Granitoid Petrogenesis and Tectonic Implications of the Late Triassic Baoji Pluton, North Qinling Orogen, China: Zircon U-Pb Ages and Geochemical and Sr-Nd-Pb-Hf Isotopic Compositions

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ABSTRACT

The Qinling orogenic belt in central China resulted from the final collision of the North China and South China blocks in the Triassic. Early Mesozoic granitoids are widespread in the Qinling orogen. Their genesis can provide key constraints on the tectonic evolution of this orogenic belt. The Late Triassic Baoji pluton, located in the North Qinling unit, consists of granodiorites, monzogranites, quartz monzodiorites, and K-feldspar granites. U-Pb zircon dating via the laser ablation ICP-MS technique yields ages of 217.4 ± 1.4, 212.3 ± 1.8, 212.6 ± 1.6, and 195.1 ± 2.0 Ma for granodiorites, monzogranites, quartz monzodiorites, and K-feldspar granites, respectively. The granitoids have high-K calc-alkaline, metaluminous to weakly peraluminous composition(s). Silica contents increase and Mg, Fe, Ti, Ca, and P contents decrease from quartz monzodiorites through granodiorites to monzogranites and K-feldspar granites. Combining our findings with evidence from whole-rock Sr-Nd and zircon Hf isotopes, we suggest that the granodiorites formed by magma-mixing processes involving metasomatized lithospheric mantle and Mesoproterozoic crustal material. The monzogranites record the contribution of an asthenospheric mantle source. The quartz monzodiorites were derived from a metasomatized lithospheric mantle source. Partial melting of crustal lithologies generated the K-feldspar granites. It is argued that the Baoji pluton formed in a late-collision setting.

Online enhancements: supplemental tables.

Introduction

The Qinling orogenic belt (QOB) records a number of geological processes, such as rifting, oceanic basin formation and destruction, continental growth and collision, and intracontinental deformation (e.g., Mattauer et al. 1985; Zhang et al. 1995, 1996; Wang et al. 2013; Li et al. 2015). Based on present knowledge, the buildup of the QOB involved at least three tectono-magmatic cycles that took place during the Neoproterozoic, Paleozoic, and Mesozoic eras. Each period was associated with extensive granitic magmatism (e.g., Lu et al. 1996; Wang et al. 2013, 2015; Dong et al. 2015b; Zhang et al. 2016).

Granitoids of the Mesozoic orogenic cycle are widely distributed in the QOB and are particularly abundant along the Shangdan suture (SDS in fig. 1). This magmatism is related to the early Mesozoic collision between the North China and South China blocks (NCB and SCB, respectively). U-Pb age data have manifested two distinct periods of magmatism during the early Mesozoic, one between 250 and 234 Ma and one between 225 and 200 Ma (Dong et al. 2011b, 2015a; Wang et al. 2013, 2015; Chen and Santosh 2014).

In many places, the geochemistry of granitoids has been employed to infer the tectonic setting. In the QOB, however, there is still considerable controversy about the relation between granite composition and regional tectonism. Zhang et al. (2001) have suggested that the Mesozoic granitoids are mainly subduction related, while others have advocated that they were formed in a collisional stage and can be divided into syncollisional and postcollisional rocks.
(e.g., Lu et al. 1996; Sun et al. 2002; J. Zhang et al. 2002b; C. Zhang et al. 2008; Wang et al. 2011). In this study, we address this issue through a combination of systematic geochemical and geochronological data on the granitoid rocks of the Baoji pluton. The currently available information is insufficient to determine the origin of the melts and the temporal relations between the various intrusions. Here we present zircon U-Pb ages and Lu-Hf isotopic, bulk-rock geochemical, and Sr-Nd-Pb isotopic compositions for the intrusive members of the Baoji pluton. Combining these with data collected from previous studies, we aim to decipher the detailed sequence of emplacement ages and the source(s) of melting. Finally, several tectonic settings are evaluated in the light of the new results.

Geological Background

The QOB connects the Dabie high-pressure–ultrahigh-pressure (UHP) terrane in the east and the Qilian and Kunlun Mountains in the west (fig. 1). The orogen formed by multistage collision of the NCB and the SCB as well as intervening microblocks [e.g., Meng and Zhang 1999, 2000; Zhang et al. 2001; Dong et al. 2015b]. The QOB is bounded by the Lingbao-Lushan-Wuyang fault in the north and the Mianlue, Bashan, and Xiangguang faults in the south (fig. 1). Two ophiolitic melange suture zones, the early Paleozoic Shand'an and the Paleozoic–Early Triassic Mianlue zones, are well documented in the QOB (fig. 1). On the basis of these faults and suture zones, the QOB has been subdivided into four tectonic units from north to south: the southern margin of the NCB, the North Qinling belt (NQB), the South Qinling belt (SQB), and the northern margin of the SCB (NSCB; e.g., Mattauer et al. 1985; Meng and Zhang 2000; Zhang et al. 2001; Dong et al. 2015b).

The Baoji pluton is one of the largest plutons in the QOB, covering an area of more than 1500 km² in Shaanxi Province. It is located between East and West Qinling (fig. 1) in the NQB and shows an east-west elongation (fig. 2). It is a composite pluton and can be subdivided into several discrete intrusions of different composition. The pluton was emplaced into Ordovician and Carboniferous sedimentary country rocks. According to Yan (1985) and BGMRS (1989), it consists of four different facies types. A granodiorite with phenocrysts of alkali feldspars (1–3 cm in diameter; fig. 3a, 3b) occurs at the eastern and southern margins (fig. 2). A medium- to coarse-grained mafic microgranular enclave (MME)-bearing monzogranite (fig. 3c, 3d) and a fine- to medium-grained monzogranite with few MMEs (fig. 3d) both crop out...
in an intermediate zone. Locally, bodies of quartz monzodiorites (a few hundred square meters in size) are exposed within the monzogranites (fig. 3e). A medium- to coarse-grained aphyric K-feldspar granite dominates in the center of the intrusion (fig. 3f). Common accessory minerals in these rocks include apatite, titanite, magnetite, ilmenite, epidote, and zircon (fig. 4).

In an earlier study, Triassic zircon U-Pb ages of 206.4 ± 1.7 and 211.3 ± 1.3 Ma were obtained for the fine- to medium-grained monzogranites and the medium- to coarse-grained monzogranites of the Baoji pluton, respectively (Zhang et al. 2006). Using zircon laser ablation ICP-MS analyses, Liu et al. (2011) obtained slightly different ages for a biotite granite (216 ± 1 Ma) and a monzogranite (212 ± 2 Ma) from the Baoji pluton.

Petrography of Samples

Twenty-one representative whole-rock samples were collected for chemical analyses from the Baoji pluton. These comprise two granodiorites, 13 monzogranites, four aphyric K-feldspar granites, and two quartz monzodiorites. The granodiorites display medium- to coarse-grained porphyritic texture and are composed of quartz (25%–30%), plagioclase (35%–45%), alkali feldspar (15%–20%), biotite (7%–10%), and hornblende (5%), together with zircon and apatite as accessory minerals. Phenocrysts in the granodiorites are idiomorphic or hypidiomorphous alkali-feldspar crystals (1–3 cm in diameter). The granodiorite also hosts numerous MMEs (fig. 3a, 3b).

The texture of the monzogranites changes from medium-to-coarse grained (six samples) to fine-to-medium grained (seven samples). The medium- to coarse-grained samples contain MMEs (fig. 3c, 3d) and a small amount of idiomorphic or hypidiomorph K-feldspar phenocrysts (1–2 cm in diameter) and are composed mainly of quartz (25%–30%), plagioclase (20%–30%), alkali feldspar (40%–45%), biotite (5%), and hornblende (3%). Compared to the medium- to coarse-grained monzogranites, the fine- to medium-grained monzogranites (fig. 3d) are aphyric and have lower alkali-feldspar content (35%–40%) and fewer
MMEs. Field observations show that the fine- to medium-grained monzogranites intruded into the medium- to coarse-grained monzogranites (Fig. 3d). On the other hand, intrusive contacts between monzogranites and granodiorites were not exposed.

The quartz monzodiorites show fine-grained granular texture and are mainly composed of plagioclase (~30%), alkali feldspar (~15%), biotite (20%–25%), hornblende (10%–15%), and quartz (~10%; Fig. 3e). In the field, quartz monzodiorites are closely associated
Figure 4. Photomicrographs of typical minerals from the Baoji granitoids: a, microline with tartan twinning under cross-polarized light; b, plagioclase with albite twins under cross-polarized light; c, amphibole, epidote, and biotite from quartz monzodiorite under plane-polarized light; d, amphibole and titanite from quartz monzodiorite under plane-polarized light; e, quartz, microline, plagioclase, biotite, titanite, and ilmenite from K-feldspar granite under plane-polarized light; f, microline and apatite from monzogranite under plane-polarized light. A color version of this figure is available online.
with the monzogranites, although contacts between the two rock types were nowhere observed.

The aphyric K-feldspar granites are light red and show medium- to coarse-grained granitic texture and massive structure. They are mainly composed of quartz (20%–30%), plagioclase (25%–30%), alkali feldspar (40%–45%), biotite (5%–15%), and hornblende (3%). Occasionally, K-feldspar granites intruded the granodiorites (fig. 3d).

**Analytical Techniques**

Zircon grains from 11 granitoid samples were isolated with standard heavy-liquid and magnetic mineral-separation techniques, handpicked under a binocular microscope, mounted in epoxy resin, and then polished to expose the crystal centers. For initial screening, all grains were examined by transmitted- and reflected-light microphotography. In order to determine the internal textures and the most suitable analytical positions, the zircons were photographed under cathodoluminescence (CL) on a scanning electron microscope. The CL image acquisition, U-Pb dating, and trace-element analyses were accomplished at the Key Laboratory of Crust-Mantle Materials and Environments, University of Science and Technology of China (USTC). U-Pb analyses were accomplished with an ArF excimer laser ablation system (193-nm wavelength), which was connected to an Agilent 7700E ICP-MS instrument. Standard zircon 91500 was used as an external standard for calibration of the U-Pb ages. The diameter of the laser ablation spot was 32 μm, with a laser frequency of 10 Hz and sometimes 6 Hz where necessary. Each analysis incorporates c. 20 s of background acquisition (gas blank) followed by 40 s of data acquisition from the sample and another 20 s of background acquisition. Every four-sample analysis was followed by one analysis of zircon 91500 in order to correct the time-dependent drift of sensitivity and mass discrimination. More details on the analytical procedure are given in Liu et al. (2007).

Element concentrations of zircon were calibrated against the NIST (National Institute of Standards and Technology) glasses 610, 612, and 614, and NIST610 was measured twice every 10 sample spots. Off-line evaluation and integration of signal to background, time-drift correction and quantitative calibration for trace-element analyses and U-Pb dating, as well as common-lead correction, were processed with the free software ICPMSDataCal 9.2 [Liu et al. 2008, 2010]. Correction factors were used for each sample to correct both instrumental mass bias and elemental and isotopic fractionation. Concordia diagrams and weighted mean calculations were done with Isoplot 4.15 [Ludwig 2009]. More than 20 spot analyses were carried out on the samples; the results are reported at the 1σ level, and uncertainties and the weighted mean ages are quoted at the 95% confidence level.

For whole-rock major- and trace-element analyses, rock samples were split into small chips and then powdered to less than 200 μm. Major elements were measured by X-ray fluorescence at ALS Minerals–ALS Chemex in Guangzhou. Loss on ignition [LOI] was analyzed by gravimetric methods using an electronic balance. Analytical uncertainties of major elements were better than 1%. Trace-element concentrations were determined on an Elan 6100 DRC ICP-MS at the Key Laboratory of Crust-Mantle Materials and Environments. About 50 mg of bulk-rock powder was weighed into a Teflon bomb for analyses, and Rh was used as the internal standard solution. Precision is better than 5% for most trace elements. More details on the ICP-MS analytical procedures are given in Hou and Wang (2007).

Rb-Sr, Sm-Nd, and Pb isotope analysis on whole-rock samples was performed in the Laboratory for Radiogenic Isotope Geochemistry, USTC. Parent and daughter nuclides were isolated from each other by standard chromatographic separation techniques. Isotope composition was measured on a Finnigan MAT-262 spectrometer. Pb was loaded with silica gel on preconditioned Ta filaments. Sr was loaded with a Ta-HF activator on preconditioned Ta filaments. Nd was loaded as phosphate on preconditioned Re filaments. Sr and Nd isotopic ratios were corrected for mass fractionation relative to 86Sr/88Sr of 0.1194 and 146Nd/144Nd of 0.7219, respectively. Standard solutions of NBS987 for Sr and La Jolla for Nd were measured during analyses. Precision of 87Sr/86Sr and 147Sm/144Nd ratios is better than 0.5%. Precision of the measured Pb isotopic ratios is better than 0.01%. Analytical precisions are stated as 2σ standard errors, and details of analytical technique are described in Chen et al. (2000, 2007).

Four samples (BJ13-05, BJ13-12, BJ13-14A, and BJ13-22B) were chosen for Hf isotope analyses. In situ zircon Lu-Hf isotopic analyses were performed on a Neptune multicollector ICP-MS equipped with a Geolas-193 laser ablation system at the Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing. Reference materials GJ-1 ([176Hf/177Hf] of 0.282020) and MUD ([176Hf/177Hf] of 0.282500) were selected for external calibration, and the ablation diameter was c. 40–60 μm. More details of the instrument parameters, analysis procedure, and interference correction are given in Xu et al. (2004) and Wu et al. (2006).
Analytical Results

**Zircon U-Pb Ages.** Eleven samples from four different rock types from the Baoji pluton were selected for U-Pb zircon age dating. U-Pb dating results and representative CL images are presented in figures 5 and 6, and the isotopic data are given in table S1 (tables S1–S4 are available online). In the chondrite-normalized rare earth element (REE) diagram, all zircon grains show similar positive Ce and negative Eu anomalies and enrichment in heavy REEs (fig. 5l).

Samples BJ13-03, BJ13-04, BJ13-10B, BJ13-12, BJ13-13, and BJ13-17A are from monzogranites of the intermediate part of the pluton (BJ13-03, BJ13-04, and BJ13-13 are fine grained, and the others are coarse grained). Zircons from these samples are short to long prismatic, subeuhedral to euhedral, and light yellow to colorless. Crystal lengths range from 100 to 250 μm.

**Figure 5.** a–k, U-Pb concordia diagrams with weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages; l, chondrite-normalized rare earth element diagram for zircon grains from the Baoji pluton. Kf-granite = K-feldspar granite. A color version of this figure is available online.
with aspect ratios from 1:1 to 1:4.5. The grains show oscillatory zoning in CL images (fig. 6a, 6b). Twenty zircons from sample BJ13-03 were analyzed and yielded Th contents of 52–652 ppm, U contents of 78–988 ppm, and Th/U ratios between 0.31 and 1.38. The U-Pb ages of the 20 analytical spots vary from 217 to 206 Ma, giving a weighted mean $^{206}$Pb/$^{238}$U age of 209.5 ± 1.7 Ma and an MSWD value of 1.5 (fig. 5a). Twenty-four spots from sample BJ13-04 have Th contents of 39–639 ppm and U contents of 104–1011 ppm, with Th/U ratios between 0.30 and 1.08. Their $^{206}$Pb/$^{238}$U ages range from 224 to 207 Ma, giving a weighted mean $^{206}$Pb/$^{238}$U age of 214.9 ± 1.6 Ma (MSWD = 1.3; fig. 5b). Zircons from sample BJ13-10B have Th contents of 78–681 ppm and U contents of 338–1693 ppm, with Th/U ratios from 0.13 to 0.76. Twenty-two spots yield $^{206}$Pb/$^{238}$U ages between 220 and 202 Ma, with a weighted mean of

Figure 6. Cathodoluminescence images of representative zircon grains chosen for laser ablation ICP-MS U-Pb and Lu-Hf analyses. The grains commonly show oscillatory zoning of magmatic origin. Laser ablation spot size was c. 44 μm. $^{206}$Pb/$^{238}$U age and initial $\varepsilon_{Hf}$ values are given beside and in white circles, respectively. A color version of this figure is available online.
211.7 ± 2.3 Ma [MSWD = 2.9; fig. 5c]. Zircon grains from sample BJ13-12 have variably high Th [116–989 ppm] and high U [316–2557 ppm] contents, with Th/U ratios varying from 0.36 to 1.22. Twenty-four zircon grains of this sample display 206Pb/238U ages between 220 and 205 Ma, with a weighted mean age of 212.3 ± 1.8 Ma [MSWD = 2.2; fig. 5d]. Twenty-nine zircon grains of sample BJ13-13 yield relatively low Th [62–531 ppm] and U [170–1185 ppm] contents, with Th/U ratios of 0.25–1.05. The U-Pb ages vary from 223 to 208 Ma, yielding a weighted mean 206Pb/238U age of 212.9 ± 1.7 Ma and an MSWD value of 1.4 [fig. 5e]. Nineteen analytical spots from sample BJ13-17A have high and variable abundances of Th [274–3396 ppm] and U [487–5465 ppm; one spot has 11,390 ppm], with Th/U ratios varying from 0.31 to 1.38. The U-Pb ages vary from 227 to 202 Ma, yielding a weighted mean 206Pb/238U age of 214.6 ± 3.2 Ma [MSWD = 4.5; fig. 5f].

Sample BJ13-14A comes from a granodiorite close to the margin of the pluton. Zircon grains of this sample are prismatic, transparent, mostly euhedral, and colorless. In CL images, most grains show oscillatory magmatic zoning (fig. 6c), a characteristic of magmatic origin. They have lengths of 200–400 m in length, with aspect ratios between 1:2 and 1:4, and show oscillatory zoning (fig. 6d). Zircon grains from this granite type have high Th [131–2812 ppm] and high U [311–4120 ppm] contents, with Th/U ratios varying from 0.16 to 1.58. A weighted mean age of 194.3 ± 4.1 Ma was obtained from 28 analyses on zircon grains from sample BJ13-20 [fig. 5g]. Twenty-three grains of sample BJ13-21 yield a weighted mean age of 198.1 ± 2.0 Ma, with an MSWD of 2.3 [fig. 5h]. Sixteen zircon grains of sample BJ13-22B have 206Pb/238U ages ranging from 203 to 191 Ma, giving a weighted mean age of 195.1 ± 2.0 Ma [MSWD = 1.6; fig. 5i].

Zircons from quartz monzodiorite sample BJ13-05 are transparent, mostly subeuhedral to euhedral in morphology, and light yellow. The grains are more than 180 μm in length, with aspect ratios between 1:1 and 1:1.5. Most zircons display oscillatory magmatic zonings [fig. 6e], and they have relatively variable Th [52–2058 ppm] and U [116–1133 ppm] contents, with Th/U ratios ranging from 0.36 to 1.82. Twenty-nine zircon grains of sample BJ13-05 were analyzed, and the U-Pb ages of 20 analytical spots vary from 221 to 206 Ma, yielding a weighted mean 206Pb/238U age of 212.6 ± 1.6 Ma [MSWD = 2.8; fig. 5k].

**Whole-Rock Major- and Trace-Element Composition.** Whole-rock major- and trace-element data for 21 granitoid samples of the Baoji pluton are given in table S2. The LOI ranges from 0.38 to 1.42 wt%. In the R1-versus-R2 diagram, most samples plot in the syenogranite and monzogranite fields [fig. 7a]. In the silica-versus-K2O diagram, the samples define a high-K calc-alkaline to shoshonitic trend [fig. 8b]. Samples from the Baoji granodiorite have high-K calc-

![Figure 7](image-url)
alkaline and metaluminous compositions (fig. 7b), with SiO₂ contents of 62.3–66.2 wt%, A/CNK [molar Al₂O₃/(CaO + Na₂O + K₂O)] values of 0.86–0.90, MgO contents of 2.1–2.8 wt%, and Mg# [100 × Mg molar/(Mg molar + Fe²⁺ molar)] of 56–58. They show high total-alkali contents [Na₂O + K₂O of 7.6], with K₂O/Na₂O ratios of 0.76–0.95, and high Sr contents (522–616 ppm), low Yb contents (1.78–1.92 ppm), and

Figure 8. Harker variation diagrams of some major oxides and trace elements for granitoids from the Baoji pluton. SiO₂-versus-K₂O diagram is modified after Peccerillo and Taylor [1976] and Middlemost [1994]. I-type trend is according to Chappell [1999], and symbols are the same as in figure 7. A color version of this figure is available online.
low Y contents (21.1–23.0 ppm), resulting in high Sr/Y ratios of 24.7–26.8. In addition, the granodiorites show a positive Pb anomaly and are enriched in large-ion lithophile elements (LILEs) and depleted in high-field-strength elements (HFSEs; fig. 9a). Chondritenormalized REE patterns show enrichment in light over heavy REEs (fig. 9b), with \([\text{La}/\text{Sm}]_\text{N}\) of 3.9–4.2 and \([\text{La}/\text{Yb}]_\text{N}\) of 16.2–16.7. The granodiorites display a weak negative Eu anomaly, with \(\text{Eu}/\text{Eu}^*\) (\(\text{Eu}_\text{N}/\{\text{Sm}_\text{N} \times \text{Gd}_\text{N}\}^{1/2}\)) of 0.62–0.64.

Compared to granodiorites, monzogranites have higher silica and alkali contents: 69.4–74.0 wt% SiO₂ and 8.1–8.8 wt% total alkalis \(\{\text{Na}_2\text{O} + \text{K}_2\text{O}\}\). K₂O/Na₂O ratios vary from 0.90 to 1.38; most samples show K₂O/Na₂O ratios of >1, except sample BJ13-24, which has a low K₂O concentration. The monzogranites are metaluminous to weakly peraluminous \(\{A/\text{CNK} \text{ of } 0.98–1.08\}\). They show lower MgO contents, from 0.20 to 1.12 wt%, and Mg# values varying from 31 to 51. Compared to granodiorites, the monzogranites have lower Sr contents (141–469 ppm), low Yb contents (0.26–2.83 ppm), and variable Y contents (3.92–30.4 ppm), resulting in variable Sr/Y ratios of 4.6–120. On the primitive mantle-normalized trace-element diagram, they are characterized by enrichment in LILEs, depletion in Nb and Ta, and positive Pb and negative Ti and P anomalies (fig. 9a). The chondrite-normalized REE patterns show enrichment in light REEs over heavy REEs (fig. 9b), with \([\text{La}/\text{Sm}]_\text{N}\) of 3.04–6.41 and \([\text{La}/\text{Yb}]_\text{N}\) of 6.59–67 (mean values are 5.09 and 26.60, respectively). They show negative Eu anomalies, with \(\text{Eu}/\text{Eu}^*\) of 0.33–0.84.

The composition of the two quartz monzodiorite samples differs from that of the other rocks in that they have low SiO₂ (53.2 and 53.4 wt%), high Na₂O + K₂O (8.19 and 8.31 wt%), and high K₂O/Na₂O ratios (5.5 and 9.5). They are strongly metaluminous \(\{A/\text{CNK} \text{ of } 0.55 \text{ and } 0.59\}\) and have high MgO (6.49 and 6.74 wt%) and Mg# (67 and 71). Sr, Y, and Yb contents (898 and 1360, 21.7 and 24.7, and 1.52 and 1.78 ppm, respectively) are higher than those in

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**Figure 9.** Primitive mantle-normalized trace-element spider diagrams \(\{\text{left}\}\) and chondrite-normalized rare earth element patterns \(\{\text{right}\}\) for granoids from the Baoji pluton. \(a, b\), Data for granodiorites, monzogranites, and quartz monzodiorites; \(c, d\), Data for K-feldspar granites. Normalization values are from Sun and McDonough [1989] and McDonough and Sun [1995], and the symbols are the same as in figure 7. A color version of this figure is available online.
the other rock types, and Sr/Y ratios are 36 and 63. On a mantle-normalized trace-element diagram, they show positive Ba, K, Pb, and P and negative Nb and Ta anomalies (fig. 9a). Light over heavy REE enrichment and weakly positive Eu anomalies \((\text{Eu/Eu}^*)\) of 1.06 and 1.09) are further characteristics of the quartz monzodiorites (fig. 9b).

The K-feldspar granites have a narrow silica range (\(\text{SiO}_2\) contents of 72.6–73.3 wt%) and \(\text{Na}_2\text{O} + \text{K}_2\text{O}\) (8.43–8.73 wt%), with high \(\text{K}_2\text{O}/\text{Na}_2\text{O}\) ratios, ranging from 1.36 to 1.49. They are weakly peraluminous, with A/\(\text{CNK}\) of 0.99–1.10. These samples show low MgO, from 0.25 to 0.41 wt%, and Mg\# varies from 31 to 34. They have 158–215 ppm Sr, 1.29–4.08 ppm Yb, and 16.5–36.8 ppm Y, resulting in low Sr/Y ratios, between 4.68 and 13.04. On a mantle-normalized trace-element diagram, they show negative Nb, Ta, P, and Ti and positive Rb, Th, K, La, and Nd anomalies (fig. 9c). Chondrite-normalized REE patterns of the granites are characterized by moderate enrichment in light REEs, nearly flat heavy REEs, and negative Eu anomalies (\(\text{Eu/Eu}^*/\text{C}^3\)) of 0.31–0.59 (fig. 9d).

Whole-Rock Sr-Nd-Pb Isotopic Composition. Sr, Nd, and Pb isotopic compositions of the granitoid samples are given in table S3. Initial \(^{87}\text{Sr}/^{86}\text{Sr} (I_{\text{Sr}})\) and \(^{143}\text{Nd}/^{144}\text{Nd} (I_{\text{Nd}})\) ratios and initial \(\varepsilon_{\text{Nd}}\) values are calculated on the basis of the zircon age record. Granodiorites, monzogranites, and contemporaneous quartz monzodiorites of the Baoji pluton have almost the same initial Sr-Nd isotopic compositions, different from those of the younger K-feldspar granites (fig. 10a).

The \(^{87}\text{Rb}/^{86}\text{Sr} (I_{\text{Sr}})\) ratios of the granodiorites range from 0.48 to 0.61, and the \(^{87}\text{Sr}/^{86}\text{Sr} (I_{\text{Sr}})\) ratios vary from 0.7074 to 0.7077. The \(I_{\text{Sr}}\) ratios vary from 0.7058 to 0.7059. The \(^{147}\text{Sm}/^{144}\text{Nd} (I_{\text{Nd}})\) ratios range from 0.1030 to 0.1044, and the \(^{143}\text{Nd}/^{144}\text{Nd} (I_{\text{Nd}})\) ratios vary between 0.512200 and 0.512212. The \(I_{\text{Nd}}\) ratios and initial \(\varepsilon_{\text{Nd}}\) values range from 0.512052 to 0.512065 and from −6.0 to −5.7, respectively (fig. 10a). Two-stage model ages \((T_{\text{DM}2})\) cluster around 1.5 Ga. The samples show the following initial Pb isotope ratios: \(^{206}\text{Pb}/^{204}\text{Pb}\) of 17.72–17.84, \(^{207}\text{Pb}/^{204}\text{Pb}\) of 15.54–15.55, and \(^{208}\text{Pb}/^{204}\text{Pb}\) of 37.91–37.95 (fig. 11).

Monzogranites have higher \(^{87}\text{Rb}/^{86}\text{Sr} (I_{\text{Sr}})\) ratios (0.67–4.33) and higher \(^{87}\text{Sr}/^{86}\text{Sr} (I_{\text{Sr}})\) ratios (0.7085–0.7204) than the granodiorites, and they have variable \(I_{\text{Sr}}\) ratios (0.7050–0.7083). The \(^{147}\text{Sm}/^{144}\text{Nd} (I_{\text{Nd}})\) ratios vary from 0.0905 to 0.1286, and the \(^{143}\text{Nd}/^{144}\text{Nd} (I_{\text{Nd}})\) ratios range from 0.511845 to 0.512412. The \(I_{\text{Nd}}\) ratios and initial \(\varepsilon_{\text{Nd}}\) values range from 0.511716 to 0.512236 and from −12.6 to −2.5, respectively (fig. 10a). The \(T_{\text{DM}2}\) model ages are between 1.2 and 2.1 Ga. The initial Pb isotope composition of the monzogranites is similar to that of the granodiorites \((^{206}\text{Pb}/^{204}\text{Pb}\) of 17.50–18.21, \(^{207}\text{Pb}/^{204}\text{Pb}\) of 15.50–15.63, and \(^{208}\text{Pb}/^{204}\text{Pb}\) of 37.79–38.39; fig. 11).

The \(^{87}\text{Rb}/^{86}\text{Sr} (I_{\text{Sr}})\) ratios of the two quartz monzodiorites are 0.22 and 0.54, and the \(^{87}\text{Sr}/^{86}\text{Sr} (I_{\text{Sr}})\) ratios are 0.7084 and 0.7093, while their \(I_{\text{Sr}}\) ratios are almost constant at ~0.7077. The quartz monzodiorites have \(^{147}\text{Sm}/^{144}\text{Nd} (I_{\text{Nd}})\) ratios of 0.0984 and 0.1000 and \(^{143}\text{Nd}/^{144}\text{Nd} (I_{\text{Nd}})\) ratios of 0.511967 and 0.512039. The \(I_{\text{Nd}}\) ratios and initial \(\varepsilon_{\text{Nd}}\) values are 0.511828 and

Figure 10. a, Initial \(^{87}\text{Sr}/^{86}\text{Sr} (I_{\text{Sr}})\) ratios versus initial \(\varepsilon_{\text{Nd}}\) values for the Baoji pluton. Fields for the Qinlin Group, the Kuanping Group, the Bikou Group, the Yaolinghe Group, and the Triassic granitoid rocks from western Qinling terrain are based on the data from Zhang et al. (2006), Z. Qin et al. (2015), J. F. Qin et al. (2013), Luo et al. (2012), and references therein. b, Initial \(\varepsilon_{\text{Nd}}\) values versus \(^{206}\text{Pb}/^{238}\text{U}\) ages of zircons from the Baoji pluton. Data are from this study and Wang et al. (2011), Qin et al. (2009), and Zhang et al. (2006). Kf-granite = K-feldspar granite; MMEs = mafic microgranular enclaves; MORB = mid-ocean ridge basalt; NQB = North Qinling belt.
The TDM2 values are 1.8 and 1.9 Ga, and the average initial Pb ratios are 17.53 for $^{206}\text{Pb}/^{204}\text{Pb}$, 15.51 for $^{207}\text{Pb}/^{204}\text{Pb}$, and 37.99 for $^{208}\text{Pb}/^{204}\text{Pb}$ (fig. 11).

**Zircon Hf Isotopic Composition.** Zircon Hf isotopic analyses were performed on one sample of each granitoid type. Analytical results are given in table S4, and data are shown in figure 10b. Initial $\varepsilon_{\text{Hf}(t)}$ values are calculated back to the average zircon crystallization age from each sample. Initial $\varepsilon_{\text{Hf}(t)}$ values exhibit a wide range, from weakly positive to strongly negative.

Thirty-seven zircon analyses on granodiorite sample BJ13-14A give initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of 0.282534–0.282568. Most spots have low $\varepsilon_{\text{Hf}(t)}$ values, from −3.6 to −0.2, and $T_{\text{DM2}}$ values from 1.19 to 1.49 Ga; only one spot has a positive $\varepsilon_{\text{Hf}(t)}$ value of 1.1 and a model age of 0.87 Ga.

Initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of 27 analytical spots on monzogranite sample BJ13-12 vary from 0.282604 to 0.282766. Most analyses show slightly positive $\varepsilon_{\text{Hf}(t)}$ values between 0.1 and 4.4, with $T_{\text{DM1}}$ values of 0.69–0.91 Ga, while three spots have negative $\varepsilon_{\text{Hf}(t)}$ values of −0.3, −0.7, and −1.3, with $T_{\text{DM2}}$ values of 1.27, 1.29, and 1.33 Ga.

Thirty analyses were done on zircon grains of quartz monzodiorite sample BJ13-05. Their initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios range from 0.282213 to 0.282376, and initial $\varepsilon_{\text{Hf}(t)}$ values are generally lower than those of the other granitoids, ranging from −15.1 to −9.3, corresponding to two-stage Hf model ages ($T_{\text{DM2}}$) of 1.84–2.20 Ga.

**Discussion**

**Emplacement Age of the Baoji Pluton.** Magmatic zircons from the Baoji granitoids yield weighted U-Pb ages of ~217 Ma for granodiorites, ~212 Ma for monzogranites and quartz monzodiorites, and ~196 Ma for K-feldspar granites. Previous dating studies on these granitoids reported U-Pb zircon ages between 217 and 210 Ma (Lu et al. 1999; Zhang et al. 2006; Liu et al. 2011; Wang et al. 2011). Combining these age data, we suggest that the Baoji pluton formed as a nested diapir during stepwise magma accumulation at 217 Ma (granodiorite), 212 Ma (monzogranite and quartz monzodiorite), and 196 Ma (K-feldspar granite), as shown in figure 12. Thereby, the Baoji pluton displays a pattern of decreasing ages from the margin to the center (fig. 2): granodiorites occur at the rim of the pluton, biotite monzogranites and quartz monzodiorites constitute the main body, and K-feldspar granites occur in the center of the pluton.
Petrogenesis of the Baoji Pluton. Genetic Classification. The granodiorites are low in Si (SiO$_2 < 67$ wt%) and metaluminous (Fig. 7b). They show the mineral assemblage amphibole + biotite and lack aluminous mineral phases such as muscovite, garnet, cordierite, and tourmaline (Barbarin 1999; Fig. 4), indicating that they are I-type granitoids (Chappell and White 1992; Chappell 1999; Li et al. 2007).

The majority of monzogranite samples are metaluminous to weakly peraluminous, with relatively low A/CNK values (<1.1; Fig. 7b) and high total-alkali contents (Na$_2$O + K$_2$O > 8 wt%). Mostly, monzogranites have high SiO$_2$ contents (>71 wt%), and some are hornblende free. They display a negative correlation between P$_2$O$_5$ and SiO$_2$ and a positive correlation between Pb and SiO$_2$ (Fig. 8i, 8j). The monzogranite samples also show increases in Y and Th with increasing Rb, typical of the I-type granite evolution trend (table S2; Li et al. 2007).

The K-feldspar granites are evolved in composition, and their major-element compositions are difficult to distinguish from those of fractionated monzogranites. They are metaluminous to peraluminous, with high SiO$_2$ and total-alkali contents (SiO$_2 > 72$ wt%; Na$_2$O + K$_2$O > 8 wt%). Most K-feldspar granites have relatively high Zr + Nb + Ce + Y (242–456 ppm) and 10000Ga/Al (2.4–3.1) but moderate FeO$_T$/MgO (4.4–5.0) and [K$_2$O + Na$_2$O]/CaO (6.5–12.0), plotting in both the fractionated granite and A-type granite fields (diagrams not shown), which means that the K-feldspar granites have characteristics of both I- and A-type granites.

Magma Mixing and Origin of the MMEs. The ubiquitous mafic enclaves in granitic magmas record interactions of different types of magma (Collins et al. 2000). The MMEs are generally considered to form by mixing and mingling processes involving mafic and felsic magma (Qin et al. 2009 and reference therein). According to previous studies, MMEs observed in QOB early Mesozoic granitoids show typical igneous texture, with feldspar megacrysts (K-feldspar and plagioclase, compositionally similar to that in host granitoids), and contain acicular apatites. The MMEs have low SiO$_2$ content [mainly <57 wt%], high Nb/Ta ratios, and high Mg# but lower MgO, TiO$_2$, and Cr contents, indicating that they were probably derived from partial melting of mantle materials and underwent fractional crystallization and crustal assimilation processes during magma emplacement. Compared to the host granitoids, the MMEs have a similar mineral assemblage, trace-element geochemistry, and initial Sr-Nd isotopic composition but a quite lower A/CNK value. Zircons from the MMEs display large variation in $\varepsilon$Hf values (from −11.0 to 8.2), and most MMEs have a negative zircon $\varepsilon$Hf(t), with a Neoproterozoic Hf model age (Qin et al. 2009, 2010; Wang et al. 2011; Duan et al. 2016). These features suggest that the MMEs are probably derived from an ancient, enriched lithosphere mantle and underwent magma mixing and assimilation.
mixing. Therefore, we propose that the presence of MMEs in the Baoji pluton indicates magma-mixing processes.

Origin and Source Nature of the Granitoids. The granodiorites have relatively low Sr/Y and (La/Yb)N ratios (fig. 13a, 13b) and concave chondrite-normalized REE patterns, suggesting that amphibole was the dominant mineral in source rocks (fig. 9a, 9b). The high Sr concentrations and slightly negative Eu anomalies indicate that plagioclase was not a major residual phase. The granodiorites display low AMF (Al2O3/(MgO + FeOT)) and CMF (CaO/(MgO + FeOT)) values of 1.17–1.42 and 0.57–0.58, respectively, implying the derivation of their precursors mainly from metabasaltic to metatonalitic rocks (fig. 13d). The low Iα ratio (0.7058), negative εNd(t) (−6.0), and negative to slightly positive zircon εHf(t) (−3.6 to 1.1), coupled with two-stage Nd model ages of 1.5 Ga and two-stage Hf model ages of 1.2–1.5 Ga (fig. 10a, 10b), suggest that the magma was mainly derived from Mesoproterozoic crustal materials. Prouteau et al. (2001) and Gao et al. (2004) argued that the high Mg# in intermediate to felsic melts are produced from a lithospheric mantle metasomatized by silica-rich melts or fluids or from ancient mafic lower continental crust that foundered into the mantle and subsequently melted and interacted with mantle peridotite. The Mg# values (56–

![Discrimination diagrams for granitoid rocks from the Baoji pluton.](image)

Figure 13. Discrimination diagrams for granitoid rocks from the Baoji pluton. a, b, Sr/Y-versus-Y (a) and chondrite-normalized [La/Yb]N-versus-YbN (b) diagrams for granitoid rocks, compared to adakite and classical island arc/normal arc magmatic rock, after Atherton and Petford (1993) and Petford and Atherton (1996). Chondrite values are from Sun and McDonough (1989). MORB = mid-ocean ridge basalt. c, Mg#-versus-SiO2 diagram, modified after Stern and Kilian (1996). The fields are shown for partial melts of crust obtained from experimental studies by dehydration melting of low-K basaltic rocks at 8–16 kbar and 1000–1050°C (Rapp and Watson 1995) and of moderately hydrous (1.7–2.3 wt.% H2O) medium- to high-K basaltic rocks at 7 kbar and 825–950°C (Sisson et al. 2005). d, Molar Al2O3/(MgO + FeO) versus CaO/(MgO + FeO) diagram showing source composition for granitoid rocks of the Baoji pluton, modified after Altherr et al. [2000]. A color version of this figure is available online.
of granodiorites are much higher than those of experimental basaltic melts (Mg# < 45; Rapp and Watson 1995), and they plot above the experimental melts derived from the partial melting of pure crustal materials or basalts and amphibolites, suggesting the involvement of mantle material (fig. 13c). Besides, the presence of MMEs in the granodiorites indicates that these rocks were probably created by partial melting of mafic lower crust, with contributions from the uppermost lithospheric mantle (Li et al. 2015 and references therein).

The monzogranites have relatively higher Sr/Y and (La/Yb)\textsubscript{N} ratios (fig. 13a, 13b). Fractionated REE patterns and moderate negative Eu and Sr anomalies (fig. 9a, 9b) suggest that the magma was probably generated by an amphibole dehydration reaction, leaving a plagioclase-enriched residue (Sisson et al. 2005). Partial melting of hydrous, mafic to intermediate metamorphic rocks in the crust can produce medium- to high-K calc-alkaline granitic magmas (Roberts and Clemens 1993). Dehydration partial-melting experiments of intermediate to felsic rocks ([SiO\textsubscript{2} = 59–70 wt%, A/\text{CNK} = 0.90–1.04] performed under mid-crustal pressures ([1.0–3.2 GPa] can generate granitic melts that have relatively high A/\text{CNK} ratios ([1.03–2.07] and high SiO\textsubscript{2} contents (>70%); Skjerlie and Johnston 1993). The Baoji monzogranites are met-aluminous to weakly peraluminous, with high K\textsubscript{2}O contents, Na\textsubscript{2}O/K\textsubscript{2}O < 1, SiO\textsubscript{2} concentrations ranging from 69.4 to 74.0 wt%, and A/\text{CNK} ratios ranging from 0.98 to 1.08. In the AMF-versus-CMF diagram, they plot in the range of metagreywacke partial melting ([fig. 13d]). Consequently, the Baoji monzogranites were likely derived from intermediate to felsic sources, probably from the partial melting of metagreywacke. Compared to the granodiorites, the monzogranites of the Baoji pluton have higher I\textsubscript{\text{Nd}} ratios (0.7050–0.7083) and lower \varepsilon\textsubscript{\text{Nd}}([t] [−12.6 to −2.5], with two-stage Nd model ages of 1.2–2.1 Ga [mostly <2.0 Ga; fig. 9a], suggesting that the magma was mainly derived from Meso- to Paleoproterozoic crustal materials. Most zircons display weakly positive \varepsilon\textsubscript{\text{Hf}}([t] ranging from 0.1 to 4.4, with single-stage Hf model ages of 0.7–0.9 Ga [fig. 10b], indicating more involvement of Neoproterozoic juvenile mafic crust or a mantle component in the source region. These characteristics and the presence of coeval quartz monzodiorites and MMEs suggest that the magma was mainly derived from Meso- to Paleoproterozoic crustal materials, with the involvement of a mantle source component.

In the Harker variation diagrams (fig. 8), monzodiorites and monzogranites show linear trends, suggesting that they may come from the same magma source and are related by fractional crystallization. This view is also supported by their overlapping Sr-Nd and zircon Hf isotopic compositions (fig. 10). In the \textsuperscript{87}Sr/\textsuperscript{86}Sr ([t]-versus-\varepsilon\textsubscript{\text{Nd}}([t]) diagram (fig. 10a), granodiorites and monzogranites display Sr-Nd isotope characteristics similar to those of Neoproterozoic Bikou and Yaolinghe metabasalts but distinct from those of the Qinling Group, the Kuaping Group, and the North Qinling basement. As shown in figure 11, the Pb isotope compositions of the granodiorites and monzogranites mainly plot in the region of the NSCB and the SQB, close to Neoproterozoic Bikou and Yaolinghe metabasalts. In this regard, the intrusions in Baoji probably record the contribution of crustal material of the Yangtze block.

The quartz monzodiorites have a hydrous mineral association of hornblende and biotite, indicating crystallization from water-saturated melts. They are characterized by high Sr, TiO\textsubscript{2}, and K\textsubscript{2}O concentrations but low Rb/Sr and Sr/Y ratios, suggesting that they were not significantly contaminated by the coeval monzogranite melt. The weakly positive Eu anomalies (fig. 9b) indicate plagioclase accumulation or derivation from a very primitive melt. The quartz monzodiorites are enriched in LILEs (particularly Ba and K) and light REEs and depleted in HFSEs [fig. 9a]. Th, light REEs, and HFSEs are mainly transported by the melt, whereas the LILs are effectivly more mobile in the presence of a fluid phase (e.g., Pearce and Peate 1995; Elliott et al. 1997). In addition, the quartz monzodiorites have negative \varepsilon\textsubscript{\text{Nd}}([t] and \varepsilon\textsubscript{\text{Hf}}([t] values and Paleoproterozoic Nd model ages. All these signatures suggest that the quartz monzodiorites formed by partial melting of a mantle that had been metasomatized (or enriched) by slab-derived fluids or melts.

The K-feldspar granites define colinear trends with the granodiorites and monzogranites (fig. 8). These rocks, however, have a Sr-Nd isotopic composition quite different from that of granodiorites and monzogranites, suggesting a distinct source. The K-feldspar granites display strongly evolved Sr-Nd isotopic composition (I\textsubscript{\text{Nd}} ratio of 0.7117 and \varepsilon\textsubscript{\text{Nd}}([t] of −13.5 to −17.2) and variable \varepsilon\textsubscript{\text{Hf}}([t] values ranging from −18.8 to −5.1. In the Sr-Nd isotope correlation diagram, the K-feldspar granites display high Sr-Nd isotopic composition (I\textsubscript{\text{Nd}} = 0.7117 and \varepsilon\textsubscript{\text{Nd}}([t] of −13.5 to −17.2) and variable \varepsilon\textsubscript{\text{Hf}}([t] values ranging from −18.8 to −5.1. In the Sr-Nd isotope correlation diagram, the K-feldspar granites plot into the field of Triassic granitoids from West Qinling and show affinity to Qinling Group gneiss (fig. 10a). Furthermore, two-stage Nd model ages (2.4–2.1 Ga) and zircon Hf model ages (2.4–1.6 Ga) of K-feldspar granites are close to the age of the Qinling Group (Zhang et al. 2006). The isotopic composition points toward the involvement of old crustal material derived mainly from Qinling Group.
Tectonic Implications. It is well accepted that the QOB was built up through the collision of the NCB and the SCB and intervening microcontinents [e.g., Zhang et al. 2001; Dong et al. 2011]. During Paleozoic to early Mesozoic times, the QOB underwent predominantly two episodes of collision: the Paleozoic subduction between the NQB and the SQB along the Shangdan suture and the Triassic collisional orogeny between the SQB and the SCB along the Mianlue suture.

The Shangdan suture is a tectonic boundary between the NQB and the SQB and represents the closure of the Shangdan Ocean, had evolved in a northward subduction un-

territorial to the northward subduction of the Mianlue Ocean continued at least until the Triassic in the western portion of South Qinling.

The emplacement ages of early Mesozoic granitoids in the QOB are regarded as representing the time of postcollisional oceanic-slab break-off, and consequently mantle upwelling induced by slab break-off is widely used in interpreting granitoid magmatism in the QOB [e.g., Sun et al. 2002; Qin et al. 2008]. However, the early Mesozoic tectonic setting during which the QOB granitoids were produced is still controversial. Recently, Wang et al. [2013] provided an overview of early Mesozoic magmatism in the QOB. In the QOB, magmatism occurred predominantly in the SQB between 252 and 185 Ma. The authors could identify two distinct stages of magmatism, one between 250 and 240 Ma and another between 225 and 185 Ma, with a cluster of ages between 225 and 200 Ma. Wang et al. [2013] stated that the first granitoid pulse mainly consists of I-type rocks that formed in a continental arc setting related to the subduction of the Mianlue Ocean. In contrast, voluminous magmatism at 225–185 Ma represents a transition from a syn- to a postcollisional setting in response to the collision between the NCB and the SCB. Dong et al. [2015b] proposed a further subdivision of the Triassic granitoids of the QOB. On the basis of systematic changes in composition and age, they distinguished between subduction-related [245–238 Ma, identical to the first group of Wang et al. 2013], syncollisional [237–210 Ma], and postcollisional [210–200 Ma] groups. According to this division, there is an extensive overlap in ages of the Baoji granitoids and the syn- to postcollisional granitoid group of the QOB. In addition, the Baoji granitoids have \(^{206} \text{Pb}/^{238} \text{U}\) ages of 217–194 Ma, which are younger than the Triassic UHP metamorphic event in the Dabie-Sulu orogenic belt but close to the retrogressive metamorphism event. Therefore, we conclude that the Baoji pluton formed in a postcollisional setting.

As discussed above, all samples from the Baoji pluton show enrichment in light REEs and LILEs but depletion in HFSEs, which are typical characteristics of arc- or subduction-related granitoids. In the Sr/Y-versus-Y and [La/Yb]_N-versus-Yb_N diagrams, they mainly plot in the fields of normal arc or classic island arc magmas [fig. 13a, 13b]. It has been argued that the compositions of the granitoids were largely controlled by their source rocks, so the arc signatures
may not represent an arc setting but could have been inherited from a previous subduction period. During continental subduction, crustal materials can be recycled into the mantle in the subduction channel. The crustal compositions could then be introduced into the overlying subcontinental lithospheric mantle by dehydration and/or partial melting. Thus, identification of crust-mantle interaction from orogenic magmatic rocks could confirm the collision process.

In the following, we present a possible formation model for the Baoji granitoids: continental crust was transported to mantle depth by subduction, and then slab break-off induced asthenospheric upwelling. This process caused partial melting of the lithospheric mantle as well as partial melting of the lower crust. Such a process might have involved two different mantle sources, one more refractory/residual and one more enriched/metasomatized. The magmas that built up the Baoji composite pluton are products of these different sources and formed by magma mixing and subsequent fractional-crystallization processes. The first melts emplaced a mixture of the enriched/metasomatized lithospheric mantle and mafic lower crust, producing the granodiorites. Ongoing partial melting in the upper mantle and lower crust produced hybrid melts from which the monzogranites were derived. At the same time, a mantle source metasomatized by fluids or melts from the subducted slab produced the geochemically and isotopically enriched quartz monzodiorites. Subsequently, partial melting of thickened lower crust produced the K-feldspar granites.

Conclusions

The granitoids of the Baoji pluton formed during late and postcollisional processes between the North China and South China blocks. Zircon U-Pb dating indicates that the pluton assembled during three episodes over 20 million years: (1) granodiorites formed at ∼217 Ma, (2) monzogranites and quartz monzodiorites at ∼212 Ma, and (3) K-feldspar granites at ∼196 Ma. The granodiorites and monzogranites were generated by partial melting of crustal materials with the involvement of mantle source that was enriched by slab-derived fluids and melts. Monzogranites and quartz monzodiorites formed simultaneously, while the latter were derived from a strongly metasomatized lithospheric mantle wedge. The K-feldspar granites formed in a postcollisional setting and were derived from partial melting of lower-crustal metagreywacke.

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