Formation of the Qiyugou porphyry gold system in East Qinling, China: insights from timing and source characteristics of Late Mesozoic magmatism

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Abstract: The Qiyugou gold deposit, located in the East Qinling Orogen, is characterized by porphyry, breccia pipe-hosted and fracture-controlled hydrothermal mineralization. Four intrusive phases are identified in this deposit: pre-mineralization quartz porphyry, breccia pipe-hosted mineralization, syn-mineralization hornblende monzogranite associated with porphyry mineralization and post-mineralization monzogranite porphyry. These granitoids are metaluminous, alkalic to calc-alkalic, shoshonitic to high-K series, and belong to highly fractionated I-type granitoids. Most of the Qiyugou granitoids show relatively lower Sr/Y (<40) and (La/Yb)N (average = 12.0) than the typical granitoids are metaluminous, alkalic to calc-alkalic, shoshonitic to high-K series, and belong to highly fractionated I-type granitoids. These granitoids were generated at different crustal levels by a lithospheric thinning process linked to the tectonic transition from collisional and subsequent post-collisional hydrothermal system, upwelling of hot asthenosphere and intense mantle–crust interaction.

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Porphyry deposits are generally associated with hydrox and oxidized magmas generated in subduction-related arc settings, which can enhance solubility of metals (e.g. Cu, Mo and Au) and supply enough hydrothermal fluids for mineralization (Sillitoe 2010; Richards 2011). However, several porphyry Mo–Au deposits in the East Qinling Orogen (EVO) occur in association with highly fractionated I-type granitoids emplaced in Late Mesozoic (160–108 Ma) continent–continent collisional and subsequent post-collisional settings (Fig. 1; Li et al. 2018; Zhao et al. 2018). The key questions on the nature of magmatic rocks and the first-order factors that control porphyry mineralization in a collisional orogen remain open.

The Qinling Orogenic Belt (QOB), located between the North China Craton (NCC) and South China Craton (SCC), witnessed continent–continent collisional and subsequent post-collisional stages during the Late Mesozoic (Dong et al. 2021), generating large-scale felsic magmatism and associated Mo–Pb–Zn–Ag–Au mineralization (Mao et al. 2010; Li et al. 2018; Zhao et al. 2018).
Several studies have addressed the mechanism of formation of the porphyry Mo mineralization and associated magmatism (e.g. Li et al. 2013a; Xue et al. 2018a; Hu et al. 2020; Yang et al. 2020). However, the porphyry gold-only deposit representing a relatively new type of economic gold ore (Sillitoe 2010) and associated magmatism in the QOB remain poorly understood. The Qiyugou gold deposit is one of the largest Au deposits in the EQO with more than 60 tons of Au reserves at an average grade of 3.05 g t\(^{-1}\) (Deng et al. 2014; Wang et al. 2020). The deposit incorporates three types of mineralization that formed porphyry, breccia pipe-hosted and fracture-hosted hydrothermal ores. The three distinct mineralization styles are spatially and temporally correlated, and are considered to constitute a unified and genetically linked porphyry system (Wang et al. 2020; Tang et al. 2021a, b). Previous work has provided constraints on the timing and genesis of the Au mineralization-related granitoids at the Qiyugou deposit (Yao et al. 2009; Qi et al. 2019; Wang et al. 2020; Tang et al. 2021a). However, controversies related to the magma source and tectonic regime remain unresolved. Previous studies have proposed different magma sources for the Late Mesozoic granitoids, such as (1) mixture of partially melted basement of the NCC and mantle-derived materials (e.g. Zhao et al. 2018; Yang et al. 2019; Pang et al. 2020), (2) mixture of partially melted lower crust of the NCC and juvenile crust (e.g. Li et al. 2018; Zou et al. 2019) and (3) partial melting of crustal material from the northern margin of the Yangtze Craton (e.g. Bao et al. 2017, 2018). Diverse tectonic models controlling the Late Mesozoic magmatism have also been proposed, such as the subduction of the Palaeo-Pacific beneath the eastern portion of the NCC or post-collisional evolution in the QOB that led to the compressional and extensional settings (Dong and Santosh 2016; Pang et al. 2020). The multiple phases of granitoid magmatism at Qiyugou represent an ideal case to study the evolution of magma sources and tectonic regime, and their controls on economic porphyry Au mineralization.

In this paper, we perform an integrated study on the three phases of Late Mesozoic granitoids at the Qiyugou gold deposit, including detailed field investigation, petrography, whole-rock geochemistry, geochronology and in situ zircon Hf–O isotopes, to (1) determine the temporal relationships of the various granitoids, (2) decipher the origin and evolution of magma, (3) evaluate the genetic relationships between the causative magma and economic Au mineralization, and (4) construct a model for Early Cretaceous magmatism and porphyry Au mineralization.

Geological background

Regional geology

The QOB is located in the eastern segment of the Central China Orogen (CCO) (Fig. 1a). From south to north, the QOB is bounded by the Longmenshan Fault, Mianlue Suture, Shangdan Suture, Luanchuan Fault and San-bao Fault, and can be subdivided into four tectonic units: the northern margin of the Yangtze Craton (NYC), the South Qinling Belt (SQB), the North Qinling Belt (NQB) and the southern margin of the North China Craton (SNCC, alternatively named the Huaxiong Block) (Fig. 1b; Chen and Santosh 2014; Dong and Santosh 2016). The Huaxiong Block is situated in the northeastern segment of the QOB and hosts numerous gold deposits with total reserves of over 800 t (Fig. 1b and c; Deng et al. 2014). The Huaxiong Block is bounded to the south by the Luanchuan Fault and to the north by the San-Bao Fault. Four main lithospheric units, the Taihua Group,
Xiong’er Group, Guandaokou Group and Luanchuan Group, constitute the Huaxiong Block (Fig. 1b and c). The timing of formation and thermal overprinting, as well as subdivision of the Taihua Group, have long been contentious. It was previously divided into the Paleoproterozoic Upper Taihua Group and Mesozoic–Neoarchean Lower Taihua Group based on rock assemblages, which formed at 2.9–1.8 Ga (Huang et al. 2010; Jia et al. 2020). The Lower Taihua Group is mainly composed of tonalite–trondhjemite–granodiorite (TTG) gneiss, TTG-like gneiss and amphibolite. A suite of graphite-bearing gneisses, biotite gneisses, marbles, banded iron formation (BIF) and amphibolite constitute the Paleoproterozoic Upper Taihua Group (Jia et al. 2020). Some other researchers proposed a tripartite division for the Taihua Group considering the Lower Taihua Group as two separate units (Chen and Zhao 1997; Li et al. 2015). The Xiong’er Group comprises a suite of volcanic rocks including andesite, dacite and rhyolite with eruption age of 1.83–1.74 Ga (He et al. 2009; Wang et al. 2010, 2019). The Xiong’er Group has been considered as the product of a continental rift event (Zhao et al. 2002), mantle plume (Peng et al. 2007, 2008) or continental arc (He et al. 2009; Zhao et al. 2009). The Mesoproterozoic Guandaokou Group and Neooproterozoic Luanchuan Group consist of marine carbonates and clastic rocks (Zhu et al. 2011).

The exposed magmatic units in the Huaxiong Block include the Triassic and Late Mesozoic mafic–felsic rocks. The Triassic magmatism mainly generated alkaline magmatic rocks, such as the Mogou pluton, which is composed of syenite stocks (Tang et al. 2019b). The Huaxiong Block also records intense magmatism and associated metallogeny in the Late Mesozoic (Mao et al. 2010; Li et al. 2018; Zhao et al. 2018). The igneous activity mainly occurred as granitic magmatism during the Late Jurassic–Early Cretaceous, which generally consists of composite plutons and small porphyry stocks (Fig. 1c).

The Huaxiong Block hosts numerous economic mineral deposits, including porphyry gold and Mo deposits (e.g. Bao et al. 2018; Qi et al. 2019; Wang et al. 2020), orogenic gold deposits (e.g. Tang et al. 2019a), breccia pipe-hosted gold deposits (Chen et al. 2009), and vein-type Mo, Au, Ag–Pb–Zn and fluorite deposits (e.g. Tang 2014; Li et al. 2016; Zhao et al. 2019; Tang et al. 2021c). Gold deposits in the Huaxiong Block occur along east–west folds, east–west-trending faults or NE- to NNE-trending faults. The mineralization is largely linked to Triassic and Late Mesozoic magmatic–hydrothermal events (Zhao et al. 2018; Tang et al. 2019a; Feng et al. 2021).

Deposit geology

The Qiyugou deposit is located in the eastern segment of the Xiong’er shan area, which is situated c. 10 km SE of the Huashan pluton (Fig. 1b). The dominant lithologies exposed in the mining area are as follows (Fig. 2a): (1) the Late Neoarchean–Paleoproterozoic Taihua Group; (2) the Paleoproterozoic Xiong’er Group; (3) a Cenozoic sedimentary sequence that overlies the basement rocks. The Taihua and Xiong’er groups are intruded by Neooproterozoic diorite and Late Mesozoic granitoid (granite porphyry, quartz porphyry, hornblende monzogranite and monzogranite porphyry) (Fig. 2) (Chen and Fu 1992).

The Qiyugou deposit includes three distinct styles of gold mineralization, with ores hosted in the hornblende monzogranite pluton (8 × 8 t at 2.15 g t⁻¹; Wan and Chen 2017), breccia pipe (>60 t at 1.68 g t⁻¹; Chen et al. 2009; Fan et al. 2011; Deng et al. 2014) and hydrothermally altered rocks in fractures (10.3 t at 10.07 g t⁻¹; Li et al. 2005).

The newly discovered porphyry ore is hosted by the Qi189 pluton, which is tabular in shape (380 m × 200 m) and extends in a NW–SE direction (dipping to the NE at 85–90°). The pluton has a surface exposure of c. 0.042 km² at the Qiyugou deposit (Fig. 2a). Drilling and mining tunnels have revealed the area of the pluton to be up to 0.127 km² at a level of 280 m above sea-level (ASL) (Fig. 2b). The main intrusive phases of the ore-bearing pluton are composed of hornblende monzogranite, granite porphyry and monzogranite porphyry (Figs 2b, c and 3). Granite porphyry appears in the mining tunnel at a level of 280 m ASL in the ore-bearing pluton. The monzogranite porphyry occurs in the centre of the ore-bearing pluton and crosscuts the hornblende monzogranite stock. Porphyry mineralization is characterized by extensive stockwork veining, and disseminated pyrite in the potassic-altered hornblende monzogranite stock. The main gold ore is spatially associated with the silicified core (c. 200 m in length and c. 70 m in width) at the apical part of the stock, which strikes NW and dips to the SW (Fig. 2b). Native gold and electrum are mainly observed as inclusions and fissure-fillings within pyrite and quartz. Five alteration types (potassic alteration, phyllic alteration, propylitization, silicification and pyritization) are systematically recognized within the Qiyugou deposit, with mineral assemblages consisting of K-feldspar, quartz and minor chlorite, sericite, carbonate, epidote and dolomite (Qi et al. 2019; Wang et al. 2020).

The Qiyugou deposit includes at least 10 auriferous breccia pipes, which are distributed along the NW-trending faults (Fig. 2; Wang et al. 2020). The largest Au orebody was identified in the J4 breccia pipe near the ore-bearing pluton, showing a length of 300 m, width of 200 m and an extent of 170 m in elevation from 475 to 310 m (Fig. 2a). The granite rock beneath the J4 breccia pipe is composed of yellowish to reddish hornblende monzogranite with clear phenocrysts and matrix (Fig. 3d and h). The breccia pipe-hosted mineralization mainly occurs as sulfide disseminations and vein stockworks. The metallic minerals in gold ores are dominated by pyrite and other sulﬁdes (e.g. chalcopyrite, molybdenite, galena and sphalerite), native gold and electrum. These minerals occur as quartz–sulfide veins or matrix cements between the breccia clasts. Gangue minerals include quartz, chlorite, calcite and K-feldspar. The hydrothermal alterations are dominated by potassic and silica alterations, which are partly overprinted by epidotization, sericitization, chloritization, carbonation, propylitization and pyritization (Chen et al. 2009; Li et al. 2012b; Xiong et al. 2019).

The fracture-hosted Au orebodies are mainly located in the NE of the Qiyugou deposit, comprising quartz–sulfide veins and stockworks, and disseminated sulfides in hydrothermally altered rocks of the Taihua Group and a small portion of the Xiong’er Group. All nine orebodies are largely restricted to alteration zones developed along the NE-striking (40–65°) and NNE-striking faults (10–25°) and their secondary structures (Fig. 2). These faults approximately range from 600 to 2520 m long and from 0.4 to 5 m wide. The orebodies strike 40–60° and dip 47–80° to the NE, and are present as lenticles or veins of 155–544 m length and 0.5–1.5 m thickness (Fig. 2a; Tang 2014). Sulfide minerals are predominantly pyrite, with lesser amounts of galena, chalcopyrite, sphalerite and argentite. Quartz, feldspar, calcite, biotite, sericite, hornblende and kaolinite are present as gangue minerals coexisting with pyrite. Hydrothermal alteration occurred along the fault zone and involved a combination of potassic, sericitic and argillic alterations (Tang 2014).

Sampling and analytical methods

Samples

Five hornblende monzogranites (QYG-B01, QYG-B02, QYG-B03, QYG-B04 and QYG-B05), two granite porphyries (QYG-BQ01 and QYG-BQ02) and three monzogranite porphyries (QYG-BR01, QYG-BR02 and QYG-BR03) from the Qi189 pluton were collected along the tunnel at a level of 280 m ASL that cuts across the pluton...
from south to north (Fig. 2b). Fine-grained (1–2 mm), greyish–reddish hornblende monzogranite is the most voluminous intrusive phase (Fig. 3a). The hornblende monzogranite contains 60–70 vol % phenocrysts (Fig. 3e). The phenocrysts comprise K-feldspar (30–40 vol%), plagioclase (30–40 vol%), quartz (10–15 vol%) and minor hornblende (c. 5 vol%). The matrix minerals consist of K-feldspar (10–15 vol%), quartz (15–20 vol%), plagioclase (10–15 vol%), chlorite (c. 5 vol%), epidote (c. 5 vol%) and accessory magnetite, apatite, zircon, titanite and rutile. The reddish grey, fine-grained granite porphyry characterized by porphyritic texture (Fig. 3b and f). The granite porphyry contains 20–30 vol% phenocrysts and 70–80 vol% matrix (Fig. 3e). Quartz (30–40 vol %), K-feldspar (20–30 vol%) and plagioclase (10–20 vol%) dominate the euhedral phenocrysts (Fig. 3f). The matrix minerals consist of quartz (60–70 vol%), plagioclase (20–30 vol%) and K-feldspar (10–15 vol%). The monzogranite porphyry is pinkish grey and dominated by K-feldspar, plagioclase and quartz phenocrysts (Fig. 3c and g). The phenocrysts include 30–40 vol% of K-feldspar (of 1–2 mm grain size), 20–30 vol% of plagioclase (of 1–2 mm grain size), 20–30 vol% of quartz (of 1–2 mm grain size), c. 5 vol% of hornblende and some megaphenocrysts of these minerals with size up to 1 × 2 cm. Plagioclase and K-feldspar phenocrysts are

Fig. 2. Geological maps, showing the Qiyugou gold deposit (a), Au orebodies at level of 280 m above sea-level (b) and section along an exploration line of the Qiyugou gold deposit (c) (modified after Qi et al. 2019).
Late Mesozoic magmatism at the Qiyugou Au deposit

Two hornblende monzogranites (QYG-B06 and QYG-B07) were collected from the monzogranite pluton beneath J4 breccia pipes (Fig. 2a). The sample locations are labelled in Figure 2b. Hornblende monzogranites are composed of 60–70 vol% phenocrysts and 30–40 vol% matrix. The phenocrysts of K-feldspar and plagioclase are larger than those in the hornblende monzogranite of the ore-bearing pluton, and show zoned and euhedral to subhedral features (Fig. 3h). The matrix minerals consist of quartz (10–15 vol%), plagioclase (5–10 vol%), K-feldspar (5–10 vol%) and a small quantity of accessory apatite, titanite, zircon and magnetite.

Whole-rock geochemistry

All samples were cleaned to remove weathered surfaces and subsequently crushed to 200 mesh powders. The major and trace elements were analysed at the Analytical Laboratory in Beijing Research Institute of Uranium Geology by X-ray fluorescence (XRF) using a Philips PW2404 system and by inductively coupled plasma mass spectrometry (ICP-MS) using a Finnigan MAT
Zircon U–Pb analysis

Zircon U–Pb–Hf–O isotope analyses were carried out on hornblende monzogranites (QYG-B02 and QYG-B06), granite porphyry (QYG-BQ01) and monzogranite porphyry (QYG-BR01).

Zircon grains were extracted using standard techniques (heavy liquid separation, magnetic separator and handpicking under a binocular microscope) at the Langfang Honesty Geological Services Co. Ltd, China. Zircon grains were mounted together with standards Plesovice (337.13 ± 0.37 Ma; Sláma et al. 2008), Penglai (4.4 ± 0.1 Ma; Li et al. 2010b) and Qinghu (159.5 ± 0.2 Ma; Li et al. 2013b) in an epoxy mount, which was then polished to section the crystals in half for analysis. The polished mount was photographed under cathodoluminescence (CL) and transmitted and reflected light. Zircon U–Pb isotope analyses were measured via secondary ion mass spectrometry (SIMS) and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS).

For samples QYG-B02, QYG-BQ01 and QYG-BR01, we used a Cameca IMS 1280-HR ion microprobe at the Analytical Laboratory in Beijing Research Institute of Uranium Geology (hereafter referred to as BRIUG). The analytical methods used for SIMS in Beijing Research Institute of Uranium Geology (hereafter referred to as BRIUG). The analytical methods used for SIMS instruments are the same as those described by Li et al. (2010a). The O2+ primary ion beam was accelerated at 10 kV, with an intensity range of c. 3.7–6.8 nA. The rectangular beam is about 20 × 30 µm in size. Positive secondary ions were extracted with a 10 kV potential, and low-energy secondary ions were selected using an energy window of 50 eV. The daily mass resolving power was c. 6000. The primary reference material used for U–Pb dating was Plesovice dated at 337.13 ± 0.37 Ma (Sláma et al. 2008) with Qinghu (159.5 ± 0.2 Ma; Li et al. 2013b) used as a secondary dating standard. The weighted average 206Pb/238U ages calculated for Plesovice and Qinghu were 337.3 ± 1.3 Ma (n = 25, MSWD = 0.32) and 158.9 ± 0.92 Ma (n = 13, MSWD = 0.77) respectively; these values are in good agreement with the ages reported by Sláma et al. (2008) and Li et al. (2013b).

Sample QYG-B06 was analysed simultaneously for U–Pb dating and trace element analyses by LA-ICP-MS at the Wuhan Sample Solution Analytical Technology Co. Ltd, Wuhan. Isotopic abundances of zircon were measured using an Agilent 7700e ICP-MS instrument, connected to a Compexpro 102 ArF excimer laser incorporating a MicroLas optical system. The analytical methods and instrument conditions were as described by Zong et al. (2017). The standards 91500 (1062.4 ± 0.4 Ma; Wiedenbeck et al. 2004) and NIST610 were used as external standards for U–Pb dating and trace element analysis, respectively. Plesovice (337.13 ± 0.37 Ma; Sláma et al. 2008) and GJ-1 (599.8 ± 1.7; Jackson et al. 2004) were used as unknown samples to monitor the precision and accuracy of the acquired U–Pb data. Plesovice and GJ-1 yielded weighted average 206Pb/238U ages of 337.3 ± 1.8 Ma (n = 8, MSWD = 0.65) and 601.6 ± 3.1 Ma (n = 10, MSWD = 0.12), respectively. Data processing was accomplished by ICPMSDataCal and Isoplot 4.15.

Zircon Lu–Hf analysis

Hafnium isotope analyses were carried out using a Resonetics Resolution M-50A-LR incorporating a Compex 102 excimer laser, attached to a Nu Instruments Plasma II MC-ICP-MS system at John de Laeter Centre at the Curtin University. The primary reference material used for monitoring accuracy and precision of internally corrected Hf isotope ratios (using 176Hf/177Hf = 0.7325) was Mud Tank zircon (Jackson et al. 2004), which yielded a corrected 176Hf/177Hf weighted average ratio of 0.282507 ± 0.000008 (MSWD = 0.84, n = 20). Zircon 91500 and Plesovice were used as secondary standards, which yielded a corrected 176Hf/177Hf weighted average ratio of 0.282294 ± 0.000017 (MSWD = 2.4, n = 20) and 0.282473 ± 0.000014 (MSWD = 0.84, n = 10), respectively (Woodhead and Hergt 2005; Sláma et al. 2008). The stable 176Hf/177Hf and 180Hf/177Hf ratios for the standard Plesovice yielded values of 1.467265 ± 0.000127 (2SD, n = 10) and 1.886511 ± 0.000251 (2SD, n = 10), respectively. Standard 91500 yielded average 176Hf/177Hf and 180Hf/177Hf ratios of 1.467302 ± 0.000174 (2SD, n = 20) and 1.886482 ± 0.000481 (2SD, n = 10), respectively. These values of the reference materials all fall within the known ranges reported by Spencer et al. (2020) (corresponding to 176Hf/177Hf between 1.46688 and 1.46746 and 180Hf/177Hf between 1.88628 and 1.88704). The analytical procedures and conditions were similar to those described by Spencer et al. (2017), and the data deduction, error propagation and interpretation of weighted means were discussed by Spencer et al. (2016).

Zircon O isotope analysis

Zircon oxygen isotopes were measured by using two different SIMS instruments. Most zircon oxygen isotopes for samples QYG-B02, QYG-BQ01 and QYG-BR01 were analysed using the Cameca IMS 1280-HR ion microprobe at BRIUG. We also used a Cameca 1280 microprobe for samples QYG-B02, QYG-BQ01 and QYG-B06 at the Centre for Microscopy, Characterisation and Analysis (CMCA), University of Western Australia.

At BRIUG and CMCA the 133Cs+ primary ion beam was accelerated at 10 kV with intensity of 2.1–2.5 nA and 2.5–3.0 nA, respectively. The beam sizes were 20 × 30 µm (BRIUG) and 15 × 20 µm (CMCA). Ions were extracted with a 10 kV voltage, and low-energy secondary ions of 16O and 18O were selected using an energy window of 50 eV. The daily mass resolving power was c. 6000. The primary reference material used for U–Pb dating was Plesovice dated at 337.13 ± 0.37 Ma (Sláma et al. 2008) with Qinghu (159.5 ± 0.2 Ma; Li et al. 2013b) used as a secondary dating standard. The weighted average 206Pb/238U ages calculated for Plesovice and Qinghu were 337.3 ± 1.3 Ma (n = 25, MSWD = 0.32) and 158.9 ± 0.92 Ma (n = 13, MSWD = 0.77) respectively; these values are in good agreement with the ages reported by Sláma et al. (2008) and Li et al. (2013b).

Sample QYG-B06 was analysed simultaneously for U–Pb dating and trace element analyses by LA-ICP-MS at the Wuhan Sample Solution Analytical Technology Co. Ltd, Wuhan. Isotopic abundances of zircon were measured using an Agilent 7700e ICP-MS instrument, connected to a Compexpro 102 ArF excimer laser incorporating a MicroLas optical system. The analytical methods and instrument conditions were as described by Zong et al. (2017). The standards 91500 (1062.4 ± 0.4 Ma; Wiedenbeck et al. 2004) and NIST610 were used as external standards for U–Pb dating and trace element analysis, respectively. Plesovice (337.13 ± 0.37 Ma; Sláma et al. 2008) and GJ-1 (599.8 ± 1.7; Jackson et al. 2004) were used as unknown samples to monitor the precision and accuracy of the acquired U–Pb data. Plesovice and GJ-1 yielded weighted average 206Pb/238U ages of 337.3 ± 1.8 Ma (n = 8, MSWD = 0.65) and 601.6 ± 3.1 Ma (n = 10, MSWD = 0.12), respectively. Data processing was accomplished by ICPMSDataCal and Isoplot 4.15.

Results

Zircon U–Pb dates

The zircon grains in the hornblende monzogranites (QYG-B02 and QYG-B06), granite porphyry (QYG-BQ01) and monzogranite porphyry (QYG-BR01) are generally colourless to brown and translucent, and are euhedral to subhedral. The grains show an average diameter of 100 µm with typical oscillatory zoning in CL images, which, in combination with their high Th/U ratios of 0.35–1.74, indicates their magmatic origin (Belousova et al. 2002; Fig. 4a, c, e and g; Supplementary Table 1).
The U–Pb analytical data of sample QYG-B02 yield a weighted mean $^{206}\text{Pb}^{238}\text{U}$ age of $131.3 \pm 0.9$ Ma (MSWD = 1.5; overdispersed; Wendt and Carl 1991; Spencer et al. 2016; Fig. 4b), representing the crystallization time of the hornblende monzogranite.
The 206Pb/238U spot ages of sample QYG-BQ01 range between 131 and 136 Ma, yielding a weighted mean age of 133.4 ± 0.8 Ma (MSWD = 1.1; single population; Fig. 4d). This age is considered to represent the crystallization age of the granite porphyry.

Seventeen analyses of sample QYG-BR01 yield a weighted mean 206Pb/238U age of 128.0 ± 0.7 Ma (MSWD = 1.0; single population; Fig. 4f), which is interpreted as the crystallization age of the monzogranite porphyry.

Fourteen zircon grains of sample QYG-B06 have ages ranging from 128 to 132 Ma and yield a weighted mean 206Pb/238U age of 129.9 ± 0.9 Ma (MSWD = 1.9; overdispersed; Fig. 4h), which is considered as the crystallization age of the hornblende monzogranite.

Whole-rock geochemistry

Major and trace element data are presented in Supplementary Table 2 and illustrated in Figures 4–7. The rocks show loss on ignition (LOI) values in the range of 1.15–3.19 wt% (Supplementary fig. 1). As shown in Supplementary Figure 1, the granitic porphyry, hornblende monzogranite and monzogranite porphyry from the Q189 pluton and the hornblende monzogranite from the J4 breccia pipe have different LOI values, which show no distinct correlation with alkali elements (Na, K, Rb) and alkali earth elements (Ca, Sr, Ba), suggesting that mobile elements of these granitoids are not modified by alteration. Furthermore, major element data of these granitoids plot as tight clusters or coherent trends and whole-rock REE and trace element compositions display similar patterns, suggesting a limited effect on elemental compositions during late alteration (Figs 5 and 6).

The hornblende monzogranites from the Q189 pluton and the J4 breccia pipe show roughly similar major and trace element compositions, which are characterized by high SiO2 contents of 65.2–69.8 wt% and total alkali (Na2O + K2O) of 8.94–10.41 wt% (Supplementary Table 2). A plot of total alkali v. silica (TAS) shows that the samples fall in the quartz monzonite field (Fig. 5a). On the quartz–alkali feldspar–plagioclase (QAP) diagram, the samples mainly plot in the monzogranite field with fewer values in the syenogranite and quartz syenite fields (Fig. 5b). They show shoshonitic, alkaline to alkaline-calcic (Fig. 5a, c and e) and metaluminous features (Fig. 5d). These samples have relatively variable Mg# (15.0–32.1), and plot in the fields of metasaltic and eclogitic melts (1.0–4.0 GPa), as well as thick lower crust-derived adakitic rock (Fig. 5f). The samples show enrichments in light REE (LREE) over heavy REE (HREE), and the hornblende monzogranites from the Q189 pluton have relatively higher (La/Yb)N (Supplementary Table 2). The hornblende monzogranite from the Q189 pluton have slightly positive Eu anomalies and higher Sr/Y ratios, in contrast to the hornblende monzogranites beneath the J4 breccia pipe, which show negative Eu anomalies and lower Sr/Y ratios (Figs 6a and 7g; Supplementary Table 2). On the chondrite-normalized spider diagram, all data show consistently negative anomalies of Th, Nb, Ta and Ti and positive Sr, Ba, U, K and Pb anomalies (Fig. 8).

Compared with the hornblende monzogranites, the granite porphyries have higher SiO2 (75.3–75.9 wt%) and lower total alkali contents (8.4–8.6 wt%), and plot in the granite field and subalkaline series in the TAS diagram (Fig. 5a), and in the syenogranite field in the QAP diagram (Fig. 5b). They are characterized by high-K, calc-alkalic and metaluminous features (Fig. 5c, d and e). The granite porphyries have low Sr/Y (<30; Fig. 6a) and La/Yb (<20; Fig. 6b) ratios (Supplementary Table 2). On the chondrite-normalized spider diagram, they have negative anomalies of Ba, Nb, Ta, P and Ti and positive anomalies of Rb, Th, U, K, Zr, Hf and Pb (Fig. 8d). They have significantly lower ΣREE values, and show strongly negative Eu anomalies and moderate LREE enrichment (Fig. 8c; Supplementary Table 2).

The monzogranite porphyries are felsic in composition (SiO2 = 65.2–65.6 wt%; Fig. 5a), with slightly lower total alkali contents (7.9–8.9 wt%), and plot in the quartz monzogranite and subalkaline fields (Fig. 5a). On the QAP diagram, the samples plot in the monzogranite field (Fig. 5b). They belong to the shoshonitic to high-K series with alkali-calcic and metaluminous features (Fig. 5c, d and e). These rocks have high Mg# (>40) and MgO (1.33–1.45 wt%) (Figs 5c and 6b). On the chondrite-normalized spider diagram, they have negative anomalies of Ba, Nb, Ta, Sr, P and Ti and positive Rb, Th, U, Sm, Nd and Pb anomalies (Fig. 8f). They have high (La/Yb)N and negative Eu/Eu* ratios (Fig. 8e; Supplementary Table 2).

Zircon Lu–Hf isotopic compositions

The hornblende monzogranite samples QYG-B02 and QYG-B06 have similar Lu–Hf isotope characteristics, displaying 176Hf/177Hf ratios of 0.282002–0.282235 and 0.281965–0.282265, respectively. They show εHf(t) values mainly ranging from −25.9 to −12.0 and crustal model ages (TDM2) in the range of 2821 to 1949 Ma (Supplementary Table 3; Figs 9 and 10). Zircon grains from QYG-BQ01 have higher 176Hf/177Hf ratios than those from QYG-B02, which display εHf(t) values of −37.4 to −29.5 and TDM2 ages of 3530–3053 Ma (Supplementary Table 3; Figs 9 and 10). Compared with QYG-B02, the zircons from QYG-BR01 have significantly higher 176Hf/177Hf ratios (0.282285–0.282374) and εHf(t) values (−14.6 to −11.4), but lower TDM2 ages (2109–1912 Ma) (Supplementary Table 3; Figs 9 and 10).

Zircon O isotopic compositions

The zircon oxygen isotopic results are presented in Figures 10 and 11 and Supplementary Table 4. Zircon grains from these granitoids have δ18OWR values of 5.19–6.53‰, which are broadly consistent with those of zircons in equilibrium with mantle-derived melts (5.3 ± 0.6‰, 2σ; Valley 2003). The whole-rock oxygen isotopic compositions (δ18OWR) were calculated on the basis of the formula of δ18OWR = δ18Ozircon – δ18OWR ≈ −0.0612SiO2 (in wt%) + 2.5 (Valley et al. 2005). The δ18OWR values range from 6.93 to 8.45‰ (Supplementary Table 4).

Discussion

Timing of Late Mesozoic magmatism and Au mineralization

Several geochronological studies, including Ar–Ar dating of hydrothermal minerals (e.g. quartz, K-feldspar, sericite), Re–Os dating of sulfide minerals (molybdenite and pyrite) and U–Pb dating of zircons, were utilized to constrain the timing of granitoid magmatism and Au mineralization at the Qiyugou deposit (Fig. 12 and references therein). As illustrated in Figure 12, the available data in combination with our new zircon–U–Pb ages provide a general geochronological framework for the Late Mesozoic multistage granitoid magmatism and Au mineralization at the Qiyugou deposit.

The magmatic–hydrothermal events in the Qiyugou deposit can be divided into two episodes (Fig. 12): (1) a Late Jurassic magmatic–hydrothermal event was dated at 158.7–150.1 Ma (Deng et al. 2014; Tang 2014; Wang et al. 2020); (2) an Early Cretaceous magmatic–hydrothermal event occurred at 136–124 Ma (this study; Yao et al. 2009; Qi et al. 2019; Wang et al. 2020; Tang et al. 2021a).

Notably, the quartz porphyry and hornblende monzogranite dykes collected from the breccia pipes and fracture-hosted orebody display zircon–U–Pb ages of 158.7–150.1 Ma, which are considered to represent the emplacement ages of the pre-mineralization intrusions (Deng et al. 2014; Tang 2014; Wang et al. 2020). For the 136–124 Ma magmatic–hydrothermal event, syn-mineralization
Fig. 5. Geochemical plots of the granitoids from the Qiyugou gold deposit. (a) Total alkali v. SiO$_2$ diagram (Middlemost 1994); the dashed line separating alkaline series from subalkaline series is from Irvine and Baragar (1971); (b) Q–A–P diagram (Streckeisen 1976); (c) K$_2$O v. SiO$_2$ diagram (modified from Peccerillo and Taylor 1976; Gill 2012); (d) A/NK (molar ratio Al$_2$O$_3$/(Na$_2$O+K$_2$O)) v. A/CNK (molar ratio Al$_2$O$_3$/(CaO + Na$_2$O+K$_2$O)) diagram (Maniar and Piccoli 1989); (e) Na$_2$O + K$_2$O – CaO v. SiO$_2$ diagram; base diagram from Frost et al. (2001); (f) Mg$^+$ v. SiO$_2$ diagram. Fields of metabasaltic and eclogitic experimental melts, delaminated and thick lower crust-derived adakitic rocks are after Zou et al. (2019). Source A is a supposed pure slab melt (Stern and Kilian 1996) and source B is the metabasaltic or eclogitic experimental melt, which is not hybridized by mantle peridotite (Rapp et al. 1999).
magmatism at 134.1–133.4 Ma that formed granite porphyry was associated with breccia pipes-hosted mineralization (this study; Yao et al. 2009). The porphyry Au mineralization is genetically linked with the later-stage magmatic–hydrothermal activity that occurred at 131.3–129.9 Ma (this study; Wang et al. 2020). Furthermore, post-mineralization magmatism represented by late dykes of monzogranite porphyry and quartz monzonite is dated at 128.9–124.7 Ma (this study; Qi et al. 2019; Wang et al. 2020).

The Ar–Ar data may reflect the resetting of the Ar radiometric system owing to Ar gain or loss during later thermal overprint (Villa and Williams 2013). The Ar–Ar ages of hydrothermal minerals from breccia pipes and porphyry orebodies are relatively young and vary from 130 ± 0.9 to 109.2 ± 0.7 Ma with large uncertainties and mean standard weighted deviation (MSWD > 10) (Wang et al. 2001, 2020; Qi et al. 2004; Tang 2014). Notably, Wang et al. (2020) recently reported an emplacement age of 128.9–127.4 Ma for a post-mineralization monzogranite porphyry dyke that cuts the auriferous breccia pipes, porphyry orebodies and fractures. The ages are highly contradictory with the Ar–Ar ages, which are younger than the zircon U–Pb ages of post-mineralization dykes (Fig. 12). The pyrites coexisting with gold from the porphyry orebody show weighted mean Re–Os ages of 127.5 ± 8.2 Ma (MSWD = 6.4; Qi et al. 2019; Fig. 12), which are also younger than the emplacement ages of post-mineralization dykes. The large uncertainties and high

Fig. 6. Harker variation diagrams showing the major element compositions of the Qiyugou granitoids from this study compared with Qiyugou granitoid data from the literature (Yao et al. 2009; Deng et al. 2014; Qi et al. 2019; Wang et al. 2020).
Late Mesozoic magmatism at the Qiyugou Au deposit

Origin of Qiyugou granitoids

The ɛHf(t) values increase gradually from the oldest granite porphyry (133.4 ± 0.8 Ma) to the youngest monzogranite porphyry (128.0 ± 0.7 Ma), ranging from −37.4 to −29.5 and changing to −14.6 to −11.4. The corresponding TDM2 ages shift from 3530–3053 Ma to 2109–1912 Ma (Figs 9 and 10). The Hf isotopic features of these granitoids suggest that the parental magma originated from ancient continental crust. The systematic change with time could be ascribed to an increased contribution from an endmember with higher zircon ɛHf(t) values.

Previous studies showed that the crustal rocks at mid- to lower crustal levels in the SNCC were mainly composed of the Taihua Group and Xiong’er Group (Wang et al. 2010; Jia et al. 2020). Some workers also considered that the crustal materials of the NQOB (Kuanping and Qinling groups) and NYC also occur at lower crust or lithosphere mantle levels in the SNCC after the subduction–collision of the Yangtze Craton and North China Craton (Yao et al. 2009; Qi et al. 2019). However, available published data show that the major eruption age and TDM2 ages of the Xiong’er Group volcanic rocks were limited to the range 1.83–1.74 Ga and 3.38–1.29 Ga respectively (Wang et al. 2019). The Kuanping Group and Qinling Group of the NQOB have ages in the range of Late Mesoproterozoic to Early Neoproterozoic (c. 1462 to 412 Ma), corresponding to TDM2 ages mainly ranging from 3.4 to 1.0 Ga (Zhu et al. 2011; Shi et al. 2013). The basement of the northern margin of the YC is mainly younger than 2.2 Ga (Archean rocks are limited to the Kongling terrain far from the QOB; Gao et al. 2011) and has a wide eHf(t) variation from −8.67 to 13.52 and old TDM2 ages from 4.26 to 3.25 Ga (Liu et al. 2008). The mineralized hornblende monzogranite contains inherited zircons with ages up to >3.5 Ga (Qi et al. 2019), and regional Late Mesozoic granitoids in the EQOB also contain abundant inherited zircons with Mesoproterozoic to Paleoproterozoic ages (mostly between 2700 and 1700 Ma; Mao et al. 2010; Gao et al. 2012; Han et al. 2013; Li et al. 2013a; Deng et al. 2014; Li et al. 2018). The inherited zircon U–Pb ages are older than those of the NQC, NQOB and Xiong’er Group. The granite porphyry with TDM2 ages from 3530 to 3053 Ma cannot be produced by the relatively young crustal materials of the NQOB and Xiong’er Group. Furthermore, the whole-rock Pb isotopic data for granitoids in the EQOB are consistent with basement rocks in the SNCC, but differ from those in the NYC (Li et al. 2018).

The Taihua Group was formed through multistage magmatic events during the period 2.9–1.8 Ga, and experienced multiple phases of strong deformation and metamorphism at 2.79–2.74 Ga and 1.96–1.82 Ga, respectively (Jia et al. 2020). The Hf crustal model ages of the Taihua Group range from 2.46 to 3.55 Ga (Jia et al. 2020). When we recalculate the eHf(t) values of the Taihua Group at the age of Late Mesozoic magmatism (set as 130 Ma), they range from −71.1 to −41.6 (data from Huang et al. 2010). This means that the Taihua Group might have been a dominant crustal source for the magmas, with Hf isotopic features consistent with those of granitoids from the Qiyugou deposit.

Fig. 7. Variation of Sr/Y v. Y (a) and La/Yb v. Yb (b) for the Qiyugou granitoids from this study compared with Qiyugou granitoid data from the literature (sources of data after Fig. 5). ‘Adakite-like rocks’ and ‘Normal andesite–dacite–rhyolite’ fields follow Richards and Kerrich (2007).
Fig. 8. Chondrite-normalized REE patterns and primitive mantle-normalized multi-element diagrams for the granitoids from the Qiugou gold deposit. Data for the Taihua Group and Xiong'er Group are shown for comparison (He et al. 2010; Huang et al. 2010). Chondrite and primitive mantle normalizing values are from Sun and McDonough (1989).
Late Mesozoic magmatism at the Qiyugou Au deposit

We propose a mixing model involving the Taihua Group and Qinling Group components of the NQOB, crustal components from the YC and mantle-derived materials to evaluate the magma sources and corresponding proportion of different endmembers (Fig. 11). Mid-ocean ridge basalt (MORB) is considered to represent the mantle endmember because granitic melts cannot be directly produced by partial melting of mantle peridotite, and can be generated only from mafic to felsic rocks. The other three endmember sources are the partial melts (fluids) of the Taihua Group, Qinling Group and crust of the YC. A mixing model of the Taihua Group and MORB shows that a mixture of 10–35% mantle material into the Taihua Group can generate the Hf–O isotopic array of monzonogranite from the Q189 pluton and J4 breccia pipe (Fig. 11). In contrast, the proportion of mantle material in the granite porphyry is constrained to be 5–20%, which is consistent with their lowest whole-rock MgO value and relatively low (La/Yb)$_n$ (Figs 6b, 13 and 14 and Supplementary Table 2). Monzonogranite porphyries have the highest proportion of MORB (20–45%), showing significant involvement of mantle-derived materials. As shown in Figure 11, few samples of Qiyugou granitoids are in accordance with the mixing curves of the Taihua Group and Qinling Group or crust of the YC, based on the similar δ$^{18}$O$_{zircon}$ values of these three endmembers. Such a range of δ$^{18}$O$_{zircon}$ variation in the Qiyugou granitoids was unlikely to be produced by partial melting of the Taihua Group mixed with crustal components of the NQOB or the YC. Furthermore, all samples do not fall in the mixing model fields of MORB and crustal components of the NQOB or the YC, which argues in favour of the Taihua Group and MORB serving as isotopic reservoirs of Qiyugou granitoids.

 Petrological constraints such as high MgO and low SiO$_2$ contents can indicate the involvement of mantle-derived materials (Zheng 2015). The SiO$_2$ content decreases gradually from the oldest granite porphyry ($133.4 \pm 0.8$ Ma, ε$^{18}$O$_{zircon} = -37.4$ to $-29.5$) to the youngest monzonogranite porphyry ($128.0 \pm 0.7$ Ma, ε$^{18}$O$_{zircon} = -14.6$ to $-11.4$), showing average values from 75.6 to 65.40 wt% (Fig. 15a). Such a transition corresponds to an increase of MgO contents, with an average from 0.10 to 1.39 wt%, respectively (Fig. 15b). Moreover, the products mixed with mantle-derived materials were also considered to show weak enrichment of large ion lithophile elements (LILE), Pb and RREE (Zheng 2015). Nevertheless, these granitoids show significant enrichment in LREE over HREE and LILE, and moderately depletion of high field strength elements (HFSE). There could be two factors contributing to the whole-rock geochemical features of these granitoids. First, the Taihua Group is probably the dominant crustal source for the magmas, so theREE and trace element normalized plots of these granitoids have similar patterns to those of the Taihua Group. Second, the Late Mesozoic granitoids at the Qiyugou deposit are classified as highly fractionated I-type granite and formed through noticeable fractional crystallization processes (Fig. 13; Li et al. 2018).

In conclusion, whole-rock geochemistry and zircon Hf–O isotopes indicate that the parental magma of the granitoids from the Qiyugou deposit was mainly sourced from partial melting of the Taihua Group, and mixed with mantle-derived materials.

 Petrogenesis and geodynamic implications

The hornblende monzogranite and monzogranite porphyry from the Q189 pluton and the hornblende monzogranite beneath the J4 breccia pipe are alkaline to alkali-calcic and shoshonitic in composition, and the granite porphyry belongs to the calc-alkalic and high-K series (Fig. 5). These granitoids are characterized by their metakalsilic nature (A/CNK < 1.1) and the absence of Al-rich minerals (e.g. muscovite, garnet, tourmaline and cordierite), excluding the origin of S-type granite (Clemens 2003). As shown in

Fig. 9. Variation of initial εHf values v. zircon U–Pb ages of the Qiyugou granitoids. Data source for Taihua Group is Huang et al. (2010), and that for Xiong’er Group is Wang et al. (2010).

Other possible endmembers for magma sources with high zircon εHf$_{zircon}$ values involved two distinct assumptions: one proposed mantle or mantle-derived materials (model 4 in the section ‘Petrogenesis and geodynamic implications’ below; Zhao et al. 2018; Hu et al. 2020; Pang et al. 2020) and the other postulated juvenile crust (model 3 in the section ‘Petrogenesis and geodynamic implications’ below; Li et al. 2018; Zou et al. 2019) as a subordinate magma source. The juvenile crust is defined as mafic crust with a residence time in the lithosphere of no more than 1 Myr after its extraction from the depleted mantle (Zheng et al. 2015). For Mesozoic and Cenozoic magmatic rocks, the juvenile crust was generated by crust–mantle differentiation in the Neoproterozoic or Phanerozoic. However, Neoproterozoic or Phanerozoic inherited zircons are rarely found in Late Mesozoic granitoids in the EQOB. A few cases reported in previous studies showed that the inherited zircons also have negative εHf$_{zircon}$ values and old T$_{DM2}$ ages (Gao et al. 2012; Li et al. 2013a; Zou et al. 2019).

Zircon grains from the granitoids of the Q189 pluton have δ$^{18}$O$_{zircon}$ values ranging from 5.04 to 6.53‰ (Fig. 12), which are consistent with the narrow range (averaging 5.3 ± 0.6‰) of mantle zircon (Valley 2003; Valley et al. 2005). The δ$^{18}$O$_{zircon}$ values of <6.5‰ result from magmas that contain a minor to negligible sedimentary component, whereas δ$^{18}$O$_{zircon}$ values higher than 6.5‰ signify supracrustal contributions (Hawkesworth and Kemp 2006; Hopkinson et al. 2017). We exclude subducted residues of the NYC and NQOB as magmatic sources, which commonly contain abundant supracrustal materials. The δ$^{18}$O$_{zircon}$ values from the Taihua Group range from 5.1 to 7.3‰ with an average value of 6.07 ± 0.3‰, which are higher than the δ$^{18}$O$_{zircon}$ of the Qiyugou granitoids (Liu et al. 2009; Xue et al. 2018b). The zircon O isotopic data from these granitoids offer robust evidence for mantle-derived magmas, which is contradictory to the crustal-like zircon Hf isotopic data. The decoupled and distinct zircon Hf–O isotopic data indicate different magmatic sources, which can be attributed to insignificant modification of a mantle source in the Hf–O isotopic system. The relatively higher zircon δ$^{18}$O$_{zircon}$ values compared with mantle values could be inherited from the parental magmas generated by partial melting of the Taihua Group. The relatively low δ$^{18}$O$_{zircon}$ fluids or melts could be generated through mantle degassing during upwelling of hot asthenosphere (Fig. 10; Eiler et al. 1998). The addition of low δ$^{18}$O$_{zircon}$ fluids or melts into the lower crust could facilitate melting of the refractory Taihua Group and modify the Hf–O isotopic system of parental magmas significantly as a result of upwelling of hot asthenosphere and thinning of the ancient lithosphere.
Figure 13, all samples plot on the border between the M-, I- and S-type granite field and A-type granite field in the 10,000Ga/Al v. Ce and Nb diagrams. However, most samples show fractionated I-type granite affinity (Fig. 13a and b). The Zr (28–74 ppm) and Zr + Nb + Y + Ce (95–192 ppm) values are markedly lower than those of typical A-type granite (Supplementary Table 2; Fig. 13d). Furthermore, these granitoids possess low Zr/Hf ratios (22–35) and Nb/Ta ratios (mainly <17, except for granite porphyry with an average value of 30; Fig. 13d) similar to those of typical highly fractionated granite (Wu et al. 2017; Zhang et al. 2017). The negative correlation between SiO₂ and P₂O₅ is consistent with the characteristic of I-type granites (Fig. 6i). Therefore, these granitoids can be unequivocally classified as highly fractionated I-type, as is further confirmed by similar geochemical features from published granitoid data for the Qiyugou gold deposit (Fig. 6). Furthermore, hornblende monzogranite and monzogranite porphyry from the Qi189 pluton carry abundant amphibole phenocrysts. Finally, no mafic alkaline minerals (e.g. arfvedsonite, riebeckite) occur in these granitoids.
Based on an evaluation of the geochemical features and mineral assemblage, we propose that these rocks are not typical A-type granitoids, and instead, belong to highly fractionated I-type granitoids. Zircon grains from the granitoids of the Qi189 pluton have $\delta^{18}$O$_{zircon}$ values ranging from 5.04 to 6.53 ‰ (Fig. 10), which are consistent with the narrow range (averaging 5.3 ± 0.6 ‰) of mantle zircon (Valley 2003; Valley et al. 2005). Furthermore, the low (<6.5 ‰) and nearly constant $\delta^{18}$O$_{zircon}$ values obtained in this study also show a negligible effect of sedimentary component (Hawkesworth and Kemp 2006; Hopkinson et al. 2017). Therefore, zircon oxygen isotopes also indicate that the granitoids of the Qiyugou deposit originated from meta-igneous sources and belong to I-type granitoids.

Four main tectonic models were proposed to interpret the petrogenesis of Late Mesozoic highly fractionated I-type granitoids in the EQO on the basis of different assumptions of the magma source and tectonic regime, as follows.

1. Bao et al. (2017, 2018) inferred that a flat and shallow continental subduction between the YC and the NCC occurred at 165–125 Ma, followed by delamination of the lithospheric mantle. The Late Mesozoic granitoids were considered to have been derived mainly from the partial melting of the crustal material from the northern margin of the YC, which was entrained underneath the lower crust or upper mantle of the NCC.

2. Some other researchers linked the genesis of Late Mesozoic granitoids to remelting of the basement of the NCC (Taihua Group and Xiong'er Group) and the North Qinling (e.g. Kuanping Group and Qinling Group), with minor contribution of mantle-derived components in a post-collisional setting (e.g. Qi et al. 2019). Therefore, zircon oxygen isotopes also indicate that the granitoids of the Qiyugou deposit originated from meta-igneous sources and belong to I-type granitoids.

3. Recently, an alternative hypothesis by Li et al. (2018) and Zou et al. (2019) proposed that the magmatic suite was generated by mixing between partially melted Archean to Mesoproterozoic basement rocks (i.e. mid- to lower crust) in the SNCC and juvenile crust. The collision between the NCC and YC led to thickening of the lower continental crust, followed by subsequent post-collisional magmatism at 160–125 Ma.

4. The fourth model proposed that Late Mesozoic granitoids were derived from partial melting of the ancient crust of the SNCC, and mixed with a different magmatic source (mantle-derived...
The models above highlight several controversies, including the following: (1) the parental magma of Late Mesozoic granitic rocks was generated by the interaction between melts from different sources; (2) the geological processes that control the multiple phases of Late Mesozoic magmatism remain unclear; (3) the timing of tectonic transition and its correlation with the emplacement of Late Mesozoic granitoids remain debated. The geochemistry, geochronology and zircon Hf–O isotopes of the four intrusive phases from the Qiyugou deposit could help in constructing a possible tectonic model for the Late Mesozoic granitoids.

The syn-mineralization granite porphyries (133.4 ± 0.8 Ma) have relatively lower amounts of LREE and middle REE (MREE), which are closer to values for the lower crust (Fig. 8c), suggesting a deeper source. In contrast, the other three granitoid phases (131.3–128.0 Ma) share similar REE and trace element patterns with significant enrichment in LREE and LILE and moderate depletion in HFSE, which are probably caused by hornblende fractionation (Fig. 8). The Sr/Y and La/Yb ratios of the Qiyugou granitoids (Fig. 7) exhibit a slight difference from typical geochemical features of Mesozoic adakitic rocks in the SNCC (Li et al. 2018; Zou et al. 2019). Most of the Qiyugou granitoids show relatively lower Sr/Y (<40) and (La/Yb)N (average = 12.0) than the typical adakite-like rocks (except for hornblende monzogranite; Fig. 7; Supplementary Fig. 14).
Fig. 15. Trace element concentration and ratio plots the Qiyugou granitoids from this study compared with Qiyugou granitoid data from the literature (data sources as for Fig. 5), showing mineral fractionation trends and correlation trends where apparent: (a) SiO$_2$ v. age; (b) MgO v. age; (c) Dy/Yb v. SiO$_2$; (d) Sr/Y v. age; (e) Eu/Eu* v. age; (f) Sr ratios v. SiO$_2$. GP is granite porphyry from the Qiyugou gold deposit. Normalization values are from Sun and McDonough (1989).
Table 2). Their parental magmas were generated under lower pressure than adakitic granitoids found along the SNCC, which were produced by partial melting of thickened lower crust (Zou et al. 2019). Calculated Mg# values of post-mineralization granitoid (mean value = 42) are higher than those of syn-mineralization granitoids (Mg# = 15–32) (Fig. 5f). The SiO₂ v. Mg# diagram also reveals that the syn-mineralization granitoids fall in the overlapped field of metabasaltic and eclogitic melts (1.0–4.0 GPa) and thick lower crust-derived adakitic rock (Fig. 5f). However, the post-mineralization granitoid shows affinity with delaminated lower crust-derived adakitic rocks, suggesting the derivation of these rocks from a relatively thinner crust (Fig. 5f).

The (La/Yb)N v. YbN and (Sm/Yb)N v. YbN diagrams also can be used to evaluate the melting depth required to produce granitoids (Zou et al. 2019). As indicated by Figure 14, the granite porphyries (133 Ma) were generated by partial melting of deeper crust, and the hornblende monzogranite and monzogranite porphyry (131–128 Ma) were produced at depths less than 40 km. In addition, previous whole-rock geochemical data at the Qiyugou deposit also indicate that the (La/Yb)N and (Sm/Yb)N ratios of the Qiyugou

Fig. 16. (a) Schematic tectonic model for the Qinling orogen at c. 136–124 Ma; (b) schematic model illustrating the formation of the Qiyugou gold deposit.
granitoids are consistent with rocks generated by partial melting in a thin crust (~40 km) (Fig. 14). Hence, the different phases of granitoids from Qiyugou mainly originated from partial melting of the Taihua Group rocks at different crustal levels.

As mentioned in the section ‘Origin of Qiyugou granitoids’, the Hf–O isotopic features show variable degrees of hybridization between mantle-derived materials and partial melting of the ancient Taihua Group through asthenosphere upwelling and anatexis of subcontinental lithospheric mantle (SCLM). The youngest monzogranite porphyries (128.0 ± 0.7 Ma) have a trend close to that for the mantle-derived materials, whereas the oldest granite porphyries (133.4 ± 0.8 Ma) show a greater contribution from the endmember of the Taihua Group.

In summary, sustained reduction of the crustal thickness over time has been linked to the tectonic transition from compression to extension, which is consistent with regional deformation of the crustal rocks, intensive crust–mantle interaction, granitoid magmatism and associated gold mineralization (Li et al. 2012a, b; Wu et al. 2019). Ancient and metasomatized SCLM was melted and removed owing to upwelling of hot asthenosphere (Fig. 16).

**Implication for Au mineralization**

Syn-mineralization magmatism can be subdivided into the granite porphyry (134.1–133.4 Ma; this study; Yao et al. 2009) associated with breccia pipe-hosted mineralization and the hornblende monzogranite (131.3–129.9 Ma; this study; Wang et al. 2020) associated with porphyry mineralization. This implies that a prolonged and multistage magmatic system provides a key factor to control the economic mineralization, which can be steadily replenished by mantle-derived materials in the magma chamber. The upwelling of hot asthenosphere may have provided mantle-derived melt and triggered partial melting of ancient deep crustal arc cumulate zones and/or metasomatized SCLM with siderophile metals (such as Mo and Au) left as residue (Fig. 16a). This would be conducive to the remobilization of ore-forming fluids and metals that ascended rapidly with ore-forming magma to the upper crust.

During the early stage magmatic–hydrothermal event at 135.6–133.4 Ma (Fig. 12), as a result of rapid ascent and cooling of the granite porphyry magma (Fig. 3b) the short period of fluid focusing was conducive to the formation of the Qiyugou breccia pipes through degassing, fluid boiling, fluidization and overpressure of the wall rocks (Fig. 16b; Chen et al. 2009; Tang et al. 2021a). The second stage of the magmatic–hydrothermal event, as recorded by fine-grained hornblende monzogranite from the Qi189 pluton (Fig. 3a) and porphyry mineralization, represents the result of slow cooling and crystallization of granitic magma from the walls and continuing inward to form an impermeable rind (Burnham 1979; Tang et al. 2021a). During the multiple stages of the magmatic–hydrothermal evolution process, recharge of mafic juvenile components rejuvenated the large silicic magma chamber (Buret et al. 2016, 2017). Several geochemical features suggest that the parental magmas underwent a distinct fractional crystallization process at the magma chamber. The selected major oxides and trace elements of hornblende monzogranite and negative correlation of MgO and Dy/Yb with SiO₂ argue for the fractional crystallization of amphibole (Figs 5 and 15c). The pronounced Eu positive anomalies as well as extremely high Sr/Y ratios of Au-bearing hornblende monzogranite (Fig. 15d and e) indicate that predominantly fractionation of hornblende occurred rather than plagioclase fractionation. In addition, strontium contents display an apparent decrease with silica contents for these granitoids, which also reflects suppressed plagioclase fractionation (Fig. 15f). The fractionation and relative abundance of hornblende indicate that the Qiyugou porphyry magma was distinctly hydrous (>4 wt% H₂O; Ridolf et al. 2010). The H₂O-rich magmas favour the formation of magmatic–hydrothermal ore deposits (Sillitoe 2010; Richards 2011).

In summary, a long-lived magmatic–hydrothermal system, upwelling of hot asthenosphere and intense mantle–crust interaction, as well as the high water contents of magma, led to the generation of economically mineralized granitoids and formation of the Qiyugou gold deposit.

**Conclusions**

(1) Geochronological studies show that the granite porphyry associated with breccia pipe-hosted mineralization, hornblende monzogranite associated with porphyry mineralization and post-mineralization monzogranite porphyry were emplaced at c. 133.4 Ma, 131.3–129.9 Ma and 128 Ma, respectively.

(2) Whole-rock geochemistry and zircon Hf–O isotopes indicate that the parental magmas of these granitoids were mainly sourced from partial melting of the Taihua Group and mixed with mantle-derived components through asthenosphere upwelling and lithospheric thinning. Sustained reduction of the thickened crust is linked to the tectonic transition from compression to extension at 133–128 Ma.

(3) Formation of the Qiyugou gold deposit is a result of the prolonged magmatic activity, with input of mantle-derived materials.

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**Data availability** All data generated or analysed during this study are included in this published article and its Supplementary files.

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