Evolution of the Mesozoic Granites in the Xiong’ershan-Waifangshan Region, Western Henan Province, China, and Its Tectonic Implications

HAN Yigui1, *, ZHANG Shihong1, Franco PIRAJNO2 and ZHANG Yuanhou1, 3
1 State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Beijing 100083, China
2 Geological Survey of Western Australia, 100 Plain Street, East Perth, WA 6004, Australia
3 The College of Earth Sciences, Jilin University, Changchun 130061, China

Abstract: Based on the new data of isotopic ages and geochemical analyses, three types of Mesozoic granites have been identified for the Xiong’ershan-Waifangshan region in western Henan Province: high-Ba-Sr I-type granite emplaced in the early stage (~160 Ma), I-type granite in the middle stage (~130 Ma) and anorogenic A-type granite in the late stage (~115 Ma). Geochemical characteristics of the high-Ba-Sr I-type granite suggest that it may have been generated from the thickened lower crust by partial melting with primary residues of amphibole and garnet. Gradual increase of negative Eu anomaly and Sr content variations reflect progressive shallowing of the source regions of these granites from the early to late stage. New 40Ar/39Ar plateau ages of the early-stage Wuzhangshan granite (156.0±1.1 Ma, amphibole) and middle-stage Heyu granite (131.8±0.7 Ma, biotite) are indistinguishable from their SHRIMP U-Pb ages previous published, indicating a rapid uplift and erosion in this region. The representative anorogenic A-type granite, Taishanmiao pluton, was emplaced at ~115 Ma. The evolution of the granites in this region reveals a tectonic regime change from post-collisional to anorogenic between ~160 Ma and ~115 Ma. The genesis of the early- and middle-stage I-type granites could be linked to delamination of subducted lithosphere of the Qinling orogenic belt, while the late-stage A-type granites represent the onset of extension and the end of orogenic process. In fact, along the Qinling-Dabie-Sulu belt, the Mesozoic granitoids in western Henan, Dabieshan and Jiaodong regions are comparable on the basis of these temporal evolutionary stages and their initial 87Sr/86Sr ratios, which may suggest a similar geodynamic process related to the collision between the North China and Yangtze cratons.

Key words: granite, Mesozoic, high Ba-Sr, 40Ar/39Ar dating, post-collision, anorogenic, western Henan

1 Introduction

During the last decade, a large-scale lithospheric thinning has been proposed to explain the tectonic evolution of eastern China in the Mesozoic (Menzies et al., 1993; Griffin et al., 1998; Gao et al., 2002, 2004; Wu et al., 2003a, 2005; Xu et al., 2004a). Such a event is commonly accompanied by intensive granitic magmatism (Kay and Kay, 1993; Collins, 1994; Lustrino, 2005). Investigations on numerous granitoids in eastern China have provided valuable information on these magmatic and geodynamic processes, but whether the subduction of the Pacific plate beneath the Eurasian continent (Wu et al., 2005; Chen et al., 2005a) or collision between the North China Craton (NCC) and the Yangtze Craton (YZC) (Jahn et al., 1999; Gao et al., 2002; Li et al., 2002; Zhang et al., 2002; Ma et al., 2004) controls the magmatic evolution of these granites remains controversial. Recent research on Mesozoic granitoids in eastern China, such as in Dabieshan, Jiaodong, Yanliao and Taibangshan regions in the NCC, and Nanling in the YZC (Liu et al., 2002a; Ma et al., 2004; Hua et al., 2005) has revealed their petrogenetic characteristics and constraints on tectonic environments. These previous studies contributed to understanding the Mesozoic geodynamic processes on the southern margin of the NCC and their relationships to the magmatism and lithospheric thinning events in eastern China.
The western Henan region lies on the southern margin of the NCC, where intensive granitic magmatism and Au-Mo mineralization took place in the Mesozoic. The previous research was mainly focused on the metallogeny of this region (Hu et al., 1988; Chen and Fu, 1992; Ren et al., 1996; Lu et al., 2002), whereas the petrogenesis and tectonic environment of the granitoids remain unclear.

Based on the new 40Ar/39Ar dating and geochemical data of key granitic intrusions in western Henan, combined with previous data, we have divided the granitoids of this region into: the early-stage high-Ba-Sr I-type granite (~160 Ma), middle-stage I-type granite (~130 Ma) and late-stage anorogenic A-type granite (~115 Ma). The evolution of these three types of granites reflects a tectonic regime transitional from post-collisional to anorogenic.

2 Regional Geology and Petrology of Granites

2.1 Regional geology

The study area is located in the Xiong’ershan-Waiyangshan region on the southern margin of the NCC (Fig. 1). The crystalline basement is the Archean-Paleoproterozoic Taihua Group, composed mainly of amphibolite to granulite high-grade metamorphic rocks (HBGMR, 1989), which is unconformably overlain by the Mesoproterozoic volcanic rocks of the Xiong’er Group and Meso- and Neoproterozoic sedimentary rocks of the Guandaokou Group and Luanchuan Group. The Xiong’er Group is composed of intermediate to felsic lavas with minor pyroclastic and sedimentary interlayers. The Xiong’er volcanic rocks are generally albitized and chloritized (Han et al., 2006). The age of the Xiong’er Group is poorly constrained, and zircon U-Pb dating yielded ages ranging from ~1950 to ~1650 Ma (Sun and Hu, 1993; Ren et al., 2000; Zhao et al., 2004). The Guandaokou Group and Luanchuan Group mainly outcrop on the southern margin of the Xiong’ershan region, and consist mostly of carbonates, quartz sandstones and mica schists. Minor Paleozoic and Mesozoic strata outcrop at the northern sides of the Xiong’ershan and Waiyangshan Mountains.

Numerous Mesozoic granitic plutons are present in this region (see Wuzhangshan, Huashani, Heyu and Taishanmiao granites in Fig. 1). They are locally associated with granitic porphyries and breccia pipes, for example Au- and Mo-bearing porphyries and breccias in the Qiyugou-Leimengou and Luanchuan areas. Recent research indicates that this granitic magmatism has a close relationship to Au and Mo mineralization (Lu et al., 2002; Mao et al., 2002; Chen et al., 2004; Zhang et al., 2005).

2.2 Petrography of granitic plutons

The NW-SE-trending Wuzhangshan granitic pluton lies near the contact zone between the Taihua Group and the Xiong’er Group in the central part of the Xiong’ershan Mountains (Fig. 1). The granitic rock types are mainly...
massive monzogranite and granodiorite, medium-coarse-grained and pale grey in color, with rare mafic enclaves. Mineral assemblages are a combination of quartz (20%–30%), K-feldspar (~20%), albite-oligoclase (~40%), amphibole (5%–10%) and minor biotite. Amphiboles are euhedral to subhedral, with almost no alteration, and mostly belong to the calcic series (Fan et al., 1994). Feldspars occur as phenocrysts, ~1.2 cm in diameter, with slight sericitization and epidotization. Accessory minerals include sphene, magnetite, apatite and zircon.

The Heyu granitic pluton consists of massive reddish megacrystic biotite monzogranites. Large phenocrysts are microcline or perthite, generally 3–4 cm in diameter and locally up to 6×10 cm. The rocks contain quartz (~20%), K-feldspar (~30%), albite-oligoclase (~30%), biotite (~10%) and amphibole (~5%), with rare mafic enclaves. Sphene, magnetite, apatite and zircon are accessory phases.

The Huashani granitic pluton intruded into the metamorphic rocks of the Taihua Group in the Xiong’ershan Mountains (Fig. 1). The rocks are mainly reddish amphibole biotite monzogranites, containing K-feldspar megacrysts. The texture, rock forming and accessory minerals are similar to those of the Heyu pluton. Mafic enclaves only occur locally.

The Taishannmiao pluton is mainly composed of K-feldspar-rich granites, which are usually red in color and show coarse- to medium-fine-grained granitic textures from center to margin of the pluton. Mineral assemblages are perthite (50%–60%), albite-oligoclase (10%–15%), quartz (~25%) and rare biotite. Accessory minerals include magnetite, zircon and fluorite. Miarolitic cavity structures are common, suggesting a relatively shallow emplacement level (Wu et al., 2003b). Mafic enclaves are rare.

3. 40Ar/39Ar Dating of the Granites

Previous isotopic ages of these plutons were determined by Rb-Sr whole-rock isochron and K-Ar methods, but most are of poor quality. For example, the points defining the Rb-Sr isochron are unevenly distributed, and some ages are much scattered even for the same pluton by the same dating method. These problems probably arose from the inhomogeneity of initial 87Sr/86Sr for the Rb-Sr method and unknown Ar isotope changes for the K-Ar method. Only recently were a few more reliable ages of these granites obtained based on the zircon U-Pb SHRIMP analysis (Mao et al., 2005; Li, 2005; Ye, 2006). In order to understand the emplacement and cooling history of these plutons, we employed the 40Ar/39Ar method to further date the Wuzhangshan pluton and Heyu pluton. Sample 03XY036B1 of granodiorite was collected from the Wuzhangshan pluton, with a GPS position of 34°12'42" N and 111°45'23" E. Sample 03XY074B1 of biotite monzogranite was collected from the Heyu pluton with a GPS position of 33°58'58" N and 111°51'5" E (Fig. 1).

Amphiboles and biotites were separated from crushed rocks (~1 mm in diameter) using a magnetic separation technique. The crystals were hand-picked under a binocular microscope to remove altered or other mineral-sticking grains, achieving a purity of up to 99%. Step heating 40Ar/39Ar analyses were performed on a MM-5400 mass spectrometer at the Geological Laboratory Center of the China University of Geosciences (Beijing). The interfering-neutron-reaction factors and experimental procedures are referred to Wang et al. (2002). Plateau and isochron ages were calculated using ISOPLOT 2.3 software (Ludwig, 2000). All errors shown represent the analytical precision of 1 σ.

The analytical results of amphiboles and biotites are listed in Table 1. Amphiboles from sample 03XY036B1 of the Wuzhangshan pluton yield a flat spectrum with a plateau age of 156.0±1.1 Ma (39Ar cumulative of 95.5% in seven heating steps from 1080°C–1280°C) (Fig. 2a). The isochron age of this sample is 156.8±3.1 Ma with 40Ar/39Ar initial ration of 291±34 (Fig. 2b).

Biotites from sample 03XY074B1 of the Heyu pluton yield a well-defined plateau age of 131.8±0.7 Ma (39Ar cumulative of 96.6% in eleven heating steps from 700°C–1170°C) and an isochron age of 132.5±1.1 Ma with 40Ar/39Ar initial ration of 292.6±7.3 (Fig. 2c, 2d).

The well-defined plateau ages of the two samples are, within error, identical to their respective isochron ages. Their 40Ar/39Ar initial ratios are similar to atmospheric component of 295±5. The two samples thus do not contain excess Ar and did not undergo Ar loss by any later tectono-thermal events; therefore, the plateau ages of 156.0±1.1 Ma and 131.8±0.7 Ma represent the cooling ages of amphiboles from the Wuzhangshan pluton and biotites from the Heyu pluton, respectively.

Isotopic systems of zircon U-Pb, amphibole Ar-Ar and biotite Ar-Ar have respective closure temperatures of 700±50°C, 500±20°C and 300±50°C (Dodson and McClellan-Brown, 1985). Recent geochronological studies gave a SHRIMP U-Pb concordant age of 156.8±1.2 Ma (MSWD=0.9) from six zircon grains for the Wuzhangshan pluton and eight zircon grains from the Heyu pluton yield a SHRIMP U-Pb concordant age of 127.2±1.4 Ma (MSWD=1.25), suggesting emplacement ages of the two intrusions (Li, 2005; Mao et al., 2005). Therefore, the Wuzhangshan pluton and Heyu pluton preserve relatively small differences between U-Pb and Ar-Ar ages, implying rapid cooling after emplacements. Recent studies have also revealed that the SHRIMP U-Pb zircon ages of the Huashan pluton and the Taishannmiao pluton are 130.7±1.4
Fig. 2. (a) and (b): Ar-Ar age spectrum and isochron plot for amphibole (sample 03YX036B1) from the Wuzhangshan pluton; (c) and (d): Ar-Ar age spectrum and isochron plot for biotite (sample 03YX074B1) from the Heyu pluton.

Table 1 40Ar/39Ar step-heating analytical results for amphibole from Wuzhangshan pluton and biotite from Heyu pluton

| Steps | Temperature (°C) | 40Ar/39Ar (λ) | 40Ar/39Ar (µ) | 40Ar/39Ar (µ) | 40Ar/39Ar (λ) | 40Ar/39Ar (µ) | 40Ar/39Ar (µ) | 40Ar/39Ar (µ) | 40Ar/39Ar (µ) | 40Ar/39Ar (µ) | 40Ar/39Ar (µ) | 40Ar/39Ar (µ) | 40Ar/39Ar (µ) | 40Ar/39Ar (µ) |
|-------|-----------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| 1     | 680             | 472.3386      | 1.203964      | 182.3408      | 151.7898      | 0.001         | 0.13          | 28.37         | 537.36        | 601.67        |               |               |               |               |               |
| 2     | 800             | 297.4121      | 0.045057      | 99.9168       | 316.6744      | 0.002         | 0.23          | 9.74          | 98.24         | 158.09        |               |               |               |               |               |
| 3     | 900             | 1753.8714     | 5.892745      | 182.3054      | 29.8684       | 0.003         | 0.39          | 2.74          | 119.15        | 988.48        |               |               |               |               |               |
| 4     | 960             | 257.7177      | 0.062786      | 13.1975       | 81.3906       | 0.004         | 0.45          | 32.14         | 307.83        | 106.66        |               |               |               |               |               |
| 5     | 1020            | 113.074       | 0.000563      | 85.7834       | 127.8194      | 0.010         | 1.19          | 105.17        | 462.44        | 106.51        |               |               |               |               |               |
| 6     | 1080            | 64.2254       | 0.082546      | 8.8444        | 40.7455       | 0.032         | 3.76          | 63.48         | 160.66        | 9.01          |               |               |               |               |               |
| 7     | 1100            | 45.3539       | 0.018773      | 5.8293        | 40.4047       | 0.026         | 2.74          | 88.82         | 159.37        | 2.48          |               |               |               |               |               |
| 8     | 1120            | 43.3636       | 0.015196      | 6.4219        | 39.528        | 0.026         | 2.74          | 90.81         | 156.06        | 2.19          |               |               |               |               |               |
| 9     | 1140            | 65.176        | 0.008359      | 13.6933       | 41.9031       | 0.012         | 2.43          | 76.97         | 153.59        | 3.04          |               |               |               |               |               |
| 10    | 1220            | 52.7241       | 0.049531      | 5.7661        | 38.6712       | 0.093         | 11.05         | 73.36         | 152.82        | 2.45          |               |               |               |               |               |
| 11    | 1280            | 67.707        | 0.007654      | 2.8422        | 32.4021       | 0.048         | 11.86         | 89.65         | 129.45        | 2.04          |               |               |               |               |               |
| 12    | 1310            | 139.8795      | 0.318286      | 8.4635        | 46.7397       | 0.018         | 2.09          | 38.06         | 131.04        | 1.81          |               |               |               |               |               |
| 13    | 1330            | 139.8795      | 0.318286      | 8.4635        | 46.7397       | 0.018         | 2.09          | 38.06         | 131.04        | 1.81          |               |               |               |               |               |

Note: Analysed at the Isotopic Laboratory of the Geological Lab Center of the China University of Geosciences (Beijing).
Ma and 115±2 Ma, respectively (Mao et al., 2005; Ye, 2006).

In conclusion, the granites in the Xiong’ershan-Waifangshan region were intruded at approximately 157 Ma (Wuzhangshan pluton), 130 Ma (Huashani and Heyu plutons) and 115 Ma (Taiannanmiao pluton). The granites of these three different ages are characterized by different chemistry, ranging from I-type to A-type. This is discussed further below.

4 Geochemistry

4.1 Analytical methods

Major, trace and rare earth elements (REE) analyses were performed at the Geological Laboratory Center of China University of Geosciences (Beijing). Major element measurements were conducted using the alkali fusion method and determined by an inductively coupled plasmaatomic emission spectrometry (ICP-AES) of the Leeman Labs (type PS-950). Chemical procedures for REE and other trace element analyses are as follows: Accurately weighed (35–45 mg) samples were put into Teflon vessels with subsequent addition of 0.5 mL HNO3 and 0.5 mL HF. Samples in the Teflon vessels were braised to near dryness on a 150°C hot plate. After addition of 1 mL HNO3, 1 mL HF, the vessels were lidded and sealed into steel containers, and then were under heat preservation in a 190°C oven over 24 hours. The vessels were then opened and dried. After adding 1 mL HNO3, the solutions were vaporised again to near dryness. 2 mL HNO3 and 2 mL 18 MΩ purified water were put into the vessels, which were then sealed into steel containers and maintained in an oven at 150°C over 24 hours to dissolve the samples completely. Afterwards, the solutions were transferred into tubes and diluted to 1000 times of sample weight by 18 MΩ purified water. 2 mL solutions with addition of 2 mL 10 ppb Rh internal standard were finally prepared for measurement. The elements were determined using a Micromass Platform ICP-HEX-MS (inductively coupled plasma-mass spectrometer with a hexapole collision cell) with analytical precision of 1%±.

4.2 Results

Analytical results are listed in Table 2. The SiO2 contents of the three differently-aged granites increase from older to younger. All the granites are high-K calc-alkaline ones, metaluminous to weakly peraluminous with small variations of A/CNK (0.9–1.1) (Fig. 3a, 3b). The Wuzhangshan, Huashani and Heyu granites have SiO2 contents between 68%–72%, high alkali contents (7%–9.5% Na2O+K2O) and the K2O/Na2O ratios close to unity, and the Wuzhangshan granite has higher alkali and Al2O3 contents relative to the Huashani and Heyu granites. The Taiannanmiao granite has the highest SiO2 content (75%–77%) with alkali of 7.5%–8.5% and K2O/Na2O ratios of 1.1–1.8, values that are indicative of potassic granite.

The Wuzhangshan, Huashani and Heyu plutons have Na2O>3.2%, A/ CNK<1.1 and less than 1% CIPW normative corundum respectively and therefore they can be classified as I-type granites (Chappell and White, 1974). On the basis of the very high Ba and Sr contents and relative ages, we further classified the Wuzhangshan pluton into the early-stage high-Ba-Sr I-type granite and the Huashani and Heyu plutons are the middle-stage I-type granites because of their similar petrological and geochemical features.

Geochemical features of REE and trace elements of these granites can be summarized as follows:

1) Early-stage high-Ba-Sr I-type granite: Wuzhangshan pluton

The Wuzhangshan granite displays significantly high Sr and Ba contents relative to other plutons: Sr 1150 ppm±, Ba 2300 ppm± and Sr/Y ratio 70± (Table 2). The pluton has slightly positive Eu anomaly, relatively high K/Rb ratios (~300) and low Y contents (~17.0), coincident with features of typical high-Ba-Sr granites (Tarney and Jones, 1994; Fowler et al., 2001) and the high Sr granites in the Dabieshan region and on the northern margin of the NCC (Liu et al. 2002b; Ma et al. 2004) (Fig. 4a, 4b). The chondrite-normalized REE patterns are LREE enriched and HREE flat. High field strength elements (HFSEs) such as Nb, Ta, P and Ti are more depleted than the Huashani and Heyu plutons (Fig. 4b).

2) Middle-stage I-type granite: Huashani and Heyu plutons

These two plutons have more enriched LREE and similar HREE contents relative to the Wuzhangshan pluton. The negative Eu anomaly and concave-upward REE patterns indicate that amphibole and feldspar played a dominant role during magma segregation (Fig. 4c). On the primitive mantle-nomalized spiderdiagram, the middle-stage granites show depletion of Ba, Nb, Ta, P and Ti and obviously low Sr than the Wuzhangshan pluton (Fig. 4d).

3) Late-stage anorogenic A-type granite: Taiannanmiao pluton and related porphyries

The Taiannanmiao pluton is different from highly fractionated I-type granites because of its relatively high Y, La, Nb, Ce contents and Ga/Al ratios (Wu et al., 2003b). The Taiannanmiao granite has very low Ca, Sr and Ba contents, relatively high Nb, Ga and Y contents, seagull-shaped REE patterns with pronounced negative Eu anomaly (Eu/Eu*= 0.04–0.43) (Fig. 4e) and strong depletion of Ba, Sr, Eu and Ti (Fig. 4f). This chemistry is typical of A-type granites (Whalen et al., 1987; Wu et al.,
Table 2 Major, trace and rare-earth elements analyses of granites in the Xiongershan-Waifangshan region, western Henan

<table>
<thead>
<tr>
<th>Pluton</th>
<th>Early (~156 Ma)</th>
<th>Middle (131–127 Ma)</th>
<th>Late (~115 Ma)</th>
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<td></td>
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<td>Huashani</td>
<td>Wuzhangshan</td>
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<td>061B1 HS</td>
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<td>1.95 (2.19)</td>
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<td>RaO</td>
<td>Total (100.06)</td>
<td>99.85 (99.72)</td>
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Notes: Chemical elements of this study were analysed at the ICP-MS laboratory of the Geological Lab Center of the China University of Geosciences (Beijing). Other element data are from: (1) Fan et al. (1994) and Wang et al. (1997); (2) Bi and Luo (1995); (3) Li et al. (1993) and (4) Liu et al. (2004). The (87Sr/86Sr) and δ18O data are from Chen et al. (2000) and Qu (1988). 

2002a). The HREE contents of the Taishanniao granite are higher than other granitic plutons in the study area. The 10000×Ga-Al-Ce diagrams (Fig. 5c), confirm that the Taishanniao granite belongs to the A-type. Moreover, on the basis of the Nb-Y-3×Ga diagram (Fig. 5c), the Taishanniao granite can be classified as A1 granite, supporting an anorogenic tectonic environment (Eby, 1992). Recent investigations have revealed that the Donggou granitic porphyry, with a SHRIMP U-Pb zircon age of 112±1 Ma (Ye et al., 2006), in the Wuzhangshan region has similar characteristics to the Taishanniao granite, and also belongs to A-type granite (Fig. 1). 

Sr and O isotopic values of these three types of granites are listed in Table 2. The Wuzhangshan and Huashani plutons have lower to medium initial 87Sr/86Sr ratios (0.7075–0.7077) and δ18O values between 6.06–9.19, which are similar to I-type granites in the Lachlan fold belt.
in Australia (Chappell and White, 1974), implying a relatively low crustal origin and some mantle contributions (Faure, 1986; Miller et al., 1999; Liu et al., 2002a). The Sr and O isotopic ratios of the Heyu granite are relatively high (initial $^{87}\text{Sr}/^{86}\text{Sr} 0.7100; \delta^{18}\text{O} 9.11−9.84), and this may be due to crustal contamination during magma ascending (Faure, 1986).

5 Discussions

5.1 Petrogenesis

High-Ba-Sr granitoids in orogenic belts have received much attention for their petrogenetic significance (Tarney and Jones, 1994; Fowler et al., 2000). Tarney and Jones (1994) considered that the high-Ba-Sr granites might be derived from sources related to subducted oceanic plateau, or underplated mafic magmas with high Ba-Sr characteristics, or penetration of asthenospheric carbonatitic melts. The late Caledonian Rogart granitic pluton in Sutherland is typical high-Ba-Sr granite, whose geochemical characteristics were inherited from enriched mantle sources with minor crustal contamination (Fowler et al., 2001). Large volumes of high-Ba-Sr granitoids in China have been found and investigated in recent years (Ma et al., 1998; Liu et al., 2002a, 2002b; Qian et al., 2002; Li et al., 2004; Lin et al., 2004; Ma et al., 2004; Zhang et al., 2004).

Reviews of previous dehydration melting experiments of various rocks show that high-Sr granites are generated under conditions of high temperature ($T \geq 850^\circ\text{C}−900^\circ\text{C}$) and high pressure ($P \geq 1.5$ GPa), which correspond to the base of thickened continental crusts (Liu et al., 2002b). Qian et al. (2002) suggested that the Badaling high-Ba-Sr granite in the northern part of the NCC might be produced from mixing of mafic magmas and crustal materials and subsequent fractional crystallization. Li et al. (2004) considered that the high-Sr low-Y granites in northern Hebei Province originated by partial melting of overthickened continental lower crust.

Our studies reveal that the Wuzhangshan pluton is typical high-Ba-Sr granite. The intrusion has the geochemical features of slightly low MREE, flat patterns of HREE, $Y/Yb$ ratios close to 10, and relatively high $\text{La}/Yb$ ratios, implying the presence of residual amphibole and garnet in the source (Wu et al., 2002b). The positive Eu anomaly reflects insignificant residual plagioclase during magma differentiation. These features suggest that the Wuzhangshan high-Ba-Sr granite might have originated from an enriched source in the thickened continental lower crust. The high-Ba-Sr granite has similar geochemical features to adakite (Zhang Qi et al., 2001) and displays more negative Ta and Nb anomalies than the middle-stage Huashani and Heyu granites, implying a subduction-related origin (Wilson, 1989), which might be inherited from enriched source regions linked to subduction of the Qinling lithospheric plate beneath the NCC during pre- and syn-collision stages.

The Eu anomaly can be used to estimate the depth of the magma source region. Weakly negative or no Eu anomaly of felsic rocks indicate that magma at depths did not equilibrate with residual plagioclase, implying a source deeper than 50–60 km, whereas a large negative Eu anomaly suggests magma generation in the lower part of a normal continental crust or in the middle part of a thickened continental crust (Zhao et al., 2001; Ma et al., 2004). The granites in the Xiong’ershan-Waifangshan region show a Eu anomaly transition from weak positive to pronounced negative from ~157 Ma to ~115 Ma (Fig. 4), indicating a progressive shallowing of the magma source regions during this interval. A similar trend was found for the granites in the Dabieshan region (Ma et al., 2004).
5.2 Comparison with granites in the eastern NCC and tectonic implications

Besides the plutons mentioned above, several other granitoids on the souther margin of the NCC have been recently dated using the SHRIMP U-Pb zircon method (Mao et al., 2005). The results indicate that the Wenyu and Niangniangshan granitic plutons in the Xiaoqinling region were emplaced at 138.4±2.5 Ma and 141.7±2.5 Ma, respectively, and the SHRIMP U-Pb zircon dating of granitic porphyries in the Xiong’ershan region yielded 136.2±1.5 Ma for Leimengou, 158.2±3.1 Ma for Nannihu and 157.6±2.7 Ma for Shangfanggou (Fig. 1) (Mao et al., 2005). The Wenyu pluton shows features of high-Ba-Sr granite (Sr 850 ppm, Ba 1695 ppm; Li et al., 1993) though other granites lack reliable geochemical data. It is suggested that the emplacement of granitoids on the...
southern margin of the NCC began at about 160 Ma, with the high-Ba-Sr granite occurring in the early stage (160−140 Ma). Hong et al. (2003) summarized the published initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the Mesozoic granitoids in the Xiaoqinling-Xiaoshan region. Based on the data from the Xiong’ershan region (Table 2), the initial $^{87}\text{Sr}/^{86}\text{Sr}$ values of Mesozoic granitoids in the southern margin of the NCC range from 0.7071 to 0.7127.

Comprehensive studies in recent years have shown that lithospheric thinning of the NCC occurred between the Late Jurassic and the Early Cretaceous, corresponding with the peak of Mesozoic magmatic activity in the eastern NCC (Wu and Sun, 1999; Yan et al., 2003; Gao et al., 2004; Xu et al., 2004a, 2004b; Zhai et al., 2004). Mesozoic magmatic evolutionary trends from high-Ba-Sr I-type granite, relatively low Ba-Sr (or calc-alkaline) I-type granite, to A-type granite have been found in the Dabieshan, Jiaodong, Yanliao and Taihangshan regions (Fig. 1). Ma et al. (1998, 2004) divided the timing of the Mesozoic granitoids in the Dabieshan region into two stages: an early stage of high Sr/Y granites (142−135 Ma) and a late stage of low Sr/Y granites (125−95 Ma), with initial $^{87}\text{Sr}/^{86}\text{Sr}$ between 0.7067 and 0.7100 (Ma et al., 1998; Chen et al., 2002). In the Jiaodong region, the Kunyushan pluton (150 Ma) and Guojialing pluton (128 Ma) are both high-Ba-Sr type granites (Yang et al., 2003; Zhang et al., 2004), and the Laoshan granitic complexes evolved from I-type to A-type between 146.8 Ma and 110.8 Ma (Zhou et al., 1997). The initial $^{87}\text{Sr}/^{86}\text{Sr}$ of the Mesozoic granitoids in the Jiaodong region are mostly between 0.7078 and 0.7120 (Zhou and Lü, 2000; Yang et al., 2003; Guo et al., 2004; Zhang et al., 2006). Therefore, the types and evolutionary sequences of the Mesozoic granitoids in the Dabieshan and Jiaodong regions are similar to those in the western Henan region. However, compared to western Henan, the Dabieshan and Jiaodong regions, the granitoids in the Yanliao and Taihangshan regions span a longer period of time and have lower initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. In the Yanliao region, the high-Ba-Sr granitoids were emplaced between 236−137 Ma; the calc-alkaline granitoids between 210−120 Ma; and the A-type granitoids between 158−98 Ma (Liu et al., 2002a, 2002b; Qian et al., 2002; Li et al., 2004; Wu et al., 2005). In the Taihangshan region, the high-Ba-Sr granites in the northern part and diorites in the southern part were formed between 140−125 Ma (Chen et al., 2003; Peng et al., 2004).
The granitoids in the Taihangshan and Yanliao regions have similar low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, ranging from 0.7040 to 0.7070 and from 0.7041 to 0.7076, respectively (Luo et al., 1999; Qian et al., 2002; Chen and Zhai, 2003; Peng et al., 2004; Chen et al., 2005b). The granitoids in western Henan, and the Dabieshan and Jiaodong regions have similar geochemical characteristics, emplacement ages and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, suggesting a similar geodynamic evolution for all three regions, between 160 Ma and 110 Ma. The differences between the three regions and the areas on the northern margin and interior of the NCC may reflect different petrogenesis. We propose that the granitoids in western Henan, and the Dabieshan and Jiaodong regions were related to the collision between the YZC and the NCC. Results of geochronological and geological investigations indicate that the collision between the two cratons occurred in the Middle-Late Triassic (238–218 Ma) (Ames et al., 1993, 1996; Chen et al., 1995; Li et al., 1997; Meng and Zhang, 1999; Zhang Guowei et al., 2001; Li, 2001; Ayers et al., 2002; Sun et al., 2002; Ratschbacher et al., 2003; Zheng et al., 2003). The extensive granitic magmatism in western Henan during 160–125 Ma has a close temporal relationship with the post-collisional evolution of the east Qinling orogenic belt (Zhang Guowei et al., 2001).

Gao et al. (1999) suggested a lower crustal delamination model in the Qinling-Dabie orogenic belt because of its relatively thin continental crust (3–7 km thinner than that of East China or the global continental crust), slower seismic velocity ($V_p$) for the lower and the whole crust, and changes of Eu/Eu* and Sr/Nd ratios. The decreasing trends of the Eu/Eu* and Sr/Nd ratios for the granites in western Henan support the delamination model (Fig. 5d). Based on inversion of rapid cooling rates of ultra-high-pressure rocks and granites in the Dabieshan region, as well as the seismic tomography results, Li et al. (2000) and Li et al. (2002) proposed that post-collisional lithospheric delamination events occurred twice in the Dabieshan region, corresponding with large-scale magmatism at 170 Ma and 130–110 Ma. Geochronological studies reveal that the Wuzhangshan and Heyu plutons have very close amphibole and biotite cooling ages and zircon U-Pb emplacement ages, suggesting rapid uplift and erosion of the crust during this granitic magmatism. Geochemical studies show that the granites in western Henan were emplaced in three stages: early-stage high-Ba-Sr I-type granite (~157 Ma), middle-stage I-type granite (~130 Ma) and late-stage anorogenic A-type granite (~115 Ma). The high-Ba-Sr I-type granite shows geochemical features of high K/Rb and Sr/Y ratios, weak positive Eu anomaly and strong depletion in Nb, Ta, P and Ti. The early-stage granite was probably generated with main residual minerals of amphibole and garnet because of their flat HREE pattern, low Y and Yb and Y/Yb close to 10, which may have originated from thickened continental lower crust. The increasing negative Eu anomalies of these three stage granites are indicative of decreasing depths of the magma sources.

(2) The emplacement of these granites in three separate stages reflects a tectonic transition from post-collisional to intraplate anorogenic on the southern margin of the NCC between 160 and 115 Ma. This extensive 160–130 Ma post-collisional granite magmatism may be linked to delamination of the lower crust in the Qinling orogenic belt, whereas the ~115 Ma A-type granites indicate the end of the continental collision and extensional tectonics.

(3) With respect to geochemical type, age and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, the western Henan granites are comparable to those in the Dabieshan and Jiaodong regions, suggesting a similar geodynamic environment, whereas the differences from the granitoids in the Yanliao and Taihangshan regions imply different petrogenetic models.

6 Conclusions

On the basis of the data presented in this paper, integrated with published geochemical and geochronological data, we conclude the following:

(1) $^{40}\text{Ar}/^{39}\text{Ar}$ dating results indicate that the Wuzhangshan and Heyu plutons have very close amphibole and biotite cooling ages and zircon U-Pb emplacement ages, suggesting rapid uplift and erosion of the crust during this granitic magmatism. Geochemical studies show that the granites in western Henan were emplaced in three stages: early-stage high-Ba-Sr I-type granite (~157 Ma), middle-stage I-type granite (~130 Ma) and late-stage anorogenic A-type granite (~115 Ma). The high-Ba-Sr I-type granite shows geochemical features of high K/Rb and Sr/Y ratios, weak positive Eu anomaly and strong depletion in Nb, Ta, P and Ti. The early-stage granite was probably generated with main residual minerals of amphibole and garnet because of their flat HREE pattern, low Y and Yb and Y/Yb close to 10, which may have originated from thickened continental lower crust. The increasing negative Eu anomalies of these three stage granites are indicative of decreasing depths of the magma sources.

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