Ca. 1.7 Ga Magmatism on Southwestern Margin of the Yangtze Block: Response to the Breakup of Columbia

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Abstract: This paper presents some data of the Jiaopingdu gabbro and Caiyuanzi granite at the southwestern margin of the Yangtze Block, on the geochemical compositions, zircon LA–ICP–MS U–Pb ages and Hf isotopic data. The Jiaopingdu gabbro gives the age of 1721 ± 5 Ma, the Caiyuanzi granite 1732 ± 6 Ma and 1735 ± 4 Ma, and the Wenjiacun porphyry granite 1713 ± 4 Ma, suggesting nearly contemporaneous formation time of the gabbro and granite. The bimodal feature is demonstrated by the gabbro SiO$_2$ content of 44.64–46.87 wt% and granite 73.81–77.03 wt%. In addition, the granite has high content of SiO$_2$ and Na$_2$O + K$_2$O, low content of Al$_2$O$_3$ and CaO, enriched in REEs (except Eu) and Zr, Nb, Ga and Y, depleted in Sr, implying it belongs to A-type granite geochemistry and origin of within-plate environment. The zircon $\varepsilon$Hf(t) of the granite and gabbro is at the range of 2–6, which is near the 2.0 Ga evolution line of the crust, implying the parent magma of the gabbro being derived from the depleted mantle and a small amount of crustal material, and the parent magma of the granite from partial melting of the juvenile crust and some ancient crustal material at the same time. Compared with 1.8–1.7 Ga magmatism during breakup of other cratons in the world, we can deduce that the Columbia has initially broken since ca. 1.8 Ga, and some continental marginal or intra-continental rifts occurred at ca. 1.73 Ga.

Key words: 1.7 Ga magmatism, bimodal intrusions, geochemistry and geochronology, Columbia supercontinent break-up, southwestern margin of Yangtze Block

1 Introduction

Since Rogers and Santosh (2002) put forward the term Columbia (or Nuna), voluminous researches have been carried out on the possible amalgamation, accretion, breakup and re-construction of the ancient supercontinent (Condie, 2002; Zhao G C et al., 2002, 2004; Kröner and Cordani, 2003; Zhai and Liu, 2003; Kusky et al., 2007; Ernst et al., 2008; Hou et al., 2008; Li et al., 2008; Reddy and Evans, 2009; Rogers and Santosh, 2009; Meert, 2012; Zhang et al., 2012a). It is generally thought that the Columbia was formed through collision orogenic events at 2.0–1.8 Ga on the global scale (Zhao G C et al., 2002, 2004). But it is rather controversial about the breakup time of the supercontinent. Some scholars pointed out that the Columbia initially broke at ca. 1.5 Ga ago, and the final breakup in the period of 1.35–1.20 Ga (Ernst et al., 2008, Hou et al., 2008). While others attributed the breakup to the super mantle plume event at ca. 1.75 Ga (Condie, 2004). The North China Craton took a role in assembling of the Columbia (Zhao G C et al., 2002; Li and Zhao, 2007), but it is still uncertain as to the separation time of the craton from the supercontinent. It may originally break at ca. 1.78 Ga (Zhao G C et al., 2002, 2004; Peng et al., 2008; Peng, 2015), or at ca. 1.62 Ga (Yang et al., 2005; Jiang et al., 2011), even at ca. 1.32 Ga (Zhang et al., 2009, 2012b). Due to scarce outcrops of the early Precambrian basement, it is still uncertain whether the Yangtze Block was involved in the assembling and breakup of the Columbia. Some researchers considered that the Yangtze Craton was once connected to the Laurentia, and the Cathaysia to the northern India, and both were parts of the Nuna/Columbia (Cawood et al., 2017). Limited data implied that two magmatism events (at 1.7 Ga and 1.5 Ga) under extensional setting occurred at the southwestern margin of the Yangtze Craton, which might be related to the breakup of the Columbia (Fan et al., 2013; Wang D B et al., 2013; Yang et al., 2015). With new geochronological and geochemical data, this paper will discuss the possibility of the breakup of the Yangtze Block at ca. 1.7 Ga on the southwestern margin from the Columbia.

2 Regional Geology

The South China Craton was assembled through the Yangtze Block and the Cathaysia Block along the Jiangnan Orogenic Belt at 0.90–0.83 Ga (Zhang G W et al., 2013; Geng, 2015; Zhao G C, 2015). The Archean-Paleoproterozoic metamorphic rocks (including metamorphosed TTG and supracrustals) are predominantly distributed in the Kongling area at the northern margin of the Yangtze Block (Qiu et al., 2000; Gao et al., 2001, 2011; Zhang S B et al., 2006; Chen K et al., 2013; Guo J L et al., 2013, 2014, 2015; Li et al., 2014), some outcrops in the Zhongxiang City (Zhang et al., 2011; Wang Z J et al., 2015), to the east of Kongling.
area, Hubei Province. The occurrences have been discerned in the Yudongzi area, Lu'eyang County, Shaanxi Province at the northwestern margin of the Yangtze Block (Zhang et al., 2010; Hui et al., 2017). Sporadic outcrops are present in the Badu area at the northern Cathaysia Block (Liu et al., 2009; Yu et al., 2009; Zhao et al., 2014). The oldest sequences at the southwestern margin of the Yangtze Block include the Dahongshan Group, Dongchuan Group, Hekou Group and Tong'an Formation, which formed at the period of 1.8–1.4 Ga, of early Mesoproterozoic in China stratigraphic table (according to NCSC, 2014). While the late Mesoproterozoic strata (1.4–1.0 Ga) cover the Kunyang, Huiili, Shennongjia and Dagushi groups, which are distributed along the southwestern to northern margins of the Yangtze Block (Fig. 1).

The Dahongshan Group is distributed in the Dahongshan Mountains and Mosha region, Yuxi City of Yunnan Province, and is dominantly composed of metasedimentary and metavolcanic rocks which host the magmatic hydrothermal iron oxide copper-gold (IOCG) deposit that formed 1.72–1.65 Ga ago (Zhao and Zhou, 2011). The Hekou Group crops out in the Lixi and Lala area, Huiili County, Sichuan Province, with the major metaclastic and metamorphosed sodium volcanic rocks that host the IOCG deposit of ca.1.70–1.65 Ga (Zhao and Zhou, 2011). The Dongchuan Group is present in the Dongchuan city and Wuding county, Yunnan Province, with the dominant metasandstone, slate and carbonate rocks which bear the IOCG and SSC (Sediment-hosted Stratiform Copper) deposits of ca. 1.7–1.5 Ga (Wang S W et al., 2016). The Tong'an Formation is situated at southern Huiili and Huidong counties, Sichuan Province, comprising the slate, metasandstone and carbonate rocks of ca. 1.7–1.5 Ga. The subdivisions, rock associations and formation data can be shown in Fig. 2. The sedimentary and volcanics rocks of early Mesoproterozoic have undergone greenschist to lower amphibolite facies metamorphism, and both the sedimentary formations and geochemistry of the volcanic rocks indicate the origin of rift in intra-plate setting (Zhao et al., 2010; Chen W T et al., 2013; Zhou et al., 2014; Wang S W et al., 2016).

Late Mesoproterozoic strata at the southwestern margin of the Yangtze Block include the Kunyang and Huili
Fig. 2. The correlation of Early Mesoproterozoic strata in the southwestern margins of Yangtze Block.

Groups. The Kunyang Group is mainly distributed in the central area of Yunnan Province, with the ascending order of Huangcaoling, Heishantou, Dalongkou and Meidang formations. The Huili Group is dominantly present in the Huili and Huidong counties, Sichuan Province, with the Limahe, Fengshanying and Tianbaoshan Formations from the lower to upper sequences. Until to now, the lower part of both the Kunyang and Huili Groups lack the reliable geochronological data, while the upper part has produced several ages a little older than 1.0 Ga (Zhu et al., 2016; Geng et al., 2007; Greentree et al., 2006; Zhang C H et al., 2007; Li et al., 2013a). Furthermore, the Kunyang Group is covered unconformably with the Liubatang Formation of 890 Ma (Gao et al., 2015), suggesting both the Kunyang and Huili Groups deposited in the late Mesoproterozoic.

Late Mesoproterozoic strata at the northern margin of the Yangtze Block are the Shennongjia and Dagushi Groups, which consist of major metaclastic rocks and dolomite, with minor volcanics. The dolomites of the two groups contain stramatolite. The volcanics or tuffs of the Shennongjia Group give the zircon U–Pb age of 1103 ± 8 Ma (Qiu et al., 2011), 1215.8 ± 2.4 Ma (Li et al., 2013b) and 1180 ± 15 Ma (Du Q D et al., 2016). While the volcanics of the Dagushi Group produces the zircon U–Pb age of 1225 ± 19 Ma and 1239 ± 23 Ma (Li et al., 2016).

Many mafic intrusions, such as dykes or stocks, can be found at the southwestern margin of the Yangtze Block, like the occurrence in the Tong’an area at the Huili County, Sichuan Province (Fig. 3a). Geological and geochronological information demonstrate that some intrusions are of Permian (Fig. 3a), ca. 1.5 Ga (Geng et al., 2012; Fan et al., 2013) or ca. 1.7 Ga (Wang D B et al., 2013). Furthermore, the dolerite is intruded in the Yinmin and Luoxue formations, Dongchuan Group, in the Dongchuan area (Zhao et al., 2010). In the Dahongshan area, 1.66 Ga basic rocks intruded into the Laochanghe and Mangdanhe formations of the Dahongshan Group (Zhao and Zhou, 2011). The diabase of 1.76 Ga intruded into the Dongchuan Group in the Wuding area, Yunnan Province (Guo Y et al., 2014; Yang et al., 2015), and the diabase of 1.7 Ga intruded into the Hekou Group in the Hekou region (Guan et al., 2011) (Fig. 2). These basic intrusions are dominated by gabbro and diabase, with minor dolerite. They are dykes and generally small sizes at the scale of 100s meters in length and several to 10 meters in width. The dyke studied in this paper crops out along Tong’an-Jiaopingdu road and the length 5 km, width from 10 to 100s meters. This dyke intrudes in the Tong’an Formation and overlain with the Sinian dolomite (Figs. 3a, 4a). The dyke is pyroxene diorite in lithology and develops a group of vertical joints which terminate at the boundary to the Sinian dolomite, suggesting the rock and its joints formed prior to the Sinian dolomite. Without substantial metamorphism or deformation, the intrusion is heterogeneous in texture in that the mineral size ranges from 1–2 mm to 3 mm.

Minor granite of ca. 1.7 Ga is identified at the southwestern margin of the Yangtze Block, such as the porphyry granite of 1.76 Ga at the Wuding area, Yunnan Province (Wang Z Z et al., 2013; Yang et al., 2015). In this study, we noticed the occurrence of granite of 1.7 Ga near the Caiyuanzi village, southern Huidong County, Sichuan Province. The granite is distributed in the diabase intrusion which was considered forming in the Hercynian, while the granite in the Indosinian (BGMRSC, 1970). But
3 Sample Collection and Analytical Methods

3.1 Sample collection and lithology

The gabbro sample (DC13-1) in this study was collected from roadside of the Tong’an-Jiaopingdu road in the Huili County, Sichuan Province (Fig. 3a), with the geographical coordinate N26°19′32.25″, E102°22′56.20″. The sample is cyanism grey, medium-coarse gabbro (Fig. 4b) of massive structure and gabbro texture (Fig. 5f), with major pyroxene, hornblende, plagioclase and minor quartz (Fig. 4e). Plagioclase is tabular and heavily epidotized on the surface (Fig. 4e, f). Hornblende is long prismatic, to the length of 3 mm, and pyroxene of 2 mm in short prismatic. The platy plagioclase formed the skeleton inside which is pyroxene, and the two minerals constitute the gabbro texture (Fig. 4f). The granite sample (DC9-1, 9-2) were taken along a lane 400 m NE of the Caiyuanzi village, Tangtang town, Huidong county (Fig. 3b), with the geographical coordinate N26°19′19.09″, E102°42′47.34″, and the two samples are 10 m apart. The granite is pink, massive to weakly foliated structure and medium-coarse texture, mainly composed of plagioclase (20%–40%), orthoclase and microcline (25%–50%), quartz (25%–40%) and minor biotite (2%–5%) (Fig. 4g). Biotite was mostly chloritized and plagioclase semi-hedral tabular with wide laminae of polysynthetic twin. Microcline is irregular and some myrmekite or graphic texture developed near the margin. Carlsbad twin can be found in K-feldspar (Fig. 4h). The sample DC9-1 is weakly altered, but DC9-2 is fresh. The porphyry granite (DC10-1) was at the Wenjiacun village, Tangtang town, Huidong county (Fig. 3b), with the geographical coordinate N26°20′52.58″, E102°43′07.88″. The rock here is strongly weathered, yellow on the surface, burnt brick on the fresh surface, with massive structure and granitic or porphyry texture (Fig. 4d). The matrix is composed of plagioclase, K-feldspar, quartz, hornblende and biotite and less melanocratic minerals in all. The porphyry minerals are feldspar and quartz, with the size of some 0.5 cm, up to 1 cm.

3.2 Analytical methods

Whole rock powder is prepared by the Institute of Regional Geology and Mineral Resources Survey in Hebei Province. Take 300–500 g of fresh sample rock to be crushed with the jaw crusher, milling the powder to 200 mesh and weigh 30–50 g for bulk chemical analysis. The bulk, trace element and REE analyses were carried out in the National Research Center of Geological Analysis, Chinese Academy of Geological Sciences. The major oxides were analyzed with the 3080E XRF of Rigaku Corporation, with analysis error < 0.5%, the trace element and REE were analyzed with the X-series of ICP–MS, error < 5%.

Zircon grains were separated in the Institute of Regional Geology and Mineral Resources Survey in Hebei Province. CL images of zircon were taken in the Beijing SHRIMP Center. In-situ U–Th–Pb isotope composition was measured with the in the LA–MC–ICP MS in the Isotope Laboratory of the Tianjin Institute of Geology and Mineral Resources, instrument equipment and processing procedures are after Li et al. (2010). GJ-1 was taken as the outer zircon age standard for correcting the U, Pb isotope fractionation (Jackson et al., 2004). Take the 208Pb correction method for correction of common lead (Anderson, 2002), and the NIST612 glass standard as the outer standard for calculating the Pb, U and Th content of the samples. geochronological calculations and concordia plot constructions were conducted using ICPMSDataCal (Liu Y S et al., 2009) and Isoplot (Ludwig, 2003).

The zircon Hf isotope composition was measured with the Neptune Plus multi-collector ICP MS and GeoLasPro193nm LA–MC–ICP–MS in the Laboratory of Continental Dynamics of the Institute of Geology, Chinese Academy of Geological Sciences. In measurement, Helium was taken as the eroding gas, and erosion diameter 44μm according to the zircon sizes. International zircon standard is the reference material for measuring. The instrument operating condition and detailed measuring procedures are according to Hou et al. (2007). The measured weighted mean value of 176Hf/177Hf of the zircon standard GJ-1 is 0.282007 ± 0.000025 (2σ). In calculating 176Hf/177Hf, the decay constant of Lu is 1.867×10^-11/a (Söderlund et al., 2004). As to the 6iLu/6f(i) calculation, the Hf isotope of the chondrite is adopted, 176Lu/177Hf = 0.0332, 175Hf/177Hf = 0.282772 (Blichert-Toft and Albarede, 1997).

For estimating the mantle Hf model age, we take the modern 176Hf/177Hf value, 0.28325, of the depleted mantle, and 176Lu/177Hf = 0.0384 (Griffin et al., 2000), an average value of 176Lu/177Hf = 0.015 in calculation of the model age of the crust (Griffin et al., 2002).

4 Analytical Results

4.1 Geochemical results

Seven gabro and three granite samples have been analyzed and the data are listed in Table 1. The gabbros have the whole rock oxide content of SiO2 44.64–46.87%, Al2O3 10.64–13.39%, MgO 8.13–10.83%, Na2O + K2O 2.47–3.93%, and Na2O content obviously higher than that of K2O. On the classification diagram of magmatic rocks (Cox et al., 1979), they are plotted within the subalkaline field (Fig. 5a). On the Nb/Y vs. Zr/TiO2 diagram, they are plotted within the field of subalkaline basalt region (Fig. 5b). The granites (including the porphyry granite) have the oxide content of SiO2 73.81–77.03%, Al2O3 12.55–12.95%, Na2O + K2O 7.24–8.05%, with Na2O content higher than
Fig. 4. Field photographs (a–d) and photomicrographs (e–h) showing geological relationships and lithological features for the gabbro and granite.

a–unconformity between gabbro and the Neoproterozoic dolomite; b–outcrop of gabbro; c–outcrop of granite (DC9–1) in the Caiziyuan area; d–porphyritic granite; e and f–photomicrograph of gabbro in Jiaopingdu area; g and h–photomicrograph of granites in the Caiziyuan area.
that of K$_2$O. On the SiO$_2$ vs. (Na$_2$O + K$_2$O) diagram, they are plotted within the granite field of subalkaline series (Fig. 5a). While on the Nb/Y vs. Zr/TiO$_2$ diagram, they belong to rhyolite/dacite (Fig. 5b). From both the

![Diagram](image-url)

**Fig. 5.** Diagrams of SiO$_2$ vs. (Na$_2$O + K$_2$O) (a, Cox, et al., 1979) and Nb/Y vs. Zr/TiO$_2$ (b, Pearce, 1996).
geochemical data (Table 1) and SiO\textsubscript{2} vs. Na\textsubscript{2}O + K\textsubscript{2}O classification diagram (Fig. 5a), we can notice that there is a substantial gap at the range of 50–70\% of SiO\textsubscript{2} content between the gabbro and granite, that is, absence of the intermediate composition rock. As both the gabbro and granite formed at the same time (see next section), they constituted the bimodal magmatism assemblage.

The gabbro has low REE content ($\Sigma$REE = 14.92–24.56 ppm). On the chondrite-normalized REE distribution diagrams, all the gabbros show flat patterns, without substantial Eu anamoly (Eu/Eu*$^\text{chondrite}$ = 0.92–1.08) and slightly negative Ce anamoly (Fig. 6a). While the granite has high REE content ($\Sigma$REE = 289–392 ppm), obviously negative Eu anamoly (Eu/Eu*$^\text{chondrite}$ = 0.47–0.60). The LREE are strongly fractionated, but the HREE have not fractionation (Fig. 6b). On the primitive mantle-normalized trace element spider diagram, the gabbro and granite are quite distinctive, with lower trace elements in the gabbro, but higher in the granite. The gabbro is enriched in Rb, Ba, K, Ta, Pb, Sr and Ti, but depleted in P and Zr (Fig. 6c). The granite is enriched in Th, U, but depleted in Sr, P and Ti (Fig. 6d). From the gabbro to granite, Th, U content changed from depletion to enrichment, on the contrary, Ti from enrichment to depletion, the changes are related to the compositions of the magma.

4.2 Geochronological results

4.2.1 Gabbro (sample DC13-1)

The zircons of the sample are mostly of short prismatic, with the length and width ratio of 2:1. CL images of the zircons are usually of platy zoning, and some grains without zoning (Fig. 7a), suggesting the mafic magmatism origin. Total 32 spots of 32 grains have been analyzed with LA–ICP–MS. Most of the spots have Th/U ratios over 1.0, consistent with their magmatic origin. Except 2 spots (14 and 20) with intensive Pb loss, the remaining 30 spots are distributed along or near the Concordia (Fig. 7b), and the weighted mean $^{207}$Pb/$^{206}$Pb age of 1721 ± 5 Ma, MSWD = 1.8. This age is rather near to 1.69 Ga (Wang D B et al., 2013) within error, so the result 1721 Ma represents the formation age of the gabbro.

4.2.2 Granites (DC9-1 and DC9-2)

The zircons of the two granite samples (DC9-1 and DC9-2) are prismatic, among them the zircons of DC9-1 are short prismatic, but long prismatic for DC902. In CL
images, prismatic zircons give banded oscillatory zoning, while the transverse sections show ring oscillatory zoning (Fig. 8). The $^{207}$Th/$^{238}$U ratio ranges from 0.3 to 0.7, suggesting the magmatic origin. 32 spots have been analyzed for samples DC9-1 and DC9-2, respectively. On the $^{207}$Pb/$^{206}$Pb vs. $^{206}$Pb/$^{238}$U concordia diagram, both samples have undergone lead loss and the plotted spots intensive from the Concordia, but a perfect disconcordia line occurs. Sample DC9-1 intersects with the Concordia line at the upper intercept 1732 ± 6 Ma (MSWD = 1.6) (Fig. 9a). The 11 spots near the upper intercept give the weighted mean age of 1733 ± 10 Ma, which is identical with the upper intercept within error. Sample DC9-2 intersects with the Concordia line at the upper intercept 1735 ± 4 Ma (MSWD = 1.21) (Fig. 9b). The 20 spots near the upper intercept give the weighted mean age of 1735 ± 8 Ma, which is also identical with the upper intercept within error. The two samples from one granite body show nearly the same age, so the ca. 1.73 Ga represents the formation time of the intrusion.

4.2.3 Porphyry granite (DC10-1)

Zircons of the sample are long prismatic, with the length and width ratio from 1:1 to 3:1. Long prismatic zircons develop dense oscillatory zonings at the margin, but no zoning in the internal core (Fig. 10a). Short prismatic zircons (possibly on the transverse sections) produce rhombus or square oscillatory zonings (Fig. 10a, spots 10, 11). Some grains show narrow bright rims which are too narrow to be analyzed, suggesting the superposition of possible later thermal events.

Total 32 spots of 32 grains have been measured on the U–Pb isotopes. The Pb content ranges from 21 to 139 ppm, U content from 65 to 889 ppm, and the Th/U ratios from 0.26 to 0.89. Both the high Th/U ratios and well-developed oscillatory zonings demonstrate magmatic origin of the zircons. Most spots are on or near the concordian curve on the $^{207}$Pb/$^{206}$Pb vs. $^{206}$Pb/$^{238}$U diagram, only some spots deviate from the curve. All the spots comprise a disconcordia, with the upper intercept at 1713 ± 4 Ma (MSWD = 1.11; Fig. 10b). The 24 spots near the upper intercept give the weighted mean $^{207}$Pb/$^{206}$Pb age 1717 ± 10 Ma. The two ages are nearly the same within error, suggesting the formation time 1713 ± 4 Ma of the porphyry granite.

4.3 Zircon Lu–Hf isotope composition

Besides the above mentioned age analyses, zircon Lu–Hf isotope composition have been measured for the gabbro and granite samples. Zircon grains for Lu–Hf isotope analysis have been measured for age determination as well, and two kinds of spots for each grain are rather near in position, so the apparent $^{207}$Pb/$^{206}$Pb age is adopted in calculating the isotope parameters.

Zircons of the gabbro (DC13-1) give the $^{176}$Lu/$^{177}$Hf and $^{176}$Hf/$^{177}$Hf values 0.000663–0.004779 and 0.281821–0.282026, respectively, and the ($^{176}$Hf/$^{177}$Hf)$_i$ value 0.281792–0.281800, $\varepsilon_{Hf}(t)$ value of 2.85–7.25. The one-stage Hf model ages ($T_{DM1}$) on depleted mantle range 1897–2079 Ma, slightly older than the formation age (1721 Ma). While the two-model ages ($T_{DM2}$), representing the crustal residence time, are at the span of 1964–2230 Ma.

Zircons of the two granite samples have similar Hf isotope composition, with $^{176}$Lu/$^{177}$Hf and $^{176}$Hf/$^{177}$Hf values 0.000764–0.004288 and 0.281772–0.281982, respectively, and the ($^{176}$Hf/$^{177}$Hf)$_i$ value 0.281747–0.281875, $\varepsilon_{Hf}(t)$ value is positive, at the range of 1.85–6.97. The one-stage Hf model ages ($T_{DM1}$) on depleted mantle range 1910–2065 Ma, slightly older than the formation age (1732–1735 Ma). While the two-model ages ($T_{DM2}$) are at the span of 1964–2276 Ma.

Zircons of the porphyry granite have the $^{176}$Lu/$^{177}$Hf and $^{176}$Hf/$^{177}$Hf values 0.000935–0.004604 and 0.281803–0.281973, respectively, the ($^{176}$Hf/$^{177}$Hf)$_i$ value 0.281730–0.281864, and $\varepsilon_{Hf}(t)$ at the range of –0.02 to 6.66, all are positive except one spot. The one-stage Hf model ages...
(T_{DM1}) on depleted mantle range 1905–2102 Ma, slightly older than the formation age (1713 Ma). While the two-model ages (T_{DM2}) are at the span of 1993–2281 Ma.

The gabbros and granites of the region are quite different in chemical compositions (Figs. 5, 6), but their zircon Hf compositions are rather similar. On the
Lu/177Hf vs. 176Hf/177Hf diagram, the gabbro, granite and porphyry granite all are plotted in the same field, and positive correlation exists between 176Lu/177Hf and 176Hf/177Hf. The calculated εHf(t) values (Fig. 11) and model ages are very similar as well, suggesting their similar magmatic sources. On the 207Pb/206Pb age–εHf(t) diagram, all the spots are concentrated at the field of εHf(t) = 2–6, and near the 2.0 Ga crustal evolution line (Fig. 11).

5 Discussion

5.1 Features of the ca. 1.7 Ga magmatism in the SW margin of the Yangtze Block

The formation time of the Jiaopingdu gabbro got in this study is 1721 ± 4 Ma, which within analysis error is similar to the 1694 ± 16 Ma obtained by Wang D B et al. (2013), suggesting a basic magmatism event at ca. 1.7 Ga. Because the Caiyuanzi granite and porphyry granie are hosted in the diabase (Fig. 3b), different opinions arose on their formation ages. In the previous geological survey, the granite in the diabase was considered forming in the Hercynian, and the granite in the Indosinian (BGMRSC, 1970). Recently, Wang Z Z et al. (2012) and Wang S W et al. (2013) obtained zircon U–Pb ages of 1040 Ma and 1063 Ma from the granite in the region, their results are quite different from the ages 1732 Ma, 1735 Ma and 1713 Ma in this study.

In CL images, most zircons of this study have platy zoning of high temperature zircon feature, consistent with the the properties of the A-type granite (see next section). So our results may represent the formation age of the A-type granite. As to the zircon Hf isotope composition, the 176Hf/177Hf values of both the depleted mantle and lower crust show the same tendency of becoming higher with younger formation time (see Wu et al., 2007, Fig. 13).

The Caiyuansi granites (1732 Ma of DC9-1, 1735 Ma of DC9-2) in this study produce zircon 176Hf/177Hf value of 0.281772–0.281951 and 0.281816–0.281973, respectively, and the porphyry granite (1713 Ma of DC10-1) have the 176Hf/177Hf of 0.281803–0.281946. The zircon Hf isotope compositions of the ca. 1.7 Ga magmatic rocks in the Yangtze Block are very similar, but quite different from that of the ca. 1.0 Ga magmatic rocks. In consideration of the 176Hf/177Hf ratios, formation age of the granite is rather

![Fig. 10. CL images (a) of zircons and LA–MC–ICP–MS U–Pb concordia diagram (b) from the porphyritic granite (DC10-1) (207Pb/206Pb ages for the spots on representative grains are shown in Ma with 1σ errors).](image1)

![Fig. 11. Zircon U–Pb ages (207Pb/206Pb age) vs. εHf(t) diagram.](image2)
Fig. 12. Geological sketch map of the southwestern margin of Yangtze Block, showing the distribution of the ca. 1.7 Ga magmatic rocks.

reasonable to be at ca. 1.7 Ga.

As ca. 1.0 Ga ages have been discerned in the granite (Wang Z Z et al., 2012; Wang S W, 2013), it is possible there existed two events of magmatism in the region, but the distribution and scale of each event cannot be distinguished due to the poor exposures.

In recent years, successive ca. 1.7 Ga magmatic rocks have been reported at the southwestern margin of the Yangtze Block, such as the 1643 ± 19 Ma gabbro intrusion in the Dahongshan Group in the Dahongshan Mountains region (Jin et al., 2015), the bimodal porphyry granite (1730 ± 15 Ma, Wang Z Z et al., 2013; 1764 ± 18 Ma, Yang et al., 2015) and diabase (1728 ± 4 Ma, Guo Y et al., 2014; 1765 ± 6 Ma, Yang et al., 2015) in the Wuding area, and the dolerite (1690 ± 15 Ma, Zhao et al., 2010) and magmatic breccia (1717 ± 22 Ma, Zhao et al., 2010) intruded in the Dongchuan Group in the Dongchuan region, Yunnan Province; the gabbro (1657 ± 21 Ma, Chen W T et al., 2013), diabase (1710 ± 8 Ma, Guan et al., 2011) and cryptic breccia (1693 ± 3 Ma, Yu et al., 2017) within the Hekou Group at the Lalachang copper deposit in Huili area, Sichuan Province. These intrusions are dominated by basic composition, with minor acid. In addition, the volcanic rocks of the Dahongshan Group in the Xining region, Yunnan Province, also erupted at ca. 1.7 Ga, so did the volcanics of the Hekou Group in the Sichuan Province (Fig. 12). These abundant intrusions and extrusions at ca. 1.7 Ga in the southwestern margin of the Yangtze Block indicate that the magmatic event was of regional significance.

5.2 Source of the bimodal magmatism and tectonic setting of the granite

In addition to the bimodal magma in this paper, the ca. 1.7 Ga diabase (SiO$_2$ = 44.46–48.26%) and porphyry granite (SiO$_2$ = 70.93–73.04%) occurred in the Wuding area, Yunnan Province. The diabase is of subalkaline tholeiite (Guo Y et al., 2014) and the porphyry granite of low-K calc-alkaline and A-type, with peraluminous and ferruginous in geochemistry (Wang Z Z et al., 2013), of bimodal magmatism association (Yang et al., 2015).

There are basically two schools on origin of bimodal volcanism (magmatism). One school considered that the acid end rhyolite (granite) and basic end basalt (diabase and gabbro) were derived from different parent magmas (Huppert and Sparks, 1988), among which the basic end member was derived from partial melting of the mantle, while the acid end member from anatexis of the crust (Cox, 1991). The association of the two end members in space may be related with the same thermal event (Sigurdsson, 1977). In this case, the rhyolite is greatly more than the basalt in area (Hildreth, 1981; Wilson, 1989; Cull et al., 1991). Since the different sources of the basic and acid magmas the resulting basalt and rhyolite have distinct compositions in trace elements, Sr, Nd and Hf isotopes (Doe and Remer, 1982; Davies and MacDonald, 1987). Another school thought that both the rhyolite and basalt in the bimodal magmatism are derived from the mutual parent magma in the mantle, and the rhyolite is formed after fractionation crystallization of the basalt magma, with minor or without crustal materials involved (Clevery et al., 1984; Grove and Kinzler, 1986; MacDonald et al., 1987; Bacon and Druitt, 1988). Here, the basic and acid rocks of the same source generally have similar trace elements and isotope features, but the acid rocks are substantially less than the basic ones in volume. Due to the differences of the formation mechanisms of bimodal igneous rocks, their manifestations are also different. Some bimodal igneous rocks are close association and formation ages are also similar, such as Kudi Neoproterozoic bimodal magmatic rocks in the southwestern Tarim (Zhang C L et al., 2006), some bimodal igneous rocks distribute in a large range and have different formation ages, such as early Mesoproterozoic Nueltin granites and gabbro dykes in western Churchill, North America (Peterson et al., 2015). The gabbros exposed in Jiaopingdu area have lower TiO$_2$ contents (0.69–0.91%) with Ti/Yb ratios of 4133–5451 and Nb/Th ratios of 6.8–10.5. On the Ti/Yb vs. Nb/Th diagram, the gabbros plot near the continental lithosphere mantle (CLM) (Fig 13), and the predominantly εHf(t) of the gabbros range between 2.87 and 7.29. Thus, we interpreted the gabbros to be derived from a continental lithosphere mantle source. The Ti/Yb and Nb/Th ratios of granites exposed in Caiyuanzi area range from 115 to 180, and 1.66 to 1.89, respectively. As can be seen from the Ti/Yb vs. Nb/Th diagram (Fig. 13), the granite parent magma can be formed through the fractional crystallization from gabbro magma, and in this process the magma can be assimilated of the lower crust, or formed by partial melting of the basic rocks in the lower crust. The Hf isotope composition of the zircons from granites in this area is similar to that of gabbros (Fig. 11), and the εHf(t) values are positive, so it can be inferred that the granite magma in this area had been underwent a low degree of crustal contamination, mainly reflecting the characteristics of partial melting of basic rocks in the lower crust.

The bimodal magmatism is generally considered continental rift origin. Recent years other possible tectonic settings have also proposed (Hochstaedter et al., 1990; Garland et al., 1995; Geist et al., 1995; Pin and Paquette, Press et al., 1995).
For clarification of the formation background of the rocks concerned, the geochemistry of the granitoids will be discussed in the following section.

The granite and porphyry granite of the study area have high content of SiO₂, Na₂O + K₂O, low Al₂O₃ and CaO, rich in REEs (except Eu) and HFSE Zr, Nb, Ga and Y, but lower in Sr (Fig. 6), indicating typical A-type granite geochemistry (Collins et al., 1982; Whalen et al., 1987; Eby, 1990; Patiño Douce, 1997). Meanwhile the granites have high 10000Ga/Al ratio (2.98–3.99), and are plotted in the A-type granite field in both the 10000Ga/Al vs. FeO/Ti/MgO and 10000Ga/Al vs. (Na₂O + K₂O)/CaO diagrams (Fig. 14a, b). Some highly differentiated I- or S-type granites also have the geochemistry of A-type granite (Whalen et al., 1987; Jiang et al., 2009), but these granites usually have high Rb, low Sr content, and content of some HFSE (Zr, Nb and Y) in the rock will decrease substantially due to fractionation crystallization of zircon from the melt. Thus, the high content of HFSE (Zr + Nb + Y + Ce) is a critical symbol to distinguish A-type from highly differentiated granite. Granites in the study area are plotted in the A-type granite field on both the Zr + Nb + Y + Ce vs. FeO/Ti/MgO and Zr + Nb + Y + Ce vs. (Na₂O + K₂O)/CaO diagrams, well apart from the non-differentiated I- or S-type granites (Figs. 14c, d). In addition, the Zr saturation temperature of the magma calculated from bulk composition (Watson and Harrison, 1983; Miller et al., 2003) is rather high (887–892°C) for the granite, consistent with the high temperature feature of the A-type granite. Therefore, the above data all imply that the granites of the studied region belong to A-type granite.

It should be noted that most A-type granites are K₂O > NaO, but some A-type granites are more sodium rich, such as Biharipur and Dabla A-type granites in Aravalli mountains, India (Chaudhri et al., 2003; Kaur et al., 2006), the Paleoproterozoic A-type granite exposed in Changyi County, Shandong Province (Lan et al., 2015), and Paleoproterozoic A-type granites exposed in Zanhuang County, Hebei Province (Du L L et al., 2016), and so on. A-type granites generally form in extensional setting, such as intra-plate rift or post-orogeny (Eby, 1990, 1992; Hong et al., 1996). According to the discrimination diagrams of Pearce et al. (1984), the ca. 1.7 Ga granites of this study were formed within plate setting. In combination of the bimodal feature, the gabbro and granite of the study region formed in extensional intra-plate
setting.

5.3 The implication of the ca. 1.7 Ga magmatism during breakup of the Columbia

The global continental collisions at 2.1–1.85 Ga resulted in amalgamation of the cratons, which was responsible for amalgamation of the Columbia (Nuna) (Rogers and Santosh, 2002; Zhao G C et al., 2002, 2004). Due to the sporadic outcrops of the Paleoproterozoic, little is known about the scale, properties and role of the Yangtze Block in the Columbia at this period. At the northern margin of the Yangtze Block, the Houhe Group (2081 ± 9 Ma, Wu et al., 2012) experienced the late Paleoproterozoic granulite facies metamorphism and later retrograded amphibolites facies metamorphism (He et al., 1995). In the Kongling region, the Archean-Paleoproterozoic metamorphic series experienced the magmatic-metamorphism event at 2.0–1.9 Ga (Qiu et al., 2000; Gao et al., 2001, 2011; Zhang S B et al., 2006; Wu et al., 2009; Yin et al., 2013), and the clockwise metamorphism PTi path of collision setting (Geng et al., 2016). The Badu Group of the Cathaysian Block in the Suichang area, Zhejiang Province, also underwent granulite facies metamorphism with clockwise PTi path (Zhou and Zhou, 2012; Zhao et al., 2014). These data demonstrate that the Archean-Paleoproterozoic rocks of the southern China blocks had universally undergone metamorphism event at 2.0–1.9 Ga, which was involved in the orogenic processes of assembling the Columbia (Geng et al., 2016).

It is generally thought that breakup of the Columbia occurred at 1.7–1.3 Ga, which was symbolized by the development of the intra-continental rifts and anorogenic magmatism (Condice, 2002; Rogers and Santosh, 2002; Zhao G C et al., 2002; Ernst et al., 2008; Evans and Mitchell, 2011; Zhang et al., 2012b). At the northern margin of the Yangtze Block, the Quanyishang granite, basic dykes and rapakivi reminiscent of extensional setting formed at ca. 1.85 Ga (Xiong et al., 2009; Peng et al., 2009, 2012; Zhang et al., 2011; Zhou et al., 2017), which was perhaps related with the initial fragmentation of the Columbia (Zhou et al., 2014). In this study, the gabbro and granite of 1735–1713 Ma at the southwestern margin of the Yangtze Block bears the bimodal magmatism characteristics, and the granites of Yunnan Province, occurred the bimodal diabase and porphyry granite of 1675–1728 Ma (Wang Z Z et al., 2013; Guo Y et al., 2014; Yang et al., 2015), and basic dykes of ca. 1.7 Ga at some localities (Zhao et al., 2010; Guan et al., 2011). The volcanic rocks of both the Dahongshan Group, in Yunnan Province, and Hekou Group, in Sichuan Province, also erupted at ca. 1.7 Ga ago (Fig. 13). These intrusive and volcanic rocks all show the geochemistry of intra-plate rift origin. Thus, it can be inferred that at ca. 1.85 Ga the Yangtze Block began to disperse from the Columbia, forming the intracontinental rifts at 1.75–1.70 Ga. In other words, the Columbia began to breakup ca. 1.7 Ga ago.

At the southern margin of the North China Craton, the volcanic rocks (Zhao T P et al., 2002, 2004, 2015) of the Xiong’er Group and accompanied intrusions formed at the period of 1789–1750 Ma in the triple rifts of continental margin setting (Zhao T P et al., 2002, 2004; He et al., 2009; Wang et al., 2010; Cui et al., 2011, 2013; Liu et al., 2011). The radial mafic dykes of ca. 1.78 Ga in the craton were widely distributed (Halls et al., 2000; Peng et al., 2006, 2007; Han et al., 2007; Peng, 2015, 2016; Wang C et al., 2016). During the later period of 1.75–1.68 Ga, the rapakivi, anorthosite, mangerite, alkali granite were formed in extensional environment in the Miyun–Chengde region (Rämö et al., 1995; Xie, 2005; Yang et al., 2005; Ren et al., 2006; Zhang et al., 2017; Gao W et al., 2008; Zhao et al., 2009; Wang W et al., 2013). In the 1.68–1.62 Ga period, the K-rich volcanics of the Tuanshanzi and Dahongyu formations of the Changcheng Group occurred in the Yan–Liao aulacogens (Gao L Z et al.; 2008; Lu et al., 2008; Li et al., 2011, 2013c; Zhang S H et al., 2013; Wang W et al., 2015). Finally, the voluminous basic sills of continental tholeiite feature erupted at 1.37–1.30 Ga (Gao et al., 2007; Su et al., 2008, Zhang et al., 2009, 2012b). The widespread geological and magmatic events at 1.78–1.30 Ga in the North China Craton imply on the one hand that the craton began to fragment from the Columbia, and on the other hand there was a continuous extensional process from 1.78 Ga to 1.30 Ga.

The magmatic events at 1.78–1.70 Ga associated with continent breakup are recorded not only in the Yangtze Block and North China Craton, but also in other continents on the world (Table 2). Some of these magmatic events related to continent breakup exist as bimodal magmatic rocks, some as large scale of mafic dyke swarms, and some as nonorogenic granites. The widespread distribution of the 1.80–1.73 Ga magmatism
events associated with continent breakup in global suggests that the Columbia initially fragmented since ca. 1.80 Ga ago.

The above analysis shows that the ca. 1.73 Ga magmatism event at the southwestern margin of the Yangtze Block can be correlated with the volcanics of the Xiong’er Group and basic dykes in the North China Craton, and 1.79–1.73 Ga magmatism events in other cratons of the world. All these important magmatism events may represent successive breaking up of the Columbia since ca.1.8 Ga.

6 Conclusions

At the southwestern margin of the Yangtze Block, the zircon U–Pb LA–ICP–MS data indicate that the Jiaopingdu gabbro in the Huili county, Sichuan Province, formed at 1721 ± 5 Ma, the Caiyuanzi granite in the Huidong county, Sichuan Province, crystallized at ages of 1732 ± 6 Ma and 1735 ± 4 Ma, the Wenjiacun porphyry granite at 1713 ± 4 Ma. There is a distinguished gap in SiO₂ content of the gabbros and granites, forming the bimodal magmatism series. The granites are of A-type feature and formed within plate setting. Both the gabbro and granite gave the εHf(t) value range of 2–6 and near the 2.0 Ga crust evolution line, suggesting the parent magma of the gabbro and granite gave the 2.0 Ga juvenile crust.

Through comparison with the 1.80–1.73 Ga magmatism events associated with extension setting in the North China Craton and other cratons on the world, it can be seen that the magmatism event was present at the southwestern margin of the Yangtze Block, and also widely distributed in the North China Craton, North Europe and South America cratons. Thus, we can deduce that the Columbia initially separated since ca. 1.8 Ga, and continental margin or within plate rift basins occurred up to ca. 1.73 Ga.

Acknowledgements

The project is jointly supported by the Key Research and Development Program of China (grant No. 2016YFC0601001), the China Geological Survey project (DD20190002 and DD20190005), and National Natural Science Foundation of China (grant No. 41472082). We would like to thank Dr. Ren Guangming and Ms. Pang Weihua and Yang Hong for them generous help during field work.

Manuscript received Mar. 7, 2019 accepted May 5, 2020 associate EIC: ZHOU Taofa edited by FANG Xiang

Reference


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