng *et al.* 2015b).

Previous researches have reported various ages for the Mogou syenite, for instance, BGMRHP (1990) constrained it to Carboniferous with a Rb–Sr isochron age of 318±29 Ma, whereas most

results constrain it to Triassic, such as K–Ar age of 212 Ma, Rb–Sr age of 226 Ma for syenite and 202 Ma for syenite vein (Zeng 1990), TIMS zircon U–Pb age of 209 Ma (Ren *et al.* 2001), and LA-ICP-MS zircon U–Pb age of 246 Ma for coarse-grained syenite (Lu *et al.* 2013). Other syenites in the Zhifang–Huangzhuang area in Songxian County were also constrained to Triassic. Zeng (1990) reported a Rb–Sr age of 226 Ma for syenites in the Zhifang–Huangzhuang area and a K–Ar age of 242 Ma for the Longtou coarse-grained syenite. Besides, a SHRIMP U–Pb age of 245 Ma was reported for the Wusanggou coarse-grained syenite (Liu *et al.* 2010). From the aforementioned studies (Zeng 1990; Liu *et al.* 2010; Lu *et al.* 2013), three

Table 2. LA-MC-ICP-MS zircon U-Pb analytical results for MG1307-12 sample from the Mogou syenite in the western Henan Province.

Spot no.	Content (ppm)		Ratios										Ages	
	Pb	U	$^{207}\text{Pb}/^{206}\text{Pb}$					$^{208}\text{Pb}/^{232}\text{Th}$					$^{206}\text{Pb}/^{238}\text{U}$	
			1 σ	$^{207}\text{Pb}/^{235}\text{U}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$	1 σ	$^{208}\text{Pb}/^{232}\text{Th}$	1 σ	$^{238}\text{U}/^{232}\text{Th}$	1 σ	$^{206}\text{Pb}/^{238}\text{U}$	1 σ	Ages
1	90	1583	0.00145	0.83583	0.01082	0.04425	0.00044	0.06707	0.00085	4.44	0.04	279	3	
2	77	1177	0.00292	1.16245	0.02125	0.04588	0.00046	0.09363	0.00174	4.40	0.04	289	3	
3	86	612	0.0073	0.21745	0.03432	0.03425	0.0005	0.03129	0.00542	4.10	0.04	217	3	
4	276	903	0.02759	0.15296	0.09125	0.02409	0.00138	0.06022	0.02011	4.55	0.05	153	9	
5	70	558	0.00603	0.22836	0.02926	0.03597	0.00096	0.0244	0.00428	3.16	0.03	228	6	
6	62	568	0.00486	0.22957	0.0239	0.03616	0.00061	0.02109	0.00336	3.78	0.04	229	4	
7	29	691	0.0012	0.50893	0.00748	0.03855	0.00031	0.07801	0.00145	12.75	0.13	244	2	
8	58	1123	0.00144	0.81874	0.00951	0.04186	0.00032	0.16045	0.00115	13.63	0.14	264	2	
9	102	1546	0.00227	1.19766	0.01446	0.04462	0.00037	0.06999	0.00081	3.07	0.03	281	2	
10	225	1048	0.02448	0.20109	0.10617	0.03167	0.00198	0.02075	0.00916	2.25	0.02	201	12	
11	110	959	0.00508	0.22927	0.02512	0.03611	0.00046	0.02168	0.00215	2.64	0.03	229	3	
12	72	1356	0.00297	0.8841	0.01808	0.04099	0.00028	0.13177	0.00247	9.65	0.1	259	2	
13	148	2384	0.00255	0.96608	0.02036	0.04215	0.00055	0.04225	0.00067	1.89	0.02	266	3	
14	104	1645	0.00131	1.08373	0.00927	0.04417	0.00059	0.07063	0.00029	3.36	0.03	279	4	
15	83	951	0.00462	0.22132	0.02134	0.03486	0.00095	0.03104	0.01133	6.74	0.07	221	6	
16	69	1031	0.00321	1.2552	0.02919	0.04614	0.00077	0.15739	0.00387	7.28	0.07	291	5	
17	43	1220	0.00047	0.25698	0.0026	0.03643	0.00033	0.0209	0.0002	9.01	0.09	231	2	
18	84	1078	0.0028	0.22757	0.01368	0.03584	0.00034	0.0254	0.002	4.26	0.04	227	2	
19	80	924	0.00329	0.24108	0.01596	0.03797	0.00102	0.03066	0.00756	3.08	0.03	240	6	
20	126	1095	0.00518	0.22452	0.02515	0.03536	0.00034	0.03341	0.00383	3.68	0.04	224	2	
21	145	1259	0.00527	0.22361	0.02534	0.03522	0.00055	0.03233	0.00557	3.61	0.04	223	3	
22	150	2520	0.00156	0.96754	0.01	0.04392	0.00031	0.08559	0.00074	4.82	0.05	277	2	
23	228	1027	0.04605	0.0131	0.20833	0.03281	0.00083	0.03844	0.00472	2.24	0.02	208	5	
24	115	1299	0.04605	0.00307	0.24569	0.01612	0.00044	0.02528	0.00304	3.58	0.04	245	3	
25	155	1678	0.04605	0.00378	0.22156	0.01794	0.00046	0.03086	0.00207	3.62	0.04	221	3

Figure 5. (a) Weighted average age, U–Pb concordant diagram, (b) cathodoluminescence images of zircons from the Mogou syenite in the Zhifang–Huangzhuang area, Songxian County, and (c) U–Pb concordant diagram of selected spots (red circle of solid line) and unselected spots (black circle of dashed line). Data from table 2.

syenitic magmatic pulses (~ 246 Ma, ~ 226 Ma and ~ 212 Ma) likely occurred in the Mogou and Zhifang–Huangzhuang areas. The first magmatic pulse (~ 246 Ma) produced mainly medium- to coarse-grained syenite, and the second (~ 226 Ma) fine-grained quartz syenite and the third syenite vein (~ 212 Ma).

Corresponding to the main period (212–246 Ma) summarized above, the LA-ICP-MS zircon U–Pb age (226.5 ± 2.7 Ma) obtained in this study indicates a Late Triassic igneous activity during a transition from syn-collision to post-collision.

5.2 Nature of magma source region and magma evolution

Since Loiselle and Wones (1979) first defined A-type granites as alkaline, anhydrous and anorogenic granites, many researchers have paid much attention to them (e.g., Collins *et al.* 1982; Whalen *et al.* 1987; Eby 1992; King *et al.* 1997; Frost *et al.* 2001; Bonin 2007). Collins *et al.* (1982) put forward the class of A-type granitoids and extended the definition to intermediate and basic rocks. Whalen *et al.* (1987) provided discrimination diagrams to

distinguish A-type granites from I- and S-type granites, and pointed out that A-type melts occurred in various tectonic settings other than anorogenic or rifting environments. Eby (1992) divided A-type granitoids into two chemical groups – A1 and A2 – as they have different sources and tectonic settings. King *et al.* (1997) elaborated aluminous A-type granites from the Lachlan Fold Belt, which are different from the traditional alkaline granites. Frost and Frost (2011) mentioned that A-type granites are rich in iron and replaced A-type with ferroan granites. Currently, the term A-type granites are considered to cover a variety of granites except for S- and I-type granites.

There are some geochemical and mineralogical characteristics for recognition of A-type granites. Geochemically, A-type granites are high in $\text{Na}_2\text{O}+\text{K}_2\text{O}$, $\text{FeO}^{\text{T}}/\text{MgO}$, LREE, HFSE (Zr, Nb, Ga, and Y) and low in Mg, Ca, P, Ti, Eu, Cr, Co, Ni, and V (Collins *et al.* 1982; Whalen *et al.* 1987). Mineralogically, A-type granites have feldspars that are chiefly alkali feldspar with limited or missing plagioclase and with mafic minerals that are often ferroan or alkaline (Whalen *et al.* 1987; Bonin 2007; Wu *et al.* 2007).

Exceedingly acidic A-type granites ($\text{SiO}_2 > 72\%$) have the same chemical and mineralogical characteristics as highly fractionated, acidic I- and S-type granites (Whalen *et al.* 1987; King *et al.* 1997). Frost *et al.* (2001) pointed out that A-type granitoids have ferroan alkali-calcic (some were ferroan alkalic) and metaluminous compositional features, while fractionated I-type granitoids are low in FeO^{T} . Among all the six samples used in this study, only MG1307-12 is excessively acidic ($\text{SiO}_2=72.17\%$), and its $\text{FeO}^{\text{T}}/\text{MgO}$ (34) is far higher than the world average values for I-type (2.27) and S-type (2.38) and even A-type (13.5) granitoids (Whalen *et al.* 1987) (figure 7).

In addition, it is easy to distinguish A-type granites from S-type granites because the latter have higher P_2O_5 contents and show increasing trend with fractionation (King *et al.* 1997). The P_2O_5 content of the Mogou syenite is low and there is no obvious trend. High Ga content and $\text{Ga}/\text{Al} > 2.6$ are treated as characteristic of A-type granites (Collins *et al.* 1982; Whalen *et al.* 1987), but not all S- and I-type granites are depleted in Ga and many highly fractionated I- and S-type could be classified as A-type granites if they have $\text{Ga}/\text{Al} > 2.6$ (Wu *et al.* 2007; Zhang *et al.* 2012). Samples from the Mogou syenite show distinct iron-enriched characteristic and plot mainly in the A-type granitoids fields in discrimination diagrams for granitoids (figures 6, 7).

As mentioned earlier, the Mogou syenite belongs to the shoshonite series, which indicates that it originated from deep magma source. Shoshonites derived from basaltic rocks by fractional crystallization (e.g., orthopyroxene fractionation) at high-pressure conditions have depths of fractional crystallization that are positively correlated with

Figure 7. FeO^*/MgO vs. SiO_2 (wt.%) diagram (after Eby *et al.* 1990) for samples from the Mogou syenite. Same symbols as in figure 3.

Figure 6. Discrimination plots for A-type granites (after Frost *et al.* 2001) and samples from the Mogou syenite in the Zhifang–Huangzhuang area, Songxian County. Same symbols as in figure 3.

potassium content (Meen 1987). Deng *et al.* (1998) pointed out that, at the bottom of thickened continental crust, namely at high pressure (2 GPa), syenitic magma without negative Eu anomaly would be generated with eclogite facies residue. Because the Mogou syenites show positive or weakly negative Eu anomalies (figure 4a), the data suggest that the original magma was driven from the Moho or even from greater depths. However, the Mogou syenite is depleted in HFSE (e.g., Nb, Ta, P, Th, U, and Ti) but enriched in large-ion lithophile elements (e.g., Ba, K, and Sr), likely due to contamination by crust material during the ascent of mafic magma (Barth *et al.* 2000), with a Nb-rich eclogitic reservoir left in the deeper lithosphere (McDonough 1991). The available Hf depleted mantle model ages ($T_{DM2}(Hf)$) of the Mogou syenite are distributed in two age clusters (1937–2591 Ma and 3003–3276 Ma) (Lu *et al.* 2013), but correspond to the major magmatic ages of the adjacent Taihua Group, suggesting assimilation of felsic Archean crust. In addition, Zeng (1990) reported elevated Pb isotopic ratios ($^{206}Pb/^{204}Pb = 17.434$, $^{207}Pb/^{204}Pb = 15.429$, $^{208}Pb/^{204}Pb = 37.800$) and those ratios plot between that of the mantle and lower crust, while the initial Sr isotope ratio with Rb–Sr age also plot in the mantle-crust source area, indicating crust-mantle mixing origin. Therefore, the alkalic composition of the Mogou syenite suggests that it was derived from partial melting of the mantle when the degree of contamination by the crust was low; whereas when the degree of crustal contamination was higher, alkali granite would have been produced (Tu 1989). In summary, the Mogou syenite originated from a mixture of mantle component and partial melt of crust rocks.

The Dy/Yb–Dy diagram (figure 8a) illustrates that the syenite magma experienced crystal fractionation. As shown in table 1, contents of K and Ba both decrease from the medium-coarse-grained syenite to fine-grained quartz syenite, indicating crystal fractionation of K-feldspar (Chen *et al.* 2002). Although, the characteristics of low distribution coefficients of REE and high ones of Sr and Eu of K-feldspar are similar to that of plagioclase, the distribution coefficients of Ba are higher in K-feldspar (Chen and Wang 2004b). On the Ba–Eu/Eu* diagram (figure 8b), there is negative correlation between Ba and Eu/Eu*, indicating the evolutionary trend from medium-coarse-grained syenite to fine-grained quartz syenite is similar to the trend of fractional crystallization of K-feldspar. The results further support the interpretation that, during the late-stage magmatic evolution, the crystallization differentiation of K-feldspar subsequent to fractionation of medium- to coarse-grained syenite contributed to the formation of the fine-grained quartz syenite. In addition, the separation of K-feldspar resulted in weak negative Eu anomalies (figure 4a) and less Sr in the fine-grained syenite compared to the medium- to coarse-grained syenite (figure 4b).

Therefore, the Mogou syenite magma was derived by a combination of partial melting of crustal rocks and underplating of the mantle, which also served as the heat source, and then experienced crystal fractionation.

5.3 Tectonic setting and implications for granitic magmatism

The Shangdan Ocean was extending prior to 514 Ma (figure 11a) and finally closed prior to

Figure 8. (a) Dy/Yb vs. Dy diagram and (b) Ba vs. Eu/Eu* diagram (after Eby *et al.* 1990) for samples from the Mogou syenite in the Zhifang–Huangzhuang area, Songxian County. The values for primitive mantle are from Sun and McDonough (1989). The values for chondrite are from Boynton (1984). The values of previous research are from Zeng (1990), Zhang *et al.* (2003) and Qiu *et al.* (1993).

Middle Devonian (figure 11c), when the Mianlue Basin began to develop and evolved into a small-scale Oceanic Basin (figure 11d) (Dong *et al.* 2011). During the Permian, the Mianlue Ocean was gradually being consumed (figure 11e) (Chen 2010; Deng *et al.* 2013; Wang *et al.* 2013a) and collision between the NCC and the YC began at ~ 247 Ma (figure 11f) (Li *et al.* 1996; Dong *et al.* 2011; Wang *et al.* 2013b; Liu *et al.* 2014) with the post-collision phase occurring 225–196 Ma ago (Chen *et al.* 2009; Gong *et al.* 2009; Wang *et al.* 2013b; Deng *et al.* 2015a) (figure 11g). As proposed earlier, the 226.5 Ma emplacement age of the Mogou syenite corresponds with the transition from syn-collision to post-collision stage, and so we propose

227 Ma as the approximate boundary of the two stages (figure 9). This age is slightly older than the emplacement age of rapakivi granite in the QO (210–217 Ma; Lu *et al.* 2004), which represents the ending of the orogenic cycle (Lu *et al.* 1999b), and marks the closure of the Triassic collision and compression and the beginning of post-collision and extension (Lu *et al.* 2008). After the collision event, vast continental sedimentary basins formed with extensional collapse occurred in the QO during late Triassic to early Jurassic (Zhang *et al.* 2001a), indicating that post-collision extension formed since late Triassic. Wan (2011) pointed out that the Xiong'er Group first experienced compression from late Permian to Triassic. In the Songxian

Figure 9. Evolution of the Qinling Orogen from Cambrian to Jurassic. Values are from previous research (Chen *et al.* 2004a, b, 2006, 2007, 2008, 2009; Gong *et al.* 2009; Guo *et al.* 2010; He *et al.* 2007; Hu *et al.* 2004; Jiang *et al.* 2009, 2010; Jin *et al.* 2005; Lerch *et al.* 1995; Li *et al.* 1993, 1996, 1999, 2000, 2006, 2008; Liu *et al.* 2003, 2007, 2009a, 2014; Lu *et al.* 1999b, 2003; Pei *et al.* 2005, 2007a, b; Qin *et al.* 2005, 2007, 2008a, b, 2009a, b; Sun 1991; Sun *et al.* 1996, 2000, 2002; Su *et al.* 2004; Tian 2003; Wang *et al.* 2005, 2006, 2008, 2009a, b; Wen *et al.* 2008; Wu *et al.* 2009; Xie *et al.* 2007; Xu *et al.* 2007, 2008; Xue *et al.* 1996; Yan *et al.* 2007, 2008; Yang *et al.* 1999, 2003, 2009; Zhang *et al.* 1999, 2001b, 2002, 2006, 2009a, b; Zhu *et al.* 2013).

Figure 10. Tectonic setting discrimination diagrams for samples from the Mogou syenite in the Zhifang–Huangzhuang area, Songxian County: (a) Nb vs. Y (after Pearce *et al.* 1984); (b) Rb/Zr vs. SiO_2 (after Harris *et al.* 1986); and (c) Rb vs. (Y+Nb) (after Pearce 1996). Same symbols as in figure 3.

Figure 11. Cross-section of geodynamic development of QO from Cambrian to Triassic (modified from Zhang *et al.* 2001a; Dong *et al.* 2011). Same symbols as in figure 1. NCC = North China Craton; S-NCC = southern margin of the NCC; NOQ = North Qinling Orogen; SQO = South Qinling Orogen; YC = Yangtze Craton.

County, the Dazhuang–Zhonghu anticline, formed in the Xiong’er Group, was intruded by the Mogou syenite, and the Mogou syenite did not experience deformation. Moreover, the 226.5 Ma age of the Mogou syenite indicates that the Mogou plutons intruded in the early stage of the post-collisional event, thus corresponding to a period of transition from compression to extension.

In the Nb *vs.* Y, Rb/Zr *vs.* SiO₂, and Rb *vs.* Y+Nb diagrams (figure 10a, b, c), the data points of syenites mainly plot in the collisional fields as well as along the boundary of syn-collision and post-collision. Therefore, we propose that the Mogou syenite was formed in a transitional tectonic setting, which is consistent with the result of discrimination constrained by zircon age. In EQO, most of the A-type granites formed within

the NCC, the leading margin of which experienced convergence, while the adjacent trailing segment experienced extension (Lu *et al.* 2000). To sum up, the Mogou syenite was emplaced during the Triassic collisional partial extensional setting of the QO (figure 11).

Zhang *et al.* (1996b) divided the syenite distribution zone of EQO into three subzones. The north subzone, in which the Mogou syenite is located, is close to the Machaoying fault (figure 1). The trend of syenites in the Zhifang–Huangzhuang area of Songxian County is mainly NW, which is similar to the WNW trend of the Machaoying fault. This multi-periodic active fault and its secondary fault comprise the igneous activity centre of the EQO (figure 1a), and controlled the regional magmatic and hydrothermal activity. In early Mesozoic, the

tectonic stress field of EQO was dominated by N–S compression, which resulted in a series of folds in the Xiong'er Group with nearly E–W axial trends, and the Machaoying fault transformed into an intra-continental compression–subduction belt, which emerged as an A-type subduction from north to south (Zeng 1990; Liu *et al.* 1998). During the transition stage of tectonic setting from compressional to extensional, the Machaoying fault and related secondary faults served as magmatic vents (Yan *et al.* 2005). The depressurization experienced by the faults during that transition stage likely contributed to the decrease of melting point of syenitic magmas. As a result, magmas intruded more easily and finally emplaced in the axial parts and the northern flanks of the Dazhuang–Zhonghu anticline (figure 1b). However, geophysical data show that the depth extent of the Machaoying fault is 34–37 km (Yan *et al.* 2005), which is insufficient to cut through the remarkably thickened crust (>55 km) (Deng *et al.* 1998). Thus, it is supposed that the Shangdan suture may have cut through the lithosphere and acted as the channel for the ascending mantle component.

6. Conclusions

- The Mogou syenite intruded at 226.5 ± 2.7 Ma, corresponding to the Triassic magmatic activity in the East Qinling Orogen.
- The Mogou syenite was derived by mixing of crust and mantle, and experienced fractional crystallization.
- The transition from syn-collision to post-collision likely occurred during the Triassic, possibly around 227 Ma.

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