Petrogenesis and tectonic significance of Early Paleozoic magmatism in the northern margin of the Qilian block, northeastern Tibetan Plateau

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ABSTRACT

Abundant Early Paleozoic magmatism is preserved in northern Tibet and has important implications for continental crustal growth in response to continental collisions. To better constrain the evolution of the northern margin of the Qilian plateau, we conducted an integrated investigation involving U-Th-Pb zircon geochronology, whole-rock geochemistry, and syntheses of existing data sets across the North Qilian orogenic belt. Zircon U–Pb dating indicates that the Early Paleozoic intrusive rocks in the study area can be divided into two stages: 460–480 Ma and 440 Ma. The 478–480 Ma meta gabbro-diorite samples belong to the calc-alkaline series and show a fractional crystallization trend in the Harker diagrams. These samples have relatively high La/Nb (2.08–3.26) and low Ba/La (0.05–0.06) ratios, indicating a subduction-modified continental-lithospheric mantle source. The 460–480 Ma meta-granite samples are I-type and classified as high-K calc-alkaline series. Both the meta gabbro-diorite and meta-granite samples are characterized by negative Nb, Ta, and Ti anomalies and enriched LILEs, and showing arc signatures that may be related to the southward subduction of the North Qilian oceanic crust. The 441 Ma hornblende syenite samples have high contents of alkalis (K2O + Na2O = 7.80%–12.07%) and belong to the alkaline series, suggesting an extensional geological setting. The 440 Ma syenogranite samples are classified as high Ba-Sr granites and belong to the shoshonitic series. The syenogranite samples were most likely generated by partial melting of lithospheric mantle that had been metasomatized by slab-derived fluids, and mixed by the crust derived granitic magmas during the ascent of the magmas. Both the hornblende syenite (441 Ma) and the syenogranite (440 Ma) samples were emplaced in a postcollisional tectonic setting associated with the closure process of the North Qilian Ocean.

1. INTRODUCTION

An orogeny is commonly accompanied by widespread magmatism in the earth (e.g., Harris et al., 1986; Finger et al., 1997; Sylvester, 1998; Yin and Harrison, 2000; Yin et al., 2007; Xiao et al., 2009a, 2009b; Wu et al., 2016, 2017, 2019; Zuza and Yin, 2017; Zuza et al., 2018). During the different stages of an orogenic process, different magmas types can be generated (e.g., Pearce, 1983, 1996; Sylvester, 1998). The study of magma allows us to better understand and piece together the tectonic history and orogenic evolution (e.g., Mahéo et al., 2009; Dokuz et al., 2010; Zuza and Yin, 2017; Wu et al., 2018). The Qilian orogen is located along the northern margin of the Tibetan plateau between the Alxa block to the north and North Qaidam–West Qinling to the south (Figs. 1A and 1B; Xiao et al., 2009a; Song et al., 2013; Wu et al., 2016, 2017; Zuza and Yin, 2016; Liu et al., 2018a; Zuza et al., 2015, 2018). This orogen is a typical oceanic suture zone and has attracted the attention of many scholars in recent decades for its Neoproterozoic to Early Paleozoic ophiolite sequences (e.g., Xiao et al., 1978; Feng and He, 1996; Zhang et al., 1997; Shi et al., 2004; Hou et al., 2006; Yin et al., 2007; Song et al., 2012, 2013; Zuza et al., 2018; Fu et al., 2018), high pressure (HP)/ultrahigh pressure (UHP) metamorphic belts (e.g., Song et al., 2006, 2007, 2013, 2014, 2019; Yin et al., 2007; Zhang et al., 2007, 2012, 2017; Mattinson et al., 2007; Wu et al., 2017; Zuza et al., 2018), island-arc rocks (e.g., Song et al., 2012, 2013; Yang et al., 2012), and tectonic/orogenic syntheses (e.g., Yin et al., 2007, 2008; Xiao et al., 2009a; Gehrels et al., 2003a, 2003b; 2011, Ye et al., 2015; Zuza et al., 2019; Li et al., 2019).

The Qilian orogen underwent a complex orogenic process in the Early Paleozoic (e.g., Xiao et al., 2009a; Song et al., 2013; Huang et al., 2014a, 2014b, 2015a, 2015b, 2016; Wu et al., 2016, 2017; Liu et al., 2018a, 2018b; Zuza et al., 2018; Chen et al., 2018). In the past two decades, the petrogenesis and tectonic settings of different types of igneous rocks in the Qilian orogen have been widely studied (e.g., Song et al., 2013; Tseng et al., 2009; Wu et al., 2009; Huang et al., 2014a, 2015a; Tung et al., 2016; Wang et al., 2017; Zuza et al., 2018; Chen et al., 2018). However, several important first-order problems regarding the development of the Qilian orogeny remain unresolved. First, the assembly pattern and subduction polarity of the North Qilian Ocean are debated. The models that illustrate these issues include (1) bidirectional subduction (Zuo and Liu, 1987; Wu et al., 2009, 2010; Zhang et al., 2012), (2) single north-dipping subduction (Xu et al., 1994;
Figure 1. (A) Tectonic division of the Tethyan orogenic system across the Tibetan Plateau (modified after Wu et al., 2017). (B) Simplified zircon U-Pb age distribution map showing magmatism across the Qilian block (modified after Wu et al., 2017; Zuza et al., 2018). Legend: Early Paleozoic granitoids, Late Paleozoic granitoids, Mafic rocks, Ultramafic rocks, Sample location, Eclogite sample, Ages and references, Fault, City.
Xia et al., 1996, 1998, 2003; Zhang et al., 1997, 1998; Song et al., 2013), and (3) single south-dipping subduction (Song, 1997; Sobel and Arnaud, 1999; Gehrels et al., 2003a; Yin et al., 2007; Wu et al., 2017; Allen et al., 2017; Zuza et al., 2018). Second, other major issues are the lack of adequate knowledge of the magmatism that occurred during the subduction/collision periods and the poor time constraints for the onset of subduction and collision (e.g., Gehrels et al., 2003a, 2003b; Huang et al., 2014a, 2015a; Song et al., 2013; Wu et al., 2013, 2017; Zuza et al., 2016, 2018). Third, the generation mechanism of the Early Paleozoic magmatism in the Qilian orogeny remains controversial (e.g., Wu et al., 2004, 2010; Chen et al., 2008; He et al., 2007; Yong et al., 2008; Song et al., 2013; Yang et al., 2015).

The Shangrimuceer area (98°30′–99°15′ E, 38°–46°N) is along the northern margin of the Qilian block and close to the North Qilian orogenic belt (Fig. 1B). Early Paleozoic intrusive rocks are widespread in this region. We have completed detailed (1:50,000 scale) geological mapping around (e.g., Tseng et al., 2006; Tung et al., 2007; Lu et al., 2009; Song et al., 2013; Yang et al., 2015) with 2.3–1.9 Ga tonalitic/granitic gneisses (e.g., Santosh et al., 2006, 2007; Gehrels et al., 2007; Song et al., 2013; Wu et al., 2013, 2017, 2018). Pressure-temperature estimates provide peak metamorphic conditions of 669 ± 5 °C and 2.1 ± 0.2 GPa, and the metamorphic age is ca. 485 Ma (Wu et al., 2017; Song et al., 2019).

Early Paleozoic ophiolite mélanges (Um) exposed in the northeast section of the study area (Fig. 2) belong to the Yushigou ophiolite suite (Xiao et al., 1978; Feng and He, 1996; Shi et al., 2004). The mélangé consists of clastic and siliceous rocks, which constitute its matrix, and ca. 550–512 Ma ultramafic and mafic blocks (e.g., Shi et al., 2004; Song et al., 2013). The mélangé contacts the Tuolai Group and Early Paleozoic low-grade metamorphosed clastic rocks by a fault (Fig. 2). The mélangé is overlain uncomfortably by Carboniferous neritic deposits (C; Fig. 2). The Permian strata (P; Fig. 2) are composed primarily of arkosic sandstone. The Mesozoic strata (T1–2, T3, J, and K; Fig. 2) are exposed in the central portion of our study area and include polymictic conglomerate arkose sandstones, siltstones, and coal-bearing shale.

The intrusive rocks in the study area are mainly divided into two stages: Neoproterozoic and Early Paleozoic (Gehrels et al., 2003a, 2011; Yin et al., 2007; Song et al., 2013; Huang et al., 2014a, 2015b; Wu et al., 2017; Zuza et al., 2018). The Neoproterozoic intrusive rocks (gn; Fig. 2) consist of arc-related medium to coarse grained plagiogneiss (ca. 900 Ma; Wu et al., 2017) and A-type meta-porphyritic diorite (ca. 820 Ma; Wu et al., 2017), which intrudes into the metamorphic basement. The Neoproterozoic intrusive rocks are intruded by Ordovician quartz monzonite (ca. 445 Ma), biotite alkali feldspar granite (ca. 449 Ma), and monzonitic mylonitic orthogneiss (ca. 472 Ma) (Wu et al., 2017; Zuza et al., 2018). The Early Paleozoic intrusive rocks consist of gabbro, diorite (gb; Fig. 2), quartz diorite, monzonite granite, granodiorite, syenogranite, and hornblende syenite (gr; Fig. 2), some of which have well-developed stretching lineations or slight deformation (Wu et al., 2017; Zuza et al., 2018).

The study area includes numerous Cenozoic thrust faults and potential strike-slip faults (Yin et al., 2008). The faults include the Shule thrust system in the south and the Tuolai thrust system in the north (Fig. 2), which are clearly described by Wu et al. (2017) and Zuza et al. (2016, 2017, 2018).

2.2. Field Occurrence and Sample Description

Thirty-four representative samples were collected from seven plutons for geochemical and geochronological analysis (Fig. 2). Lithological classifications of the analyzed samples are based on visual analysis of the hand specimens, thin sections, as well as chemical analyses. According to the petrological characteristics and the degree of metamorphism, these intrusive rocks can be divided into meta gabbro-diorites, meta granitoids, hornblende syenites, and syenogranites. They are described separately below.

2.2.1. Meta Gabbro-Diorite

The meta gabbro-diorite exposed in the southeast part of the study area covers an area of 18 km² and includes two plutons. The meta gabbro intruded the Tuolai Group, but was intruded by the meta granitoid (Ogr) and hornblende syenite (ξgr) (Figs. 3A, 3B, and 3C). In the Pingtoushan area, the pluton is composed of coarse- to medium-grained meta diorite in the core and medium- to fine-grained meta gabbro in the rim (Fig. 3D). Contacts between the two intrusive phases are gradational and over 50 to 100 m.
Figure 2. Simplified geologic map of the study area (modified after Wu et al., 2017). See also Figure 1 legend.
Figure 3. Representative photographs of the Early Paleozoic intrusive rocks from the study area.
The meta gabbro (sample D8524) displays a columnar granoblastic texture and massive structure (Fig. 3I) and is composed of plagioclase (±50%), hornblende (45%–50%), and biotite (1%–5%). The scattered hornblende grains are green in color with a xenomorphic columnar texture. The hornblende grain size is between 0.3 and 2 mm in diameter, and the grains are generally altered by quartz and biotite. The plagioclase grains are gray in color with a xenomorphic granular texture, and have grain sizes between 0.2 and 0.5 mm in diameter, which display evidence of clayization and zoisitization. The biotites are brownish in color and are 0.05–0.1 mm in grain size. Accessory minerals comprise opaque minerals, titanite, and zircon. Secondary minerals are sericite, chloride, and epidote.

The hornblende syenite (sample D8523) is black-gray in color, coarse-to-medium-grained, has subhedral crystals, and is granular and massive in structure. The sample consists of plagioclase (±50%), hornblende (45%–50%), biotite (±5%), and quartz (1%–5%), and has a 0.1–0.4 mm grain size. Accessory minerals are magnetite, zircon, apatite, and grotite. Secondary minerals are sericite, chloride, epidote, and calcite.

2.2.2. Meta Granitoid

The NW-trending meta granitoid plutons intrude the Tuolai Group metamorphic rocks and meta gabbro, and cover a total of 280 km² in the study area (Fig. 2). The meta granitoids comprise meta monzonitic granite (Figs. 3A, 3B, and 3C), meta granodiorite (Fig. 3E), and meta quartz diorite, all of which underwent strong ductile deformation.

The meta monzonitic granite (samples D1203 and PM101.3) displays a columnar mylonitic texture and massive structure (Fig. 3I), and consists of plagioclase (40%–45%), K-feldspar (30%), quartz (20%–25%), and biotite (5%–10%) with grain sizes between 0.5 and 1.0 mm. Accessory minerals are magnetite, zircon, apatite, and grotite. Secondary minerals are sericite and epidote.

The meta granodiorite (sample SRM004) possesses a mylonitic texture and porphyritic structure (Fig. 3K). The rock is composed of phenocrysts (±20%) and substrates (80%). The phenocrysts are composed mainly of K-feldspar (10%), plagioclase (±8%), and muscovite (±2%), which range from 0.4 to 3.3 mm in grain size. The substrates consist of fine-grained felsic mylonitic minerals (70%), muscovite (±6%), biotite (4%), and neogenic minerals, which display linear or strip-shaped distribution patterns and are 0.01–0.3 mm in grain size. Accessory minerals include opaque minerals and apatite. Secondary minerals are kainite, sericite, and chlorite.

Meta quartz diorite (sample BCC001) possesses a relict fine-grained subhedral texture and oriented structure and is composed of plagioclase (±60%), quartz (±10%), and biotite (±30%) with 0.1–0.7 mm grain sizes. Accessory minerals are opaque minerals, apatite, and sphe. Secondary minerals include sericite and epidote.

2.2.3. Hornblende Syenite

The hornblende syenite consists of two plutons that are situated in the Fangdingshan and Pingtoushan areas and are exposed over 100 km². The hornblende syenite intrudes into the Tuolai Group (Fig. 3F) and the meta gabbro-diorite, and wall-rock xenoliths are widespread in the pluton. In addition, a series of acidic dykes developed in the pluton in NE-trending area. The hornblende syenite (sample D0006) is red in color with coarse to medium subhedral grains, and a granular and massive structure (Fig. 3G). The rock consists of hornblende (±55%) and K-feldspar (±45%) that are 2–5 mm in grain size. Accessory minerals are magnetite, zircon, and apatite, and the secondary minerals include sericite and epidote.

2.2.4. Syenogranite

The syenogranite outcrops in the south of the Yushigou ophiolite unit display a planar distribution in the NE-trending area. The pluton is in contact with the fault, Carboniferous strata, and the Neoproterozoic intrusive rocks. The pluton is mainly composed of syenogranite and contains abundant mafic microgranular enclaves (Fig. 3H). The syenogranite (sample Yc2008) is composed of K-feldspar (45%), quartz (20%), plagioclase (20%), amphibole (10%), and biotite (5%), with grain sizes between 0.5 and 2 mm (Fig. 3L). Accessory minerals mainly consist of opaque oxides, apatite, and titanite.

3. ANALYTICAL METHODS

3.1. Zircon U-Pb Dating

Samples were first crushed using conventional crushing methods and then separated using heavy liquids and a magnetic separator at the Langfang Mineral Separation Laboratory of the Bureau of Geology and Mineral Resources of Hebei Province. Zircon grains were separated using conventional magnetic and density techniques. The grains were hand-picked under a binocular microscope. The internal structures of the zircon grains were examined using a transmitted electron microscope and imaged by backscattered electron (BSE) and cathode luminescence (CL) prior to U-Pb isotopic analyses. The BSE and CL imaging was carried out using a LEO1450VP scanning electron microscope with a MiniCL detector at the Institute of Geology, Chinese Academy of Geological Sciences. Zircon analyses were performed on the Neptune multi-collector–inductively coupled plasma–mass spectrometer (MC-ICP-MS Thermo Fisher Ltd.) with a 193 nm-FX ArF excimer laser-ablation system (ESI Ltd.) at the Isotopic Laboratory, Tianjin Institute of Geology and Mineral Resources. NIST610 glass was used as an external standard to calculate U, Th, and Pb concentrations in the zircons. The common Pb correction was used with the 206Pb method (Stacey and Kramers, 1975), and the Temora zircon was used as an external standard to normalize isotopic fractionation during the analysis. Uncertainties of the individual analyses are reported with 1σ errors; weighted-mean ages are reported at the 2σ confidence level. The age calculations and concordia diagram plots were completed using Isoplots (Ludwig, 2003). The detailed analytical techniques are described in Li et al. (2009).

3.2. Major and Trace Element Determinations

Major elements were analyzed by X-ray fluorescence analysis (XRF; PHILIPS PW1480) using fused glass disks at the Langfang Regional Geological Survey, Hebei Province, China. The content of oxide was analyzed using wet chemical methods, and loss-on-ignition was determined by the gravity method. Analysis accuracy was better than 1%. Trace element and rare earth element (REE) abundances were measured using inductively coupled plasma–mass spectrometry (ICP-MS) following the techniques of Liang et al. (2000) and Gao et al. (2008) with analytical precision for Zr, Hf, Nb, and Ta better than 5%; most elements had values within 10% of certified values.

4. ANALYTICAL RESULTS

4.1. Zircon U-Pb Geochronology

Eight samples were collected in this study for laser-ablation (LA)-ICP-MS zircon U-Pb dating (Fig. 2); the detailed analysis data are shown in Table DR1. Representative CL images for igneous zircons of our samples are presented in Figure 4. The zircon grains exhibit clear euhedral–subhedral...
crystals with oscillatory growth zoning (Fig. 4). Most of the dated zircon grains have Th/U ratios ≥ 0.3, which are indicative of magmatic origin (e.g., Pupin 1980; Koschek 1993).

4.1.1. Meta Gabbro-Diorite
Twenty-four zircons from the meta gabbro (sample D8524) were analyzed and U-Pb ages range from 467 to 493 Ma (Table DR1). The weighted average of twenty-four concordant analyses is 478 ± 4 Ma (mean square of weighted deviates [MSWD] = 0.42) (Fig. 5A). Twenty-four zircon grains from the meta diorite (sample D8523) were analyzed and yield a weighted mean 206Pb/238U age of 480 ± 4 Ma (MSWD = 0.21; n = 24) (Table DR1; Fig. 5B), which we interpret to represent the crystallization age of the meta diorite.

4.1.2. Meta Granitoid
Sample D1203 is a meta monzonitic granite collected from the Pintoushan area. The 206Pb/238U ages for 24 zircon analyses range from 351 to 510 Ma, and 16 concordant analyses yield a weighted mean 206Pb/238U age of 480 ± 2 Ma (MSWD = 0.52; n = 16; Fig. 5C; Table DR1). Sample PM101.3 was collected from the Fangdingshan area. A total of 33 analyses yield a weighted mean 206Pb/238U age of 480 ± 3 Ma (MSWD = 0.21; n = 24) (Table DR1; Fig. 5B), which we interpret to represent the crystallization age of the meta diorite.

4.1.3. Hornblende Syenite (Sample D0006)
In the 206Pb/238U–207Pb/235U concordia diagram (Fig. 5G), 24 analytical spots yield two groups of 206Pb/238U concordia ages: 441 ± 3 Ma (MSWD = 0.39, n = 14) and 461 ± 5 Ma (MSWD = 0.42, n = 7). The younger age represents the time of eruption for the hornblende syenite, and the older ages represent the crystallization ages of zircons that were captured or entrained from the wall rock during the ascent of the magma.

4.1.4. Syenogranite (Sample YC2008)
We analyzed 28 zircon grains from the syenogranite sample. All of the analyses are concordant within analytical error (Table DR1; Fig. 5D) and yield a weighted mean 206Pb/238U age of 460 ± 2 Ma (MSWD = 0.42, n = 7). The younger age represents the time of eruption for the hornblende syenite, and the older ages represent the crystallization ages of zircons that were captured or entrained from the wall rock during the ascent of the magma.

4.2. Major and Trace Elements
4.2.1. Meta Gabbro-Diorite
The meta gabbro-diorite is characterized by low contents of MgO (2.34–5.14 wt%), medium concentrations of K₂O (5.37%–6.94%), CaO
(13.51%–14.72%), and FeOT (7.12%–10.48%), and high concentrations of Al₂O₃ (14.36%–16.32%) and SiO₂ (51.33–59.71 wt%). Most samples plot in the gabbroic-diorite area on the TAS diagram (Fig. 6A). All of the rocks belong to the sub-alkaline (Fig. 6A) and calc-alkaline series on the K₂O versus SiO₂ diagram (Fig. 6B). These rocks also plot in the calc-alkaline series field in the AFM diagram (Fig. 6D). The meta gabbro-diorite samples exhibit medium to high total rare earth element (ΣREE) values (179.32–324.58 ppm), enrichment in light rare earth elements (LREE) ((La/Yb)N = 6.20–8.29) and weak negative Eu anomalies (Eu/Eu* = 0.75–0.90) (Table DR2) (Fig. 7A). In the primitive mantle normalized spider diagram (Fig. 7B), these rocks show relatively enriched large ion lithophile elements (LILE) and high field strength elements (HFSE), with a notable depletion of Nb, Ta, and Ti.

4.2.2. Meta Granitoid

The meta granitoid samples have SiO₂ = 72.18%–74.91%, Al₂O₃ = 13.16%–14.16%, MgO = 0.37%–0.77%, σ = 1.42–2.17, K₂O = 3.29%–5.02%, and Na₂O + K₂O = 6.66%–8.14% (Table DR2). The meta granitoid samples are classified as sub-alkaline (Fig. 6A) and part of the high-K calc-alkaline series (Fig. 6B). The A/CNK [molar Al₂O₃ / (CaO + K₂O + Na₂O)] values range from 1.02 to 1.12, which is indicative of peraluminous granites (Fig. 6C). The samples are also LREE and LILE enriched, and HREE and HFSE depleted (Figs. 7A and 7B). Their (La/Yb)N ratio and δEu values are 2.8–10.3 and 0.35–0.61, respectively, and exhibit medium total REE abundances (ΣREE = 158.20–277.77 ppm).

4.2.3. Hornblende Syenite

In contrast with the meta granitoid, the hornblende syenite samples have high contents of alkalis (K₂O + Na₂O = 7.80%–12.07%), K (K₂O/Na₂O > 1.5), and Al (Al₂O₃ = 15.05%–17.98%), low contents of SiO₂ (53.30%–63.23%), and A/CNK (0.88–0.93), and they belong to the alkaline (Fig. 6B) and shoshonitic series. In a chondrite-normalized REE diagram (Fig. 7A), these rocks exhibit LREE-enriched and relatively HREE-depleted...
Figure 6. Geochemistry diagrams for the Early Paleozoic intrusive rocks from the study area. (A) SiO$_2$-(K$_2$O+Na$_2$O) (TAS) Diagram (after Middlemost, 1994). (B) K$_2$O versus SiO$_2$ diagram (after Le Maitre, 1984, and Rickwood, 1989). (C) A/NK (molar/molar) versus A/CNK (molar/molar) diagram. Normalization values are from Le Maitre (1984) and Rickwood (1989). (D) AFM diagram (after Irvine and Baragar, 1971).

Figure 7. Chondrite-normalized rare earth element patterns (A), and primitive mantle-normalized trace element spider diagrams (B) for the Early Paleozoic intrusive rocks. Chondrite-normalized and primitive mantle-normalized values are from Boynton (1984) and McDonough and Sun (1995), respectively.
patterns and negative Eu anomalies (Eu/Eu* = 0.57–0.78, with one exception of 1.03; Table DR2). In a primitive mantle-normalized trace element spider diagram (Fig. 7B), these rocks are enriched in Rb, K, Th, and U, and depleted in Ba, Sr, Nb, Ta, P, and Ti.

4.2.4. Syenogranite

In contrast with the meta granitoid, the syenogranite samples are characterized by low SiO₂ (64.18–66.65 wt%), high MgO (2.00–2.47), Fe₂O₃ (3.74–4.63), Ba (824–1123 ppm), Sr (361–448 ppm), and A/CK (0.86–0.93). Based on the TAS diagram (Fig. 6A), the rocks belong to the subalkaline and shoshonitic series (Fig. 6B), and most samples plot in the boundary area of the quartz monzonite and the granodiorite. The rocks have total REE contents in the range of 171–209 ppm, and are depleted in HREE (La / Ybₙ = 9.84–13.55) with weak negative Eu anomalies (Eu/Eu* = 0.76–0.88) (Fig. 7A). In a primitive mantle-normalized trace element spider diagram (Fig. 7B), all samples exhibit enrichment in LILE (e.g., Rb, K, Th, and U) and LREE (e.g., La and Sm), and depletion in HFSE (e.g., Nb, Ta and Ti).

5. DISCUSSION

5.1. Petrogenesis and Magma Sources

5.1.1. Meta Gabbro-Diorite

The meta gabbro-diorite samples were derived from a highly fractionated magma, or from a low degree of partial melting of an enriched source, as evidenced by the high SiO₂ (51.33–59.71 wt%) content and the low to medium Mg# (34–52) and V contents (143–254 ppm). This is further supported by the low Cr (8–62 ppm), Co (20–31 ppm), and Ni (6.3–19.9 ppm) contents. The Harker diagrams show that the meta gabbro-diorite exhibits a fractional crystallization trend (Fig. 8). The samples are characterized by a positive correlation between Mg# and SiO₂, CaO, and Al₂O₃, and a negative correlation between the Mg# and TiO₂, P₂O₅, and MnO (Fig. 8). These lines indicate that minor phases of plagioclase, apatite, and Fe–Ti oxides (rutile, ilmenite, and sphene) were involved in the fractional crystallization history. Ni and Cr show very minor changes with Mg#, which suggests no fractionation of olivine and pyroxene, whereas the positive correlation between CaO/Al₂O₃ and CaO indicates the fractionation of clinopyroxene. These types of crystallization sequences can also be recognized from petrographical characteristics and geochronological data.

The meta gabbro-diorite samples are characterized by negative Nb, Ta, and Ti anomalies and enriched LILE, which show arc signatures or suggest that the compositions of these rocks were affected by the assimilation of continental crustal material and/or contamination by subducted sediments. These mafic rocks have relatively high La/Nb (2.08–3.26) and low La/Ba (0.05–0.06) ratios (Fig. 9A), indicating a subduction-modified continental-lithospheric mantle source (Saunders et al., 1992). Furthermore, the samples exhibit constant Ba/La ratios and variable Th/Yb ratios (Fig. 9B), indicating significant involvement of sediments (Woodhead et al., 2001; Fu et al., 2016). In addition, all the samples show positive Zr–Hf anomalies (Fig. 7B) and high Th/Ce (0.11–0.29) ratios, suggesting that crustal contamination played a significant role during the evolution of the magma (Taylor and McLennan, 1995; Plank,
2005; Xia, 2014). The primary magma for the meta gabbro-diorite could have been derived by partial melting of a lithospheric mantle that was metasomatized by subduction-derived components and affected by continental contamination (Bonin, 2004; Clift et al., 2009). The fractional crystallization process occurred during the magmatic evolution.

5.1.2. Meta Granitoid

The meta granitoid samples are classified as a high-K calc-alkaline series and peraluminous granites (Figs. 6B and 6C), and are characterized by enrichment in LREEs and LIL elements, and by depletion in HFSEs (Figs. 7A and 7B). The samples have low Nb/Ta (ranging from 7.10 to 11.66 with an average value of 10.04) and Zr/Hf ratios (ranging from 26.35 to 33.53 with an average value of 29.48), which are close to the values of melted crustal materials (Gao et al., 2004). This evidence indicates that the meta granitoid likely originated from partial melting of crustal materials. In the Harker diagrams, all the samples show a decrease of MgO, FeOt, CaO, Al2O3, MnO and Na2O (Fig. 10) with increasing SiO2 content, which suggests fractionation dominated by pyroxene, amphibole, and plagioclase. The increase of K2O with increasing silica indicates that K-feldspar was not an early fractionation phase. This is also supported by the striking depletions in Ba, Sr, Nb, P, Ti, and Eu shown in the spider diagrams (Fig. 7A). Moreover, the variation trend of Sr versus Ba and Sr versus Ba/Sr indicates that K-feldspar is the major crystallization phase (Figs. 11A and 11B). The P2O5 concentration decreases with increasing SiO2 (Fig. 10), indicating that the meta granitoid is an I-type granite (Chappell and White, 1992).

5.1.3. Hornblende Syenite

Syenite samples belong to the alkaline series, which are produced by: (1) magmatic mixing of mafic magma derived from an enriched mantle, felsic magma derived from partial melting of ancient metamorphic rocks in the middle–lower crust (Baker et al. 1995; Sheppard, 1995; Litvinovsky et al., 2002), or melting of crustal source rocks affected by mantle-derived volatile flux; (2) fractional crystallization from mantle-derived parental basaltic magma (Brown and Becker, 1986; Sutcliffe et al., 1990; Yang et al., 2005); (3) the products of partial melting of felsic crust at high pressure (Huang and Wyllie, 1981); and (4) the partial melting of intra-crustal tonalitic I-type rocks (e.g., Anderson, 1983; Creaser et al., 1991; King et al., 1997).

In this study, we propose that the hornblende syenites are derived from an enriched mantle metasomatized by subducted material for the following reasons: (1) the samples are enriched in HREE and have high contents of La, Ce, Sr and Ba; (2) the hornblende syenites are characterized by strong fractionation between LREE and HREE and have negative Ta–Nb and Ti anomalies (Fig. 7), which are common features of the arc magma (e.g., Peacock, 1990; Scambelluri and Philippot, 2001); and (3) the hornblende syenites have low Nb/U (4.1–7.7) and Ce/Ph (3.2–17.2) ratios, which are significantly lower than those of mid-ocean ridge basalts, ocean island basalts (47 and 25; Hofmann et al., 1988; Kelemen et al., 2003), continental arc volcanic rocks (12 and 7.7; Kelemen et al., 2003), and even lower than the average crust (6.2 and 3.9; Rudnick and Gao, 2003). These trace element constraints provide a strong link to subduction-related melting rather than “normal” mantle melting processes (Hofmann et al., 1988; Kelemen et al., 2003).

5.1.4. Syenogranite

This granite can be divided into a high Ba-Sr granite and a low Ba-Sr granite (Turney and Jones, 1994). The high Ba-Sr granites are alkali-rich and characterized by K2O/Na2O >1, high Ba, Sr and LREEs, and low Nb, Ta and HREEs (Fowler et al., 2001, 2008; Turney and Jones, 1994). The syenogranite displays high Ba (888–2145 ppm) and Sr (390–653 ppm) contents, which are comparable to those of typical high Ba-Sr granite. In the Rb-Sr-Ba diagram, all samples plot into the high Ba-Sr granite (Fig. 12). Several models have been proposed for the production of high Ba-Sr granites, such as partial melting of subducted oceanic islands or oceanic plateaus (Litvinovsky et al., 2002; Yang et al., 2005), partial melting of mafic lower crust (Ye et al., 2008; Choi et al., 2009), partial melting of enriched lithospheric mantle that has been metasomatized by asthenosphere-derived carbonatitic melts (Eklund et al., 1998; Fowler et al., 2001, 2008; Peng et al., 2013), and magma mixing of crust derived granitic magmas with mantle-derived mafic magmas (Zhang et al., 2006; Wang et al., 2012).

The studied syenogranite samples also show the characteristics of shoshonite (Fig. 6B). Models of the production of shoshonite series include: (1) partial melting of continental crustal rocks (Bitenecourt and Nardi, 2004), (2) the assimilation of fractional (AFC) products of mantle-derived potassic magmas (López-Moro and López-Plaza, 2004), and (3) partial melting of the lithospheric mantle that had been metasomatized by slab-derived fluids (Jiang et al., 2006).

Compared to typical arc and adakite rocks, the syenogranite is characterized by significantly lower Sr/Y and (La/Yb)N ratios, which indicate that magma could not have originated by partial melting of subducted oceanic islands or oceanic plateaus (e.g., Defant and Drummond, 1990; Martin, 1999). The magma also did not originate from partial melting of an enriched lithospheric mantle that was metasomatized by asthenosphere-derived carbonatitic melts, as this scenario would predict high Zr/Hf ratios (e.g., Dupuy et al., 1992; Yaxley and Green, 1996). The lower continental crust is characterized by low MgO or Mg# values and
Figure 10. Harker diagrams for the meta granitoid showing content variation of the major elements.

Figure 11. (A) Ba/Sr versus Sr and (B) Ba versus Sr. Indicates that K-feldspar is the major crystallization phases. Abbreviations of minerals shown in the figure are: Opx—orthopyroxene; Cpx—clinopyroxene; Hb—hornblende; Bi—biotite; Pl—plagioclase; Ks—K-feldspar. Modified after Hanson (1978) and Rollinson (1993).
low Cr and Ni contents (Atherton and Petford 1993; Huang et al. 2009; Xiong et al. 2005). The syenogranite has intermediate to high Mg# values (49.78–50.95), and relatively high Cr (26.8–40.5 ppm) and Ni (7.1–11.3 ppm) contents, which are incomparable to those of lower crust-derived rocks (e.g., Gao et al., 2004). The syenogranite has high K2O, Ba and Sr contents and a small variation range of SiO2, which argues against AFC processes. In addition, the pluton contains abundant mafic microgranular enclaves (Fig. 5H) that display igneous microtextures. The above evidence suggests that the syenogranite was generated by partial melting of the lithospheric mantle that was metasomatized by a slab-derived fluid. During the ascent of the magma, the magma mixed with the crust-derived granitic magmas, which played an important role.

5.2. Timing of Early Paleozoic Magmatism in the Qilian Block

Early Paleozoic plutons are exposed in the Qilian block (Fig. 1). Numerous individual zircon ages (n = 85) from this paper and other recent publications show three major age peaks at 470 Ma, 451 Ma, and 440 Ma (Fig. 13). In addition, the Early Paleozoic magmatism in the Qilian block can be subdivided into three stages: Cambrian–Middle Ordovician (540–460 Ma), Late Ordovician (460–442 Ma), and Silurian–Early Devonian (440–415 Ma).

The Cambrian–Middle Ordovician magmatism mainly consists of I-type acidic magmatic rocks, calc-alkaline intermediate-basic intrusive rocks, and few low-K plagiogranites, such as the Yemanshan granite (i.e., ca. 480 Ma; Gehrels et al., 2003a), the Danghennanshan Quartz diorite (i.e., ca. 482 Ma; Gehrels et al., 2003a), and the Kokoli plagiogranite (512 Ma; Wu et al., 2010). These rocks exhibit arc signatures with negative Nb, Ta, and Ti anomalies and enriched in LILE. In the study area, the Ordovician magmatism contains the meta gabbro-diorite and meta granitoid (460–480 Ma). In the three diagrams of Hf-Th-Nb (Wood, 1980), La/Nb–Ba/Nb (Jahn et al., 1999), and Ta/Yb–Th/Yb (Pearce, 1983), all of the meta gabbro-diorite samples plot in the “Arc volcanic rocks” field (Fig. 14). In the Nb-Zr-Y diagram (Meschede, 1986), the samples plot along the boundary of the “Within Plate Basalt” and “Volcanic Arc Basin” fields (Fig. 14). In this study, the meta granitoid samples plot in the volcanic arc granites field in the diagrams (Fig. 15; Pearce et al., 1984), which implies that the Cambrian–Middle Ordovician magmatism in the Qilian block may have been generated by the subduction of oceanic crust.

The Late Ordovician magmatism mainly consists of I-type and S-type granites and few calc-alkaline gabbros, which is similar to the Silurian–Early Devonian magmatism. It is difficult to distinguish the petrogeochemical characteristics between syncollisional magmatism and postcollisional magmatism. However, some specific rock types can clearly indicate their tectonic settings, such as the alkaline intrusive rocks and high Ba-Sr granites (e.g., Baker et al., 1995; Defant and Drummond, 1990). Our hornblende syenite samples belong to the alkaline series, indicating an extensional geological setting. The rocks have high contents of Ga, Zn, Zr, and Ce, and the majority of the rocks plot within the A-type granite field on the discrimination diagrams (Fig. 16). In the Y/Nb-Ce/Nb diagram, the samples plot in the A1 area, indicating a postcollisional tectonic setting. The syenogranite in study area belongs to the high Ba-Sr granite (Fig. 12) and shoshonitic series, and were likely emplaced in a postcollisional tectonic setting (Fowler et al., 2001, 2008; Qian et al., 2003; Ye et al., 2008; Choi et al., 2009; Jiang et al., 2012). Both the hornblende syenite and the syenogranite samples were emplaced ca. 440 Ma. Moreover, the high Ba-Sr/Sr/Y granites were widespread in the Qilian block, such as the Binglinshiu biotite granite (ca. 432 Ma; Yang, 2016; Yang et al., 2016), the Qingchengshan biotite monzogranite (ca. 420 Ma and ca. 430 Ma; Li et al., 2017), and the Tongwei monzogranite (ca. 440 Ma; Li et al., 2017). These lines indicate that the Qilian block underwent the post-orogenic stage after ca. 440 Ma (Wu et al., 2017; Zuza et al., 2018). We propose that the tectonic setting of the Silurian–Early Devonian (440–415 Ma) and Late Ordovician (460–442 Ma) magmatism in the Qilian block are postcollisional and syncollisional, respectively.

5.3. Geodynamic Implication

As described above, the Cambrian–Middle Ordovician magmatism of the Qilian block is related to the subduction of the oceanic crust. This may have been caused by the subduction of the south-dipping North Qilian oceanic crust (Song, 1997; Sobel and Arnaud, 1999; Gehrels et al., 2003a; Yin et al., 2007) or the north-dipping subduction of the Qilian oceanic crust (Song, 1997; Sobel and Arnaud, 1999; Gehrels et al., 2003a; Yin et al., 2007) or the north-dipping subduction of the Qilian oceanic crust (Song, 1997; Sobel and Arnaud, 1999; Gehrels et al., 2003a; Yin et al., 2007) or the north-dipping subduction of the Qilian oceanic crust (Song, 1997; Sobel and Arnaud, 1999; Gehrels et al., 2003a; Yin et al., 2007).
Previous geochronological studies of the eclogites from the north Qilian Mountains shows that the eclogite-facies metamorphic ages are between 463 Ma and 489 Ma (Song et al., 2006; Zhang et al., 2007, 2012). Recently, Dayanglong retrograded eclogites were discovered in the study area, which show a UHP metamorphic age of 485 Ma (Song et al., 2019; Wu et al., 2017). The coeval eclogites of the North Qilian Mountains and the northern margin of the Qilian block strongly suggest that the rocks with different protolith natures and various ages were carried to the great depths of the subduction zone during the south-dipping subduction of the North Qilian oceanic crust during the late Cambrian to Middle Ordovician (Kylander-Clark et al., 2012). Li et al. (2018) reported an Early Paleozoic arc-back-arc system along the southeastern margin of the North Qilian Orogen, which also supports the southern subduction model. In addition, the distribution of the Early Paleozoic plutons in the Qilian block is not random but shows a northeastward younging trend throughout the Qilian Shan (e.g., Zuza et al., 2016, 2018; Wu et al., 2016, 2017). These features could be explained by the presumed North Qilian oceanic lithosphere subducting southward beneath the Qilian block, and northward slab rollback at the south-dipping Qilian arc subduction zone. Subsequent collision orogenies and post-orogenic extension resulted from the different magma types of the Qilian block during the late Ordovician to Silurian. The high Ba-Sr and high Sr/Y granites (e.g., Yang, 2016; Yang et al., 2016), which originated from the thickened lower crust, are distributed in the orogenic belt and the adjacent areas, and the alkaline rocks and postcollisional granites are distributed throughout the region (e.g., Wu et al., 2010; Huang et al., 2015a). Due to contamination from previous arc materials or break-off slabs, some intrusive rocks of the Qilian block still have features of arc magma. Based on our field observations, petrology, geochronology,
and geochemistry of the pluton, taken together with previous data, we suggest that the magmatism of the study area should be divided into three phases in the Early Paleozoic (Fig. 17): the Cambrian–Middle Ordovician (540–460 Ma), the Late Ordovician (460–442 Ma), and the Silurian–Early Devonian (440–415 Ma).

(A) Cambrian–Middle Ordovician (540–460 Ma): the south-dipping subduction of the North Qilian oceanic crust started in the Early Cambrian, and the arc magmatic activity began. The subduction peaked at approximately ca. 485 Ma. At the same time, HP-UHP metamorphic rocks, including eclogite and blueschist, formed along the subduction zone. As the subduction continued, the arc magma peaked at ca. 470 Ma and ceased at ca. 460 Ma.

(B) Late Ordovician (460–442 Ma): Liu et al. (2018b) reported zircon U-Pb ages of 464 Ma for the gabbro from the suprasubduction zone–type southern belt of the North Qilian ophiolite belt, which implies that the North Qilian Ocean was still being subducted during this time period. Both the hornblende syenite and the syenogranite were emplaced at 440 Ma; therefore, we suggest that the collision between the Alxa block and the Qilian block started before 440 Ma. The latest arc granite in the study area and the north margin of the Qilian block is dated to 460 Ma. Therefore, we propose that the continent-continent collision occurred between 460 and 440 Ma. There have been no reports of syn- and postcollisional granitoids in the ophiolite-bearing accretionary complex, but Late Ordovician to Early Silurian strata in the Hexi-Corridor have been classified as flysch deposits that transition to Late Silurian to Devonian molasse rocks (Xu et al., 2010; Zhao et al., 2016). These reports strongly support that the closure of the North Qilian Ocean during the Late Ordovician to Silurian. During this stage, the North Qilian Ocean closed and caused syncollisional

Figure 15. Tectonic discrimination diagrams for the meta granitoid. (A) Rb versus (Yb+Ta) diagram; (B) Rb versus (Y+Nb) diagram; (C) Nb versus Y diagram; (D) Ta versus Yb diagram (after Pearce et al., 1984) showing the field for postcollision granite (post-COLG) from Pearce (1996). Abbreviations: syn-COLG—syncollision granite; post-COLG—postcollision granite; VAG—volcanic arc granite; WPG—within-plate granite; ORG—ocean ridge granite.
magmatism. At the same time, the ophiolite belt was emplaced and the precollisional and/or arc magmatic rocks underwent metamorphism and deformation to different degrees (Wu et al., 2017; Zuza et al., 2018).

(C) Silurian–Early Devonian (440–415 Ma): the alkaline hornblende syenite was emplaced at 440 Ma, which indicates that the tectonic environment switched into an extensional regime. Meanwhile, numerous high Ba-Sr and high Sr granites were triggered by slab break-off. Continuous extension causes mantle upwelling and crustal melting to form postcollisional granitic intrusions in the southern margin of the Alxa block and the northern Qilian block.

Each stage of the typical Wilson orogenic cycle has a standard magma assemblage (Barbarin, 1990, 1996, 1999; Pearce et al., 1984; Harris et al., 1986; Pupin, 1988). In the Qilian block, the volume of syn- and postcollisional intrusive rocks is significantly larger than precollisional/arc intrusive rocks (Fig. 13). This phenomenon is common in other typical orogenic belts around the world, such as the Central Asian orogenic belt (Şengör and Natal’ in, 1996) and the Qinling-Kunlun orogenic belt (Xiao et al., 2009b). The reasons for this phenomenon are changes in the magmatic source area and dynamic conditions, which also reflects the different continental growth patterns in the different stages of an orogeny. During the subduction stage of the North Qilian oceanic crust, the magmatism in the Qilian block is dominated by adakite and calc-alkaline series I-type granites. These rocks have positive $\varepsilon_{Hf}(t)$ and $\varepsilon_{Nd}(t)$ values (e.g., Huang et al., 2015a; Yang et al., 2016), which indicate the lateral growth of the continental crust (Barr et al., 1999). In contrast to precollision magmatism, the syn- and postcollision intrusive rocks in the Qilian block mainly consist of high-K calc-alkaline, high Sr/Y, peraluminous and alkaline rocks, which were triggered by mantle magma underplating, plate delamination, and magma mixing. The $\varepsilon_{Hf}(t)$ and $\varepsilon_{Nd}(t)$ values of these rocks vary widely (e.g., Yang et al., 2016; Huang et al., 2015a), which indicates the magmatic source is complicated and varied, and that a strong materials exchange between the crust and mantle led the vertical continental crust growth.

Figure 16. (A) (10,000*Ga/Al) versus Nb diagram (Whalen et al., 1987); (B) (10,000*Ga/Al) versus Zr diagram (Whalen et al., 1987); (C) K$_2$O versus Na$_2$O diagram (Collins et al., 1982); and (D) Y/Nb versus Ce/Nb for A-type granitoids for the hornblende syenite (Eby, 1992). IAB—ocean-island basalt; OIB—ocean-island basalt.
6. CONCLUSIONS

Based on petrological, geochemical, and geochronological data of the Early Paleozoic intrusive rocks in the Shangrimuceer area, northern margin of the Qilian block, we draw the following conclusions.

(1) Early Paleozoic magmatism in the study area can be subdivided into two stages: 460–480 Ma and 440 Ma.

(2) The meta gabbro-diorite belongs to the calc-alkaline series, and is derived from a highly fractionated magma or a low degree of partial melting of an enriched source. The meta granitoids are I-type granites and are classified as a high-K calc-alkaline series. Both of these rocks are characterized by negative Nb, Ta, and Ti anomalies and are enriched in LILE. They also show arc signatures, which are related to the southern subduction of the North Qilian oceanic crust.

(3) The hornblende syenite belongs to the alkaline series, and the syenogranite is classified as a high Ba-Sr granite and belongs to the shoshonitic series. These rocks are derived from an enriched mantle that was metasomatized by subducted material and are commonly emplaced in postcollisional tectonic settings; thus, these rocks may be related to the closure process of the North Qilian Ocean.

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REFERENCES CITED


