Hydrous melting of metasomatized mantle wedge and crustal growth in the post-collisional stage: Evidence from Late Triassic monzodiorite and its mafic enclaves in the south Qinling (central China)

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ABSTRACT

Triassic collision between the Yangtze and North China blocks is a key aspect of the evolution of the Paleo-Tethys in East Asia. This paper reports age and geochemistry for Late Triassic monzodiorite and its mafic enclaves from the south Qinling (central China). The host monzodiorite and mafic enclaves have identical zircon U-Pb ages of 227 ± 3 Ma and 221 ± 3 Ma, respectively. The host monzodiorite displays moderate SiO2 (62.44–63.85 wt%) and MgO (3.44–4.47 wt%) contents and high Cr (157–244 ppm) and Ni (78–108 ppm) contents. It has evolved whole-rock Sr-Nd isotopic compositions (εNd(t) = –6.2 to –5.0) and slightly positive zircon εHf(t) values (up to +6.4). Given these characteristics in combination with high Th/Nb and Nb/Yb ratios, the host monzodiorite is considered to have been derived from hydrous melting of metasomatized mantle lithosphere. Its moderate Sr/Y and low Yb/Lu ratios indicate the fractional crystallization of hornblende. The mafic enclaves have lower SiO2 (52.85–58.53 wt%) and higher MgO (8.26–9.45 wt%) contents. Most zircons in the mafic enclaves display positive εHf(t) values of +0.9 to +16.5. These features indicate that the pristine mafic melt was derived from depleted mantle lithosphere. Minor grains in the mafic enclaves display lower εHf(t) values (−4 to 0) than the zircons in the host monzodiorite, suggesting that the mafic melt had incorporated some evolved crustal component before it intruded into the host monzodiorite chamber. In summary, in the circumstance of slab break-off and asthenosphere upwelling, hydrous melting of mantle lithosphere has contributed greatly to crustal-derived granites in the Qinling orogenic belts. These results have the following implications for the Triassic granites in the Qinling orogenic belts: (1) hydrous melting of metasomatized mantle wedge greatly contributes to crustal growth in orogenic processes; and (2) mantle-derived hydrous mafic melts induced the extensive melting of crust and led to the voluminous Triassic granites in the Qinling orogen.

INTRODUCTION

The Triassic Qinling-Dabie-Sulu orogenic belt is the most prominent tectonic feature in central China, and resulted from the collision between the North China block and Yangtze block (Meng and Zhang, 2000; Ratschbacher et al., 2003; Zheng et al., 2011; Dong et al., 2015). It also plays a key role in understanding the tectonic evolution of the Paleo-Tethys and eastern Asia continents (Ernst et al., 2007). There is a striking difference between the western part (the Qinling) and the eastern part (the Dabie and Sulu): in the eastern part, the exposure of high-pressure (HP) and ultrahigh-pressure (UHP) metamorphic rocks indicates deep continental subduction (Zheng et al., 2011), whereas widespread high-K calc-alkaline granites and associated mafic rocks occur in the western part (Sun et al., 2002; Qin et al., 2008a, 2009, 2010a, 2010b, 2013; Wang et al., 2013).

What is the cause of the striking contrast between the Qinling and Dabie-Sulu parts of the orogenic belt? What geodynamic model can account for the genesis of the Triassic granitoids and related mafic rocks in the Qinling area: delamination of lower crust; a slab break-off model (Sun et al., 2002; Qin et al., 2008b); melting of subducted Yangtze continental lithosphere during the exhumation process (Qin et al., 2010b, 2013); or partial melting of subducted Paleo-Tethys oceanic crust (Jiang et al., 2010)? Understanding these issues has great significance for investigating the complete tectonic evolution of the Triassic Qinling-Dabie orogenetic belt.

In this paper, we present new mineral chemistry, major- and trace-element compositions, Sr-Nd-Pb isotopic compositions, zircon U-Pb dating, and Lu-Hf isotopic compositions for the Late Triassic Gaoqiao monzodiorite and its mafic enclaves from the south Qinling. We use the new data to explore the following two issues: (1) origin of the host monzodiorite and its mafic enclaves; and (2) the genetic link between the melting of mantle lithosphere and formation of Triassic granites in the Qinling orogenic belt.

GEOLOGICAL BACKGROUND AND FIELD GEOLOGY

The geological background of the Triassic Qinling-Dabie-Sulu orogenic belt has been described by many previous workers (Meng and...
Rounded mafic enclaves hosted in the monzodiorite are mostly 5–60 cm in diameter. In some outcrops, the mafic enclaves are conspicuously associated with Devonian metamorphic quartzite of the Liuling Group (Fig. 1C). The boundaries between mafic enclaves and host monzodiorite change from sharp to diffuse. Some felsic veins cut the host monzodiorite and its mafic enclaves (Figs. 2A, 2D). The host monzodiorite displays medium-grained texture (Figs. 2A, 2C) and consists of plagioclase (45%–48%), alkali feldspar (14%–16%), hornblende (7%–9%), biotite (18%–21%), and quartz (7%–9%). The plagioclase is oligoclase (anorthite composition), and the alkali feldspar consists of late Paleozoic medium-grade metamorphic rocks and volcanic Triassic granitoids (Sun et al., 2002; Qin et al., 2007, 2008a, 2008b, 2009, 2010a, 2010b, 2013); (4) the Mianlue suture zone, which contains metatbasalts with normal mid-ocean-ridge basalt (MORB) affinity (Xu et al., 2002; Lai et al., 2008); and (5) the northern margin of the Yangtze block. The Triassic collision between the Yangtze and North China blocks (Dong et al., 2015) along the Mianlue suture caused fold-thrust deformation, greenschist facies metamorphism, and granitic magmatism across the Qinling area (Dong et al., 2015).

The Gaoqiao pluton is located to the west of the Dongjiangkou pluton (Fig. 1C). Previous Rb-Sr dating results indicate that the diorite in the Gaoqiao pluton has a Late Paleozoic age of 285 Ma (SBGMR, 1989). The pluton trends WNW-ESE and is exposed over an area of >120 km² (Fig. 1C). The northern and southern margins of the pluton are in contact with Devonian metamorphic quartzite of the Liuling Group (Fig. 1C).

All analytical work for this paper was performed at the State Key Laboratory of Continental Dynamics, Northwest University, Xi’an, China.

**Electron Microprobe Analysis**

The major-element composition of rock-forming minerals was determined using an electron microprobe (JXA-8230). The operating conditions included an acceleration voltage of 15 kV, a beam current of 10 nA, and a beam diameter of 1 µm. Natural and synthetic microprobe standards were supplied by SPI (USA), including jadeite for Si, Al, and Na, diopside for Ca, olivine for Mg, sanidine for K, hematite for Fe, rhodonite for Mn, and rutile for Ti. The analytical uncertainties for other major elements are generally <2%.

**Zircon Laser Ablation–Inductively Coupled Plasma–Mass Spectrometry U-Pb Dating and Hf Isotope Analysis**

The zircon grains were separated using heavy liquid and magnetic techniques. Representative zircon grains were handpicked and mounted in epoxy resin discs, which were then polished and coated with carbon. Internal morphology was examined using cathodoluminescence (CL) prior to U-Pb and Lu-Hf isotopic analyses. Laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) zircon U-Pb analyses were conducted on an Agilent 7500a ICP-MS equipped with a 193 nm laser, following the method of Yuan et al. (2008). The U.S. National Institute of Standards and Technology (NIST) 610 standard silicate glass was used to optimize the instrument to obtain the maximum signal intensity (239U signal intensity of >2000 cps/g at a beam diameter of 30 µm and a laser frequency of 6 Hz) and low oxide production (ThO/Th <1%). The ion signal intensity ratio measured for both 238U and 232Th (NIST SRM 610) (238U/232Th = 1) was used as an indicator of complete vaporization (Günther and Hattendorf, 2005). The 206Pb/208Pb and 207Pb/206Pb ratios were calculated using the GLITTER program (version 4.4., Macquarie University). Common Pb contents were then evaluated using the method described by Anders (2002). Age calculations and plotting of concordia diagrams were made using Isoplot (version 3.0) (Ludwig, 2003). Concentrations of U, Th, Pb, and trace elements were calibrated using 204Pb as an internal standard and NIST SRM 610 as an external standard. The two standard zircons yielded weighted mean 206Pb/238U ages of 1064.2 ± 3.1 Ma (n = 14, 2σ) and 603.1 ± 3.4 Ma (n = 12, 2σ), respectively, which are in good agreement with the recommended isotope dilution–thermal ionization mass spectrometry (ID-TIMS) ages (Wiedenbeck et al., 1995).

In situ zircon Hf isotopic analyses were conducted using a Neptune multicollector ICP-MS (MC-ICP-MS) equipped with a 193 nm laser. During analyses, a laser repetition rate of 10 Hz at 100 mJ was used and spot sizes were 44 µm. The 176Hf/177Hf value of 0.288481 ± 10 (2σ) was measured using the solution method (Wiedenbeck et al., 1995). The detailed analytical technique is described by Yuan et al. (2008). During analyses, the 176Hf/177Hf ratio of the standard zircon (91500) was 0.282294 ± 15 (2σ, n = 20), similar to the commonly accepted 176Hf/177Hf ratios of 0.28230 ± 8 and 0.28230 ± 8 (2σ) measured using the solution method (Gooalaerts et al., 2004; Woodhead et al., 2004); the 176Lu/177Hf ratio of the standard zircon was 0.00031.

**Major- and Trace-Element Analysis**

For major- and trace-element analysis, fresh chips of whole-rock samples were powdered to 80 µm using a tungsten carbide ball mill. Major and trace elements were analyzed using X-ray fluorescence (XRF) (Rikagu RIIX 2100) and ICP-MS (Agilent 7500a), respectively. Analyses of U.S. Geological Survey and Chinese national rock standards (BCR-2, GSR-1, and GSR-3) indicate that both analytical precision and accuracy for major elements are generally better than 5%. For trace-element analysis, sample powders were digested using an HF + HNO₃ mixture in high-pressure Teflon bombs at 190 °C for 48 h. Analytical precision is better than 10% for most of the trace elements.

**Whole-Rock Sr-Nd-Pb Isotope Analysis**

Whole-rock Sr-Nd-Pb isotopic data were obtained using a Nu Plasma HR multicollector mass spectrometer; Sr and Nd isotopic fractionation was corrected to 87Sr/86Sr = 0.1194 and 143Nd/144Nd = 0.7219, respectively. Standard NIST SRM 987 yielded an average value of 87Sr/86Sr = 0.710250 ± 12 (2σ, n = 15), and the La Jolla standard gave an average of 143Nd/144Nd = 0.511859 ± 6 (2σ, n = 20). Whole-rock Pb was separated by anion exchange in HCl-Br columns; Pb isotopic fractionation was corrected to 208Pb/206Pb = 0.00031.
Figure 1. (A) Sketch geological map of China. (B) Geological map of the Triassic Qinling-Tongbai-Dabie orogenic belt (after Li et al., 2007). (C) Geological map of the Gaoqiao pluton (based on SBGMR, 1989). Abbreviations in A: CAO—Central Asia orogen; TM—Tarim block; NCC—North China craton; CCO—Central China orogen; SGO—Songpan Ganzi orogen; YZ—Yangtze craton; CC—Cathaysia craton; AHO—Alpine-Himalaya orogeny.
Figure 2. Field photographs and microscope images of rocks of the Gaoqiao pluton. (A, B) Field relationship of the host monzodiorite and mafic enclaves. (C) Microscope image of the host monzodiorite. (D) Microscope image of the mafic enclaves. (E, F) Backscattered electron images for the host monzodiorite (E) and mafic enclaves (F). Mineral abbreviations: Af — alkali feldspar; Amp — amphibole; Ap — apatite; Bi — biotite; Plg — plagioclase.
RESULTS

Mineral Chemistry and Pressure Calculation

Hornblende, biotite, plagioclase, and alkali feldspar from the host monzodiorite and mafic enclaves have been analyzed by microprobe for major-element composition. The data for these analyses are listed in Table DR1 in the GSA Data Repository1.

**Hornblende and Biotite**

Hornblende from the host monzodiorite displays high Al₂O₃ (7.16–7.85 wt%), TiO₂ (0.98–1.26 wt%), K₂O (0.71–0.89 wt%), and Na₂O (0.69–0.96 wt.%) contents, and has a magnesiohornblende composition (Leake et al., 1997). Hornblende in enclaves displays actinolite to magnesiohornblende composition (Fig. 3A); it has Al₂O₃ = 3.39–6.47 wt%, TiO₂ = 0.20–0.64 wt%, and K₂O = 0.25–0.52 wt%. Compared with the hornblende in the host monzodiorite, it displays higher Mg# [Mg# = molar 100 × Mg / (Mg + Total Fe²⁺)] (67–72) values. We use the new method proposed by Ridolfi et al. (2010) to calculate the hornblende crystallization pressure and temperature in the host monzodiorite and mafic enclaves. According to the results, the hornblende in the host monzodiorite has a crystallization pressure of 1.23–1.41 kbar, corresponding to a continental depth of 4.5–5.3 km. The hornblende in the mafic enclaves has a crystallization pressure of 0.60–0.96 kbar, corresponding to a continental depth of 2.4–3.6 km (Table DR1). These results indicate that the mafic enclaves crystallized at relatively shallow depth.

Biotite from the host monzodiorite (Fig. 3B) has MgO = 12.85–13.69 wt%, TiO₂ = 1.61–2.37 wt%, FeOt = 16.45–18.16 wt%, and Mg# values of 57–60. Biotite from the mafic enclaves has higher MgO (13.54–14.20 wt%) and TiO₂ (2.05–3.35 wt%) contents, lower FeOt (15.40–16.02 wt%) content, and higher Mg# values of 61–62.

**Plagioclase and Alkali Feldspar**

Plagioclase from the host monzodiorite is mainly oligoclase (An = 10–31) (Table DR1), with Al₂O₃ = 21.18–25.08 wt% and CaO = 1.86–6.18 wt%. Plagioclase in the mafic enclaves is andesine to oligoclase (An = 28–49). The alkali feldspar in the host monzodiorite has high K₂O (15.37–16.52 wt%) and low Al₂O₃ (18.51–18.92 wt%). Alkali feldspar was not analyzed in the mafic enclaves.

Zircon LA-ICP-MS U-Pb Dating

Samples of host monzodiorite (sample GQ-1) and mafic enclaves (sample GQB-1) were selected for zircon U-Pb isotope analysis. Zircon CL images and U-Pb concordant diagrams are presented in Figure 4, and the U-Th-Pb isotope data are listed in Table DR2.

Zircons from the host monzodiorite (sample GQ-1) are subhedral to euhedral, and fawn colored to colorless. Most grains display a long prismatic shape, with aspect ratios of 2:1–3:1. They have well-developed oscillatory zoning (Fig. 4A). Nine spots display discordant ages; spots 4 and 29 display older 206Pb/238U ages of 479 ± 8 Ma and 734 ± 13 Ma, respectively, suggesting a xenocrystic origin. The other 25 spots display concordant U-Pb ages and have Th = 107–246 ppm, U = 174–268 ppm, with Th/U ratios of 0.64–0.92, suggesting a magmatic origin. These grains have 206Pb/238U ages of 209 ± 6 Ma to 236 ± 6 Ma, yielding a weighted mean age of 227 ± 3 Ma (mean square of weighted deviates [MSWD] = 1.4, 2σ), which represents the crystallization age of the host monzodiorite (Fig. 4B). Zircons from the mafic enclaves (sample GQB-1) are subhedral and orange-brown, with crystal lengths of 50–100 μm. As shown in the CL images, most grains are dark and unzoned; only few zircons display poorly developed oscillatory zoning (Fig. 4C). Zircons from the mafic enclaves have U = 151–751 ppm, Th = 98–868 ppm, and Th/U ratios of 0.65–1.22. Spots 4 and 10 display discordant ages; five spots (26, 30, 31, 33, and 35) display concordant U-Pb ages and have MgO = 12.85–13.69 wt%, TiO₂ = 1.61–2.37 wt%, FeOt = 16.45–18.16 wt%, and Mg# values of 57–60. Biotite from the mafic enclaves has higher MgO (13.54–14.20 wt%) and TiO₂ (2.05–3.35 wt%) contents, lower FeOt (15.40–16.02 wt%) content, and higher Mg# values of 61–62.

![Diagram](https://example.com/diagram.png)

**Figure 3. Si versus Mg / (Mg + Fe²⁺) diagram for hornblende (A) (after Leake et al., 1997) and MgO-FeOt-Al₂O₃ diagram for biotite (B) (after Abdel-Rahman 1994) from the host monzodiorite and mafic enclaves of the Gaoqiao pluton.**

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1 GSA Data Repository Item 2018389, which includes Table DR1: Analytical results of representative minerals from the host monzodiorite and mafic enclaves from the Gaoqiao pluton, south Qinling; Table DR2: Zircon LA-ICP-MS U-Pb results for the host monzodiorite and enclaves from the Gaoqiao pluton; Table DR3: Zircon Lu-Hf isotopic compositions of the host monzodiorite and enclaves from the Gaoqiao pluton, south Qinling; and Table DR4: FCA results, is available at http://www.geoscienceworld.org/datarepository/2018389 or on request from editing@geosociety.org.
display lower U contents and younger $^{206}\text{Pb}^{238}\text{U}$ ages of 200–208 Ma, which may have been caused by Pb loss (Mezger and Krogstad, 1997). The other 29 spots have $^{206}\text{Pb}^{238}\text{U}$ ages of 210 ± 4 Ma to 236 ± 6 Ma, yielding a weighted mean $^{206}\text{Pb}^{238}\text{U}$ age of 221 ± 3 Ma (MSWD = 1.7, 2σ) (Fig. 4D), considered to be the crystallization age of the mafic enclaves. Considering the analysis errors, we propose that the host monzodiorite and mafic enclaves are contemporary.

**Major- and Trace-Element Chemistry**

Major- and trace-element analysis results for the monzodiorite and enclaves are listed in Table 1. The host monzodiorite displays tonalitic to dioritic composition (Fig. 5A), with SiO$_2$ = 62.44–63.85 wt%, TiO$_2$ = 0.56–0.73 wt%, Na$_2$O = 3.41–3.78 wt%, K$_2$O = 3.32–3.78 wt%, Na$_2$O/K$_2$O = 0.90–1.16, and Al$_2$O$_3$ = 14.44–15.76 wt%, with A/CNK ratios [molar ratios Al$_2$O$_3$ / (CaO + Na$_2$O + K$_2$O)] of 0.82–0.90 (Fig. 5B). It has high MgO contents of 3.44–4.47 wt% with Mg# values of 63.7–65.5. As shown in the SiO$_2$ versus major elements diagrams (Fig. 6), the host monzodiorite plots beyond the mixing line. The monzodiorite has high Ni (78–108 ppm) and Cr (157–244 ppm) contents, with Cr/Ni ratios of 2.0–2.3. It is enriched in LREEs (light rare earth elements [REEs]) and depleted in HREEs (heavy REEs) (Fig. 7A) and has (La/Yb)$_n$ = 14.4–21.9, Eu*/Eu = 0.76–0.90, total REE (ΣREE) contents of 126.96–177.80 ppm, and Yb$_n$ = 7.9–11.0. It has spikes in Rb, Sr, and Th and troughs in Nb and Ta (Fig. 7B), high Sr (666–724 ppm) and Ba (1115–1369 ppm) contents, and low Y (14.3–20.2 ppm) contents, resulting in moderate Sr/Y (33.5–50.2) and Y/Yb (10.5–11.0) ratios.

The mafic enclaves are mainly gabbro to diorite in composition (Fig. 5A); they have lower SiO$_2$ (52.85–58.53 wt%) and higher TiO$_2$ (0.55–0.79 wt%), CaO (5.48–8.69 wt%), and MgO (8.26–9.45 wt%) contents. They have high Mg# values of 70.6–76.7, Na$_2$O/K$_2$O = 0.83–1.90, and similar Al$_2$O$_3$ (12.57–14.62 wt%) and lower A/CNK (0.55–0.72). The mafic enclaves show slight enrichment in LREEs (Fig. 7C), with lower (La/Yb)$_n$ ratios of 10.8–15.6 and Eu/Eu* = 0.84–0.95 (Fig. 7C); they show...
| Major Elements (wt%) | Host monzodiorite | Enclaves |
|---------------------|------------------|----------|
| SiO₂                | 62.25            | 58.53    |
| Al₂O₃               | 14.60            | 13.17    |
| Fe₂O₃               | 5.50             | 5.86     |
| MnO                 | 0.08             | 0.10     |
| MgO                 | 4.47             | 8.28     |
| Na₂O                | 3.16             | 5.48     |
| K₂O                 | 3.16             | 2.85     |
| P₂O₅                | 0.23             | 3.40     |
| LOI                 | 0.25             | 0.24     |
| Total               | 99.98            | 99.75    |
| Trace Elements (ppm) |                  |          |
| Li                  | 38.0             | 49.7     |
| Be                  | 2.71             | 2.35     |
| Sc                  | 15.6             | 18.7     |
| V                   | 129              | 128      |
| Cr                  | 244              | 717      |
| Co                  | 90.0             | 80.8     |
| Ni                  | 108              | 264      |
| Cu                  | 44.6             | 37.5     |
| Zn                  | 66.6             | 61.8     |
| Ga                  | 18.7             | 15.6     |
| Ge                  | 1.29             | 1.44     |
| Rb                  | 142              | 153      |
| Sr                  | 678              | 697      |
| Y                   | 20.2             | 264      |
| Zr                  | 236              | 130      |
| Nb                  | 18.6             | 130      |
| Cs                  | 3.67             | 10.4     |
| Ba                  | 1316             | 1560     |
| La                  | 38.5             | 270      |
| Ce                  | 77.1             | 50.8     |
| Pr                  | 8.48             | 5.34     |
| Nd                  | 32.7             | 21.1     |
| Sm                  | 5.71             | 3.75     |
| Eu                  | 1.28             | 1.09     |
| Gd                  | 4.66             | 3.26     |
| Tb                  | 0.65             | 0.44     |
| Dy                  | 3.65             | 2.43     |
| Ho                  | 0.72             | 0.49     |
| Er                  | 1.94             | 1.31     |
| Tm                  | 0.29             | 0.20     |
| Yb                  | 1.83             | 1.25     |
| Lu                  | 0.27             | 0.18     |
| Hf                  | 6.21             | 3.59     |
| Ta                  | 1.27             | 0.81     |
| Pb                  | 23.4             | 23.9     |
| Th                  | 19.8             | 7.78     |
| U                   | 2.08             | 2.92     |
| Sr/Y                | 33.5             | 53.1     |
| Nb/Ta               | 14.6             | 11.3     |
| Y/Yb                | 11.1             | 10.5     |
| Nb/U                | 8.9              | 3.1      |
| Ce/Pb               | 3.3              | 2.1      |
| Eu/Eu               | 0.76             | 0.95     |

Note: T in Fe₂O₃—Total; LOI—Loss on ignition; A/CNK—molar ratios Al₂O₃/(CaO + Na₂O + K₂O); Mg#—molar 100 × Mg/(Mg + Total Fe²⁺); Eu*=SQRT(Sm×Gd)/N.
Figure 5. (A) R1 versus R2 diagram for classification of plutonic rocks (after De la Roche et al., 1980); (B) A/CNK [molar ratio Al₂O₃ / (CaO + Na₂O + K₂O)] versus A/NK [Al₂O₃ / (Na₂O + K₂O)]; (C) SiO₂ versus MgO; and (D) SiO₂ versus Mg# [Mg# = Mg / (Mg + Fe) × 100] diagrams (after Wang et al., 2006, and references therein) for the host monzodiorite and mafic enclaves of the Gaoqiao pluton. An—anorthite; Ab—albite; Or—orthoclase.

Adakite from delaminated crust
Adakite from thickened basic continental crust
Adakite from eclogite or metabasalt
(1-4.0 GPa)
Adakite from subducting oceanic crust
experimental melts of the root of an oceanic magma chamber
(after Erdmann et al., 2015)
Figure 6. SiO$_2$ versus major elements variation diagrams for the host monzodiorite and mafic enclaves of the Gaoqiao pluton. Samples GQ-21 and GQ-B09 are selected to represent the felsic and mafic end members, respectively.
spikes in Rb, Ba, U, Th, K, La, and Nd and troughs in Nb, Ta, P, and Ti (Fig. 7D). They have high Sr (647–710 ppm) and Ba (550–1560 ppm) and varied Y (13.1–22.4 ppm) contents.

Whole-Rock Sr-Nd-Pb Isotopic Compositions

Whole-rock Sr-Nd-Pb isotopic compositions are given in Tables 2 and 3. Initial isotopic values were calculated according to the zircon U-Pb age. Whole-rock Nd model ages were calculated using the model of DePaolo (1981).

The host monzodiorite has $^{87}\text{Sr}/^{86}\text{Sr}$ = 0.7052–0.7056 and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of 0.512058–0.512119, with negative $\varepsilon_{\text{Nd}}(t)$ values of –6.2 to –5.0 and two-stage Nd model ages of 1.2–1.3 Ga. The mafic enclaves have $^{87}\text{Sr}/^{86}\text{Sr}$ = 0.7059, $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of 0.512200, $\varepsilon_{\text{Nd}}(t)$ values of –3.4, and a two-stage Nd model age of 1.1 Ga. As shown in the $\varepsilon_{\text{Nd}}(t)$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ diagram (Fig. 8), the host monzodiorite and mafic enclaves display Sr-Nd isotopic compositions similar to those of other Triassic granites in the south Qinling (Qin et al., 2007, 2008b; Wang et al., 2013), western Qinling (Zhang et al., 2007a), and Songpan-Graze fold belt (Zhang et al., 2006). Clearly different from the characteristics of MORB (Tribuzio et al., 2004), these features indicate a relatively evolved source.

The host monzodiorite has $^{206}\text{Pb}/^{204}\text{Pb}$ = 17.621–17.627, $^{207}\text{Pb}/^{204}\text{Pb}$ = 15.512–15.516, and $^{208}\text{Pb}/^{204}\text{Pb}$ i = 37.790–37.816; the mafic enclaves have $^{206}\text{Pb}/^{204}\text{Pb}$ = 17.677, $^{207}\text{Pb}/^{204}\text{Pb}$ = 15.526, and $^{208}\text{Pb}/^{204}\text{Pb}$ i = 37.830. In the $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{208}\text{Pb}/^{204}\text{Pb}$ diagrams (Figs. 9A, 9B), the host monzodiorite and its enclaves plot in the transitional zone between the compositions of the North China and Yangtze blocks (Zhang et al., 1997). They also display a similar Pb isotopic composition to that of the Neoproterozoic Bikou (Yan et al., 2004) and Yaolinghe basalts (Xia et al., 2008).

Figure 7. (A, C) Chondrite-normalized rare-earth-element and (B, D) primitive mantle–normalized trace-element spider diagrams for the host monzodiorite and mafic enclaves of the Gaoqiao pluton. Chondrite and primitive mantle values are from Sun and McDonough (1989).

Table 2. Whole-rock Sr and Nd isotopic composition for the host monzodiorite and mafic enclaves of the Gaoqiao pluton, South Qinling, China

| Rock type        | Sample | Sr (ppm) | Rb (ppm) | $^{87}\text{Sr}/^{86}\text{Sr}$ | $^{87}\text{Rb}/^{86}\text{Sr}$ | $^{143}\text{Nd}/^{144}\text{Nd}$ | $^{147}\text{Sm}/^{144}\text{Nd}$ | $^{143}\text{Nd}/^{144}\text{Nd}$ | $^{143}\text{Nd}/^{144}\text{Nd}$ | $^{143}\text{Nd}/^{144}\text{Nd}$ | $^{143}\text{Nd}/^{144}\text{Nd}$ | $^{143}\text{Nd}/^{144}\text{Nd}$ |
|------------------|--------|----------|----------|-------------------------------|-----------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Enclaves         | GQ-B09 | 710      | 64.5     | 0.706746                      | 13                          | 0.263                         | 0.705961                      | 29.5                          | 6.53                          | 0.512384                      | 8                             | 0.134                        |
| Monzodiorite     | GQ-03  | 710      | 64.5     | 0.706746                      | 13                          | 0.263                         | 0.705961                      | 29.5                          | 6.53                          | 0.512384                      | 8                             | 0.134                        |
| Monzodiorite     | GQ-05  | 710      | 64.5     | 0.706746                      | 13                          | 0.263                         | 0.705961                      | 29.5                          | 6.53                          | 0.512384                      | 8                             | 0.134                        |
| Monzodiorite     | GQ-08  | 710      | 64.5     | 0.706746                      | 13                          | 0.263                         | 0.705961                      | 29.5                          | 6.53                          | 0.512384                      | 8                             | 0.134                        |
| Monzodiorite     | GQ-09  | 710      | 64.5     | 0.706746                      | 13                          | 0.263                         | 0.705961                      | 29.5                          | 6.53                          | 0.512384                      | 8                             | 0.134                        |
| Monzodiorite     | GQ-10  | 710      | 64.5     | 0.706746                      | 13                          | 0.263                         | 0.705961                      | 29.5                          | 6.53                          | 0.512384                      | 8                             | 0.134                        |
| Monzodiorite     | GQ-11  | 710      | 64.5     | 0.706746                      | 13                          | 0.263                         | 0.705961                      | 29.5                          | 6.53                          | 0.512384                      | 8                             | 0.134                        |

Note: CHUR—Chondritic Uniform Reservoir.

$^{87}\text{Rb}/^{86}\text{Sr}$ ratios were calculated using Rb, Sr, Sm, and Nd contents measured by inductively coupled plasma–mass spectrometry.

Initial Sr and Nd isotopic compositions were calculated using Rb, Sr, Sm, and Nd contents measured by inductively coupled plasma–mass spectrometry.

The host monzodiorite has $^{143}\text{Nd}/^{144}\text{Nd}$ = 0.512384. $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were calculated using present-day $^{143}\text{Sm}/^{144}\text{Nd} = 0.2137$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were calculated using present-day $^{143}\text{Sm}/^{144}\text{Nd} = 0.51315$. $\varepsilon_{\text{Nd}}(t)$ values were calculated using present-day $^{143}\text{Nd}/^{144}\text{Nd}$ = 0.1967 and $^{143}\text{Nd}/^{144}\text{Nd}$ = 0.512638.
Zircon Lu-Hf Isotope and Trace-Element Chemistry

Zircons from the host monzodiorite and mafic enclaves that were dated by U-Pb were also selected for Lu-Hf analysis in the same domain. The results are listed in Table DR3. Initial $^{176}$Hf/$^{177}$Hf ratios and $\varepsilon_{Hf(t)}$ values of the magmatic zircons were calculated according to their U-Pb ages. Figure 10A shows $\varepsilon_{Hf(t)}$ values versus crystallization ages.

Twenty-four (24) out of 36 spots in the host monzodiorite (sample GQ-11) were collected for Lu-Hf isotope analysis. Spots 1, 5, 6, 10, 15, 16, and 22 display discordant U-Pb ages; their Hf isotopic compositions have no geological significance. The other 17 grains display variable Hf isotopic compositions, $\varepsilon_{Hf(t)} = -0.4$ to +6.4, with corresponding two-stage Hf model ages of 738–1053 Ma. Twenty-four (24) out of 36 spots in the mafic enclaves (sample GQB-1) were selected for Lu-Hf analysis. Spots 1, 5, 6, 10, 15, 16, and 22 display discordant U-Pb ages; their Hf isotopic compositions have no geological significance. The other 17 grains display variable Hf isotopic compositions, $\varepsilon_{Hf(t)} = -0.4$ to +6.4, with corresponding two-stage Hf model ages of 738–1053 Ma. Twenty-four (24) out of 36 spots in the mafic enclaves (sample GQB-1) were selected for Lu-Hf analysis. Spots 1, 5, 6, 10, 15, 16, and 22 display discordant U-Pb ages; their Hf isotopic compositions have no geological significance. The other 17 grains display variable Hf isotopic compositions, $\varepsilon_{Hf(t)} = -0.4$ to +6.4, with corresponding two-stage Hf model ages of 738–1053 Ma. Twenty-four (24) out of 36 spots in the mafic enclaves (sample GQB-1) were selected for Lu-Hf analysis. Spots 1, 5, 6, 10, 15, 16, and 22 display discordant U-Pb ages; their Hf isotopic compositions have no geological significance. The other 17 grains display variable Hf isotopic compositions, $\varepsilon_{Hf(t)} = -0.4$ to +6.4, with corresponding two-stage Hf model ages of 738–1053 Ma. Twenty-four (24) out of 36 spots in the mafic enclaves (sample GQB-1) were selected for Lu-Hf analysis. Spots 1, 5, 6, 10, 15, 16, and 22 display discordant U-Pb ages; their Hf isotopic compositions have no geological significance. The other 17 grains display variable Hf isotopic compositions, $\varepsilon_{Hf(t)} = -0.4$ to +6.4, with corresponding two-stage Hf model ages of 738–1053 Ma. Twenty-four (24) out of 36 spots in the mafic enclaves (sample GQB-1) were selected for Lu-Hf analysis. Spots 1, 5, 6, 10, 15, 16, and 22 display discordant U-Pb ages; their Hf isotopic compositions have no geological significance. The other 17 grains display variable Hf isotopic compositions, $\varepsilon_{Hf(t)} = -0.4$ to +6.4, with corresponding two-stage Hf model ages of 738–1053 Ma. Twenty-four (24) out of 36 spots in the mafic enclaves (sample GQB-1) were selected for Lu-Hf analysis. Spots 1, 5, 6, 10, 15, 16, and 22 display discordant U-Pb ages; their Hf isotopic compositions have no geological significance. The other 17 grains display variable Hf isotopic compositions, $\varepsilon_{Hf(t)} = -0.4$ to +6.4, with corresponding two-stage Hf model ages of 738–1053 Ma. Twenty-four (24) out of 36 spots in the mafic enclaves (sample GQB-1) were selected for Lu-Hf analysis. Spots 1, 5, 6, 10, 15, 16, and 22 display discordant U-Pb ages; their Hf isotopic compositions have no geological significance. The other 17 grains display variable Hf isotopic compositions, $\varepsilon_{Hf(t)} = -0.4$ to +6.4, with corresponding two-stage Hf model ages of 738–1053 Ma. Twenty-four (24) out of 36 spots in the mafic enclaves (sample GQB-1) were selected for Lu-Hf analysis. Spots 1, 5, 6, 10, 15, 16, and 22 display discordant U-Pb ages; their Hf isotopic compositions have no geological significance. The other 17 grains display variable Hf isotopic compositions, $\varepsilon_{Hf(t)} = -0.4$ to +6.4, with corresponding two-stage Hf model ages of 738–1053 Ma. Twenty-four (24) out of 36 spots in the mafic enclaves (sample GQB-1) were selected for Lu-Hf analysis. Spots 1, 5, 6, 10, 15, 16, and 22 display discordant U-Pb ages; their Hf isotopic compositions have no geological significance. The other 17 grains display variable Hf isotopic compositions, $\varepsilon_{Hf(t)} = -0.4$ to +6.4, with corresponding two-stage Hf model ages of 738–1053 Ma. Twenty-four (24) out of 36 spots in the mafic enclaves (sample GQB-1) were selected for Lu-Hf analysis. Spots 1, 5, 6, 10, 15, 16, and 22 display discordant U-Pb ages; their Hf isotopic compositions have no geological significance. The other 17 grains display variable Hf isotopic compositions, $\varepsilon_{Hf(t)} = -0.4$ to +6.4, with corresponding two-stage Hf model ages of 738–1053 Ma. Twenty-four (24) out of 36 spots in the mafic enclaves (sample GQB-1) were selected for Lu-Hf analysis. Spots 1, 5, 6, 10, 15, 16, and 22 display discordant U-Pb ages; their Hf isotopic compositions have no geological significance. The other 17 grains display variable Hf isotopic compositions, $\varepsilon_{Hf(t)} = -0.4$ to +6.4, with corresponding two-stage Hf model ages of 738–1053 Ma. Twenty-four (24) out of 36 spots in the mafic enclaves (sample GQB-1) were selected for Lu-Hf analysis.
DISCUSSION

Genetic Link Between the Host Monzodiorite and Its Mafic Enclaves

Mafic enclaves in granitic rocks are usually considered to be formed by mixing or mingling of felsic and mafic melt or to represent wall-rock xenoliths, melting restite (Chappell and Wyborn, 2012), or quenched cumulates (Phillips et al., 1981; Donaire et al., 2005; Pascual et al., 2008). The mafic enclaves and host monzodiorite studied here have identical zircon U-Pb ages of ca. 220 Ma (Fig. 4); this indicates that the mafic enclaves formed by a contemporaneous magmatic event, rather than as xenoliths or melting restite. Most mafic enclaves in the Gaoqiao pluton display a sharp contact boundary with the host monzodiorite (Fig. 2A), indicating limited magma mingling. In addition, we selected host monzodiorite (sample GQ-21, which has the highest SiO₂ of 63.85%) and mafic enclaves (sample GQ-B09 with the lowest SiO₂ of 52.85%) as the end members of felsic and mafic melts, respectively. As shown in the variation diagrams (Fig. 6), most samples plotted beyond the magma mixing line, suggesting limited magma mixing. Furthermore, hornblende in the host

Figure 9. (A) ²⁰⁶Pb/²⁰⁴Pb versus ²⁰⁷Pb/²⁰⁴Pb and (B) ²⁰⁶Pb/²⁰⁴Pb versus ²⁰⁸Pb/²⁰⁴Pb diagrams for the host monzodiorite and mafic enclaves of the Gaoqiao pluton (after Zhang et al., 1997). NHRL—Northern Hemisphere reference line (Th/U = 0.4). Field for Triassic granites from the Qinling orogenic belt is from Zhang et al. (2006, 2007a, 2007b) and Qin et al. (2007, 2008a); for Neoproterozoic Yanglinghe and Bikou metavolcanic rocks, from Xia et al. (2008). Symbols are as in Figure 5.

Figure 10. (A) ε⁵⁷Hf(t) versus age diagram and (B) ε⁵⁷Hf(t) distribution patterns for the host monzodiorite and mafic enclaves of the Gaoqiao pluton. Dotted vertical line defines the mixing line between a hypothetical Neoproterozoic juvenile crust and Paleoproterozoic continental crust. Symbols are as in Figure 5.
monzodiorite displays higher crystallization pressures (1.23–1.41 kbar) than those of the hornblende in the mafic enclaves (0.60–0.96 kbar), suggesting that the hornblende in the mafic enclaves crystallized at relatively shallow depth; this result also indicates that the mafic enclaves represent mafic melts that intruded into the partially crystallized monzodiorite chamber in a relatively late stage.

It is intriguing to consider whether or not the host monzodiorite and mafic enclaves derived from the same source region. Several lines of compelling evidence indicate that the host monzodiorite was not formed by the fractional crystallization of the mafic melt that is represented by the mafic enclaves: (1) there is an obvious compositional gap (Fig. 6) between the mafic enclaves and host monzodiorite, which is contradictory to continuous fractional crystallization; (2) zircons from the mafic enclaves and host monzodiorite display different crystallization pressures (Table DR1), suggesting different crystallization paths.

In summary, we propose that the host monzodiorite and mafic enclaves represent contemporaneous magma that derived from two distinct mantle source regions, with the magma mingling process having limited effect on their geochemistry.

Origin of the High-Mg# Monzodiorite: Evolved Hydrous Mafic Magma Derived from Metasomatized Mantle Wedge

Compared with typical crustal-derived granites (Pitcher, 1997; Clemens et al., 2009), the host monzodiorite displays moderate SiO₂ (62.44–63.85 wt%) contents, relatively higher MgO (3.44–4.47 wt%), Cr (157–244 ppm), and Ni (78–108 ppm) contents, and higher Mg# (63.7–65.5) values. As shown in the SiO₂-MgO and SiO₂-Mg# diagrams (Figs. 5C, 5D), the host monzodiorite displays identical features to modern natural high-Mg adakites (Tatsumi, 2006) from subduction zones, and obvious higher MgO contents and Mg# values than experimental melts from amphibolite in lower crust (Zhang et al., 2013) or oceanic crust (Erdmann et al., 2015). These features suggest significant mantle hybridization.

Intermediate rocks with high Mg# (>45) are proposed to form by: (1) interaction of slab-derived melts with overlying mantle wedge (Tatsumi, 2006); (2) primitive mafic melts assimilating significant crustal components in the emplacement process; (3) interaction of felsic melts derived from delaminated crust with surrounding asthenosphere (Gao et al., 2004); and (4) evolved mafic melts derived from metasomatized mantle wedge (Shellnutt and Zellmer, 2010).

The following evidence indicates that the first three mechanisms are not plausible for the genesis of the host monzodiorite: (1) The host monzodiorite is enriched in large-ion lithophile elements (LILEs) and LREEs,
depleted in Nb, Ta, and Ti (Fig. 6), and displays the typical signature of continental or arc crust (Wilson, 1989). Zircons from host monzogranite display slightly depleted Lu-Hf isotopic compositions (Fig. 10A), i.e., $\varepsilon_{\text{Hf}(t)} = -0.4$ to +6.4. It also has evolved Sr-Nd isotopic compositions (Table 2). These features suggest that the host monzodiorite was derived from melting of metasomatized enriched mantle lithosphere rather than a depleted source region. Compared with the sanukite of the Setouchi volcanic belt, Japan (Tatsumi, 2006), the monzodiorite displays higher Th/La (0.42–0.51) and Th/Yb (10.3–13.4) ratios (Fig. 12), indicating significant involvement of sediment-derived melts (Tatsumi, 2006). (2) Zircons from the host monzodiorite have a unimodal Lu-Hf distribution (Fig. 10B), inconsistent with the model of primitive mafic melts assimilating significant crustal components. (3) The absence of Triassic extensional tectonics in the Qinling area argues against the delamination model (Dong et al., 2015).

Compared with the host monzodiorite, primitive high-Mg andesitic melts derived from hydrous melting of harzburgite have lower SiO$_2$ (54.0%–55.2%) and higher MgO (7.2%–11.9%) contents (Wood and Turner, 2009). This feature indicates that the primitive mafic melt underwent fractional crystallization of hornblende and other mafic minerals. The mafic enclaves sample (GQB-09) is used as starting parental melt composition to determine if the host monzodiorite was crystallized from mafic melts (we argue that sample GQB-09 can roughly represent the pristine mafic melt, although it may be derived from a more depleted source region). The FC-AFC-FCA (fractional crystallization–assimilation fractional crystallization–fractional crystallization assimilation) and mixing modeler of Ersoy and Helvacı (2010) is used to assess the role of hornblende fractional crystallization in the formation of the host monzodiorite. The results indicate that 15%–20% fractional crystallization of hornblende (80%) + plagioclase (20%), with 20% assimilation of lower continental crust (Rudnick and Fountain, 1995), can form intermediate melts similar to those that formed the host monzodiorite (Fig. 13). This possibility is supported by the host monzodiorite flat HREE patterns (Fig. 7A), and its low Yb/Lu (6.7–6.8), Dy/Yb (1.90–1.99), and (Ho/Yb)$_{\text{N}}$ (1.15–1.18) ratios indicate depletion in middle REEs (MREEs) (Moyen and Martin, 2012).

In summary, we propose that the host monzodiorite represents evolved mafic melts that derived from hydrous melting of metasomatized enriched mantle wedge; fractional crystallization of hornblende can account for its moderate Sr/Y and Yb/Lu ratios (Moyen and Martin, 2012). Its evolved Sr-Nd isotopic compositions and high Th/La and Th/Yb ratios suggest metasomatism by sediment-derived melts.

### Mafic Enclaves: Hydrous Mafic Melts Derived from a Relatively Depleted Mantle Source

The mafic enclaves display relatively low SiO$_2$ (52.85–58.53 wt%) and high TiO$_2$ (0.55–0.79 wt) and MgO (8.26–9.45 wt%) contents and high Mg# values of 70.6–76.7 (Fig. 5). Euhedral hornblende in the mafic enclaves displays high and constant Mg# values of 67–72, which are higher than those of the hornblende in the monzodiorite (Table DR1). The above features are identical with sanukite (SiO$_2$ > 53%, TiO$_2$ < 0.5%, MgO > 8%) in a subduction zone (Tatsumi, 2006). Sanukites are generally ascribed to partial melting of hydrous lherzolite in relatively low-temperature (<1000 °C) conditions (Kushiro, 1990; Hirose, 1997; Wood and Turner, 2009).

Geochemical analysis reveals both enriched and depleted components in the mafic enclaves. On one hand, the mafic enclaves display enrichment in Rb, Ba, U, Th, K, La, and Nd and depletion in Nb, Ta, P, and Ti. They have variable K$_2$O (1.69–3.40 wt%), Rb (64.5–153 ppm), and

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**Figure 12.** (A) Y versus Sr/Y, (B) Sr/Y versus Th/La, and (C) Ba/La versus Th/Yb discrimination diagrams (after Tatsumi, 2006) for the host monzodiorite and mafic enclaves of the Gaoqiao pluton.
Ba (550–1560 ppm) contents, with variable Nb/Ta ratios of 11.2–17.9 (Table 61). They have similar Nb/U (1.9–6.1) and Ce/Pb (2.1–3.8) ratios to continental crust (Nb/U = 6.2 and Ce/Pb = 3.9; Rudnick and Fountain, 1995). They also have evolved Sr-Nd-Pb isotopic compositions (Fig. 7). The above features suggest an enriched component in the mafic enclaves. On the other hand, the mafic enclaves have identical U/Th ratios (0.37–0.41) with depleted mantle (0.33); these ratios are higher than those of the host monzodiorite (0.10–0.17) and continental crust (0.25), suggesting depleted components (Hawkesworth et al., 1997). Most zircons in the mafic enclaves display positive $\varepsilon_{\text{Hf}}(t)$ values of +0.9 to +16.5, with single-stage Hf model ages of 208–1018 Ma, which should have been inherited from their depleted source region.

The mafic enclaves display decoupled whole-rock Nd and zircon Hf isotopic compositions (Table 2; Table DR2). Considering the extremely refractory Lu-Hf system in zircons (Hawkesworth and Kemp, 2006), we argue that the zircon grains with positive $\varepsilon_{\text{Hf}}(t)$ values were crystallized from pristine depleted mafic melts. Assimilation of evolved crustal rocks may account for the evolved Sr-Nd isotopic compositions (Fig. 7). The zircon grains that have negative $\varepsilon_{\text{Hf}}(t)$ values suggest incorporation from evolved crustal melts before the pristine mafic melt intruded into the host monzodiorite chamber.

In summary, it can be considered that the mafic enclaves represent hydrous mafic melt derived from melting of a relatively depleted mantle source. The occurrence of zircon grains with negative $\varepsilon_{\text{Hf}}(t)$ values and their evolved Sr-Nd isotopic compositions suggest the assimilation of evolved crustal-derived melts before the mafic enclaves intruded into the host monzodiorite chamber.

**Implication for the Hydrous Melting of Metasomatized Mantle Wedge and Crustal Growth in a Post-Collisional Setting**

Triassic granites in the Qinling area recorded the most important information about the collision process between the South China and North China blocks. Most workers argued that these granites were caused by the northward subduction of the Mianlue ocean (Jiang et al., 2010; Li et al., 2015). Qin et al. (2010b, 2013) proposed that decompression melting of subducted Yangtze continental lithosphere during the exhumation may have produced the Triassic granitoids in the Qinling orogen. The extensive Triassic granitoids across the Qinling orogen (Sun et al., 2002; Jiang et al., 2010; Qin et al., 2010a, 2010b, 2013) indicate an extensive Triassic crustal melting event in the Qinling orogen, which would have needed a gigantic heat source to trigger the crustal melting in the orogenic process.

We have summarized the age and key geochemical features of the Gaoqiao monzodiorite and other crustal-derived granites in the Qinling area (Table 4). It is obvious that the Gaoqiao monzodiorite is synchronous with most Triassic granites in the Qinling orogenic belt, suggesting an extensive melting event. Furthermore, it has the lowest SiO$_2$ contents, highest MgO and Cr contents, and relatively high positive zircon $\varepsilon_{\text{Hf}}(t)$ values; these features indicate that the Gaoqiao monzodiorite was formed by evolved mafic melts that derived from melting of enriched metasomatized mantle lithosphere. This indicates that melting of mantle lithosphere and generation of mafic melt provide essential heat for crustal melting. In combination with regional geological background, we propose that slab break-off may be the most plausible model to explain the genesis of the Triassic granites in the Qinling orogen (Fig. 14): (1) In the circumstance...
Hydrous melting of metasomatized mantle wedge and crustal growth

Yangtze Block

Qinling terrane

~220Ma

1. Hydrous melting of metasomatized mantle wedge
2. Fractional crystallization of hornblende and assimilation of crustal rocks in the pristine mafic melts
3. Crystallization of the host monzodiorite
4. Injection of pristine mafic melts into the partially crystallized monzodiorite chamber, magma mingling to form the enclaves
5. The mafic melts provide essential heat for crustal melting and formation of other crustal derived granites

Figure 14. Proposed model for the Triassic high-Mg# \(Mg# = \frac{\text{molar 100} \times Mg}{(Mg + \text{Total Fe}^2+)}\) monzodiorite and its mafic enclaves in the Gaoqiao pluton (after Ledru et al., 2001).

Note: Mg# = \([\text{molar 100} \times Mg / (Mg + \text{Total Fe}^2+)\]).

### Table 4. Age and Key Geochemical Features of Late Triassic Granitoids in the South Qinling Orogenic Belt, China

| Pluton name     | Lithology           | Age (Ma±1) | SiO₂ (wt%) | MgO (wt%) | Mg#  | Sr/Y  | La/Yb | Zircon Hf | Reference               |
|-----------------|---------------------|------------|------------|-----------|------|-------|-------|-----------|-------------------------|
| Gaoqiao        | Monzodiorite        | 217±3      | 62.25–63.85| 3.44–4.47 | 63.5–65.5| 33.6–50.1 | 20–30.3 | -0.4 to +6.4 | This study               |
| Dongjiangkou   | Granitoid           | 217±1      | 64–69.4    | 2.19–3.69 | 58–64 | 38.5–78.9 | 12.43–21.45 | -18.1 to -0.4 | Hu et al., 2017          |
| Zhashui        | Granitoid           | 200±1      | 68.38–72.2 | 0.51–1.42 | 34–55 | 18.9–40.6 | 14.45–24.45 | -3.5 to +2.3 | Hu et al., 2017          |
| Shahewan       | Granitoid           | 214±3      | 62.88–69.04| 1.49–2.45 | 55–58 | 54.3–83.0 | 11.6–21.5 | -1.3 to +3.2 | Lu et al., 2017          |
| Caoping        | Granitoid           | 216±3      | 62.88–68.05| 2.02–3.05 | 55–61 | 39.9–77.3 | 11.6–16.5 | -0.1 to +3.1 | Lu et al., 2017          |
| Zhashui        | Granitoid           | 208±2      | 69.32–75.94| 0.15–0.9  | 26–44 | 9.6–48.6  | 14.4–32.5 | -0.7 to +2.3 | Lu et al., 2017          |
| Huayang        | Granite             | 207–202 Ma | 70.6–76.5  | 0.01–1.02 | 2–51  | 0.8–53.2  | 5.09–68.25 | -14.1 to +1.1 | Hu et al., 2018          |
| Huayang        | Tonalite            | 207±2 Ma   | 61.3–69.0  | 0.74–1.85 | 38–49 | 24.9–134.0 | 30.26–48.62 | -6.7 to +1.9 | Hu et al., 2018          |
| Caoping        | Fine-grained granites| 216±1 Ma  | 70.8–73.2  | 0.40–0.83 | 37–65 | 18.4–70.5 | 21.60–39.34 | -8.6 to +4.3 | Hu et al., 2016          |
| Zhashui        | Medium-grained granitoid | 215±1 Ma | 60.1–68.5  | 1.92–4.88 | 51–64 | 28.5–41.5 | 11.69–15.38 | +1.0 to +2.8 | Hu et al., 2016          |
| Shahewan       | Porphyritic granitoid| 214±1 Ma  | 63.8–69.6  | 1.53–3.58 | 55–68 | 34.8–69.6 | 15.60–25.29 | -0.7 to +1.2 | Hu et al., 2016          |
| Dongjiangkou   | Tonalite            | 222±2 Ma   | 65.02–68.11| 2.35–3.03 | 63–65 | 58.9–75.6 | 13.3–30.5 | -7.5 to +3.1 | J.F. Qin et al., 2010    |
| Dongjiangkou   | Tonalite            | 214±2 Ma   | 65.56–68.24| 1.93–2.42 | 62–63 | 65.3–74.6 | 13.4–17.7 | -8.9 to +1.4 | J.F. Qin et al., 2010    |
| Dongjiangkou   | Granodiorite        | 220±2 Ma   | 63.45–67.29| 2.13–3.32 | 60–63 | 68.3–114.8| 10.9–22.9 | -9.8 to +2.8 | J.F. Qin et al., 2010    |
| Guangtoushan   | Granite             | 211±5 Ma   | 70.20–75.58| 0.08–0.52 | 28–37 | 10.8–102.8 | 2.7–31.8 | -9.2 to -2.6 | Lu et al., 2016          |
| Huayang        | Granite             | 212±4 Ma   | 67.75–72.66| 0.33–1.37 | 34–52 | 12.8–17.7 | 17.2–235.3 | -12.9 to -2.0 | Lu et al., 2016          |
| Wulong         | Quartz diorite      | 225–233 Ma | 60.65–67.97| 1.93–3.87 | 57–67 | 50–102  | 12.3–34.4 | -9.9 to +2.6 | Qin et al., 2013         |
| Wulong         | Granodiorite        | 218±2 Ma   | 69.16–70.82| 0.64–0.81 | 41–45 | 37–82   | 15.7–32.5 | -6.6 to +10.1 | Qin et al., 2013         |
| Wulong         | Monzogranite        | 207±2 Ma   | 67.68–70.29| 0.64–1.10 | 42–47 | 86–151  | 29.3–74.4 | -8.5 to +3.3 | Qin et al., 2013         |

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of slab break-off, upwelling of asthenosphere would have caused extension in mantle lithosphere (Davies and von Blankenburg, 1995). (2) Hydrous melting of metasomatized mantle wedge (which was formed by a previous subduction event) would have produced hydrous mafic melts. (3) Fractional crystallization of hornblende would account for the moderate Sr/Y and Yb/Lu ratios; the final product would have identical geochemistry with the host monzodiorite. Zircons that crystallized in this evolved mafic magma would have transitional Lu-Hf isotopic compositions. (4) The late-stage pristine hydrous mafic melts would have assimilated some crustal rocks before they intruded into the partially crystallized monzodiorite chamber. Limited magma mingling would have formed the mafic enclaves.

These results have the following important implications for the genesis of the Triassic granites in the Qinling area: (1) The Triassic collision caused the heterogeneity of the mantle lithosphere in the Qinling orogenic belt; (2) hydrous melting of metasomatized enriched mantle lithosphere produced high-Mg diorites similar to the host monzodiorite; (3) melting of relatively depleted mantle produced prismatic mafic melts that had depleted isotopic compositions; these prismatic mafic melts incorporated evolved crustal components before they intruded into the host monzodiorite chamber; (4) the mafic melts that derived from melting of mantle lithosphere provided an essential heat source for the crustal-derived granites in the Qinling orogenic belt.

CONCLUSIONS

(1) The host monzodiorite and its mafic enclaves from the Gaoqiao pluton have identical ages of 227 ± 3 Ma (MSWD = 1.4, 2σ) and 221 ± 3 Ma (MSWD = 1.7, 2σ), respectively. These ages are roughly contemporaneous with those of other Late Triassic granitoids and mafic enclaves in the Qinling orogenic belt. (2) The host monzodiorite was derived from hydrous melting of metasomatized enriched mantle wedge. Subsequent fractional crystallization of hornblende can account for the moderate Sr/Y and Yb/Lu ratios. (3) The mafic enclaves represent hydrous mafic melt that was derived from melting of relatively depleted mantle source. Their evolved Sr-Nd isotopic compositions were caused by assimilation of some evolved crustal components before they intruded into the host monzodiorite magma chamber. (4) These results indicate that melting of mantle wedge in the postcollisional stage may greatly contribute to crustal growth and lead to the extensive Triassic granites in the Qinling orogenic belt.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (41421002, 41102037), the Foundation for the Author of Excellent Doctoral Dissertation of China (201324), and a research grant of the State Key Laboratory of Continental Dynamics of China (SKLCD-04). We are grateful to the reviewers for their thorough reviews and valuable comments on the early draft of the manuscript.

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