

Article

The Early Silurian gabbro in the Eastern Kunlun Orogenic Belt, Northeast Tibet: Constraints on the Proto-Tethyan Ocean closure

Wenxiao Zhou ^{1*}, Haiquan Li ^{1,2}, Feng Chang ^{1,2} and Xinbiao Lv ^{1,4,5}

- ¹ Institute of Geological survey, China University of Geosciences, Wuhan 430074, Hubei; zhouwenxiao@cug.edu.cn
- ² Resaerch Institute of Petroleum Exploration & Development, Sinopec Northwest China Petroleum Bureau., Urumqi 830011, Xinjiang; lhq@cug.edu.cn
- ³ School of Earth and Space Sciences, Peking University, Beijing 100871, Beijing; 1308353546@qq.com
- ⁴ Faculty of Earth Resources, China University of Geosciences, Wuhan 430074, Hubei; lvxb_01@163.com
- ⁵ State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan 430074, Hubei
- * Correspondence: zhouwenxiao@cug.edu.cn; Tel.: +86-0027-6788-3017

Abstract: The Early Paleozoic is a crucial period in the formation and evolution of the Eastern Kunlun Orogenic Belt (EKOB), which is of great significance for understanding the evolutionary history of the Proto-Tethyan Ocean. This paper presents new petrography, geochemistry, zircon U–Pb dating, and Lu–Hf isotopic research on the Yuejingshan gabbro from the eastern segment of the EKOB. Zircons U–Pb data suggests the gabbro formed in the Early Silurian (435 ± 2 Ma). All samples have relatively low TiO₂ contents (0.45–2.97%), widely varying MgO (6.58–8.41%) and Mg[#] (58–65) contents, rich in large ion lithophile elements (LILE such as Rb, Ba, Th, and U) and light rare earth elements (LREE),which indicate it has a similar geochemical composition than island arc basalt. The major elements features indicate that the formation of this gabbro underwent fractional crystallization of clinopyroxene, olivine, and plagioclase. The depletion of high field strength elements (HFSE such as Nb, Ta, and Ti), and feature a slightly enriched Hf isotope composition (with εHf (t) ranging from 1.13 to 2.45) may be related to the partial melting of spinel-bearing peridotite, led by the slab fluid metasomatism. The significantly earlier than the metamorphic age (428 Ma) of the collision-related eclogite facies and the peak metamorphic age (427 Ma) of medium pressure (epidotization) amphibolite facies in the Eastern Kunlun Orogenic Belt indicates that its formation is still closely related to the subduction of the Eastern Kunlun oceanic crust. The gabbro likely represents magmatic records of the latest period of the Early Paleozoic oceanic crust subduction in the Eastern Kunlun. Therefore, the final closure of the Proto-Tethyan Ocean and the beginning of collisional orogeny, occurred before the Early Silurian.

Keywords: Northeast Tibet; Proto-Tethyan Ocean; Early Silurian; Eastern Kunlun Orogenic Belt; Gabbro; Zircons U–Pb age

1. Introduction

The Eastern Kunlun Orogenic Belt (EKOB) extends more than 1200 km along the northern margin of the Qinghai–Tibet Plateau and connects the Qaidam Block to the north with the Bayan Har–Songpanganzi Terrane (BH–SG) to the south [1, 2]. The Eastern Kunlun region has undergone at least two stages of orogeny, which are closely related to the subduction of the Proto-Tethyan Ocean during the Neoproterozoic–Early Paleozoic and the Paleo-Tethyan Ocean during the Late Carboniferous–Triassic, respectively. Furthermore, these two complete tectonic cycles have established the present tectonic framework of the Eastern Kunlun region.

It is generally accepted that the Proto-Tethyan Ocean had been opened and consistently expanded into the Eastern Kunlun region during the Early Cambrian; the subduction of the oceanic crust lasted until the beginning of the Early Silurian [3-6]. However, precise evidence to constrain the tectonic evolution in the Eastern Kunlun region from compression to extension during the late Silurian is still absent. Especially, it is still debated when the post-collision extension regime was initiated. For example, Zhu, Lin [7] suggested that subduction of the oceanic crust still existed during the Early Devonian, while Dong, He [8] argued that the Proto-Tethys Ocean in the EKOB had been closed and that the post-collision extension setting occurred since the Early Devonian. Zhou, Dong [9] considered that the post-collision extension regime was initiated during the Late Ordovician. In contrast, Lu, Zhang [5] considered that post-collision extension had been initiated at least during the Early Devonian, maybe even the Early Silurian. Therefore, it remains unclear when and how the transition from compression to extension occurred in this area.

Gabbro provide significant evidence, present a record of regional tectonic evolutions, and are widespread throughout the EKOB region [10]. Although an increasing number of relevant gabbros have recently been found in the center and the east of the North Kunlun Fault or the Central Kunlun Fault, their temporal and spatial distributions as well as petrogenesis still remain vague, which results in much controversy in the tectonic evolution of this area [11-13]. Moreover, the ore bodies of magmatic sulfide deposits are found in the EKOB, such as the giant Xiarihamu Ni-Cu sulfide deposit, the large Shitoukengde Ni-Cu sulfide deposit, and the small Binggounan Ni-Cu sulfide deposit, which are hosted in olivine-websterite, surrounded by gabbro. The gabbro age of these three sulfide deposits are almost identical (Xiarihamu gabbro formed in 431 Ma, Shitoukengde gabbro formed 425 Ma, and Binggounan gabbro formed 427 Ma). However, before 435 Ma, there are no deposits of mining value in the EKOB. Therefore, it is necessary to conduct new and accurate petrology, geochemistry, and geochronology research on gabbros of the EKOB to constrain the tectonic evolution of this region. This paper reports new zircon U-Pb dating, geochemical, and Lu-Hf isotopic data for gabbros of the central EKOB. These new data provide insight to the Early Paleozoic tectonic evolution of the EKOB.

2. Regional Geological Setting

The EKOB is part of the Central Orogenic System of China [14-16] and is located in the northern margin of the Qinghai-Tibet Plateau (Figure 1a). It crosses two plates of Tethyan tectonic domains: the North China Plate and the South China Plate [17]. The EKOB is located north of Bayan Kala and south of the Qaidam Basin. The western end is truncated by the Altyn Tagh strike-slip fault, while the eastern end is divided from the arc system of the Qinling by the Tangemu fault and the SaiShentang-Kuhai fault. The basic geological tectonic framework consists of several deep E-W-striking fault zones [17]. In addition to extensive magmatic activities, two ophiolite zones and three fault zones are located in the EKOB [18-20], and two ophiolite zones correspond to the Central Kunlun Orogenic Belt (CEKF) and the Southern East Kunlun Fault zone (SEKF). The tectonic affinities of the basement, the development of the overlying strata, and the regional tectonic evolution identify the CEKF as a brittle-ductile fracture zone with clear surface trace and stepping geometry at depth. It separates the stable block to the north from the active block to the south. The SEKF is composed of a south-dipping thrust zone and an ophiolitic mélange zone. To date, several schemes have been proposed to divide the tectonic units of the EKOB. Although the names of these tectonic units differ, the divisions and boundaries are generally similar, mostly dividing the area into northern, central, and southern regions, which are bounded by the CEKF and the SEKF [17, 21-23].

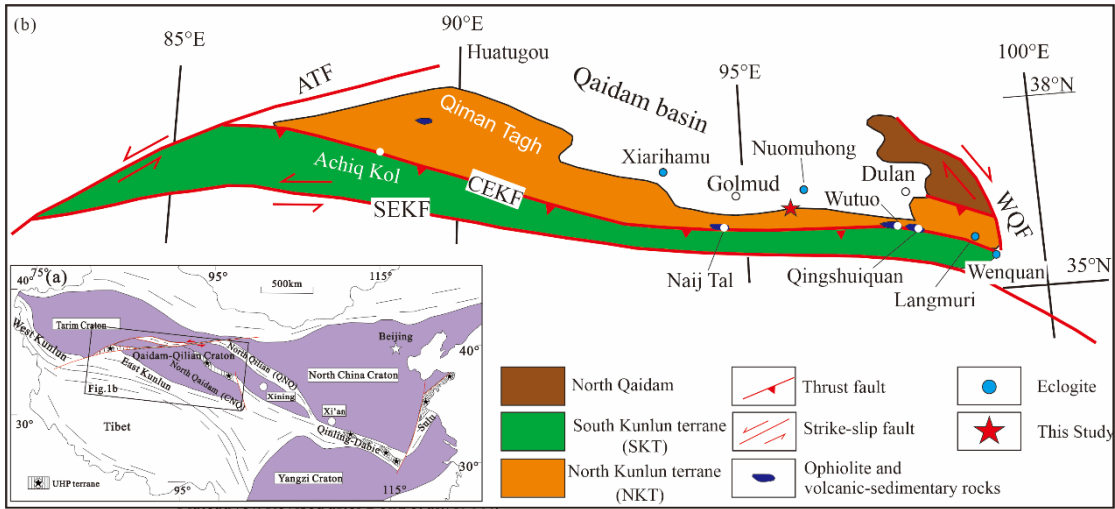


Figure 1. Geological map of the East Kunlun Orogen Belt (EKOB) and its tectonics. Abbreviations: ATF, Altyn Tagh Fault; SEKF, Southern East Kunlun Fault; WQF, Wenquan Fault. Locations of other eclogites can be found in [24-27].

The East Kunlun consists of the North Kunlun Terrane(NKT) and the South Kunlun Block (SKB), which are divided by the CEKF [15, 28-30]. The NKT is located between the southern margin of the Qaidam Basin and the CEKF. It is generally accepted that the EKOB experienced four orogenic cycles: Neo-Archean to Proterozoic (summarized as the Precambrian cycle by Mo, Luo [31]), the early Paleozoic cycle (the eclogite blocks that developed in the EKOB are most related to this cycle), the late Paleozoic–early Mesozoic cycle, and the Mesozoic to Cenozoic cycle. Zircon U-Pb chronology indicates that geotectonic-thermal events distribute in a wide range of 2500–1680 Ma in the source area of the Qaidam-East Kunlun basement, according to the Neo-Archean to Paleo-Proterozoic cycle [32, 33]. Moreover, the crystallization basement was further solidified in the Neoproterozoic stage, and early magmatic activities occurred 1050–750 Ma according to geochronological data of the basalt in the lower Wanbaogou Group and Sanchakou granodiorite gneiss of the Qingshuiquan area [29]. In the process of the early Paleozoic cycle, the peripheral ocean around Qaidam experienced an important tectonic transition during which the stable Qaidam continental margin changed to an active continental margin, accompanied by extensive magmatism. Furthermore, during this cycle the tectonic evolution of the Proto-Tethys Ocean transformed from subduction–collision [29, 34] to post-collision–extension. The third cycle began with the occurrence of the Late Devonian and contributed over eighty igneous rocks all over the EKOB, related to the tectonic evolution of the Paleo-Tethys Ocean [35]. After the Late Triassic, the Tethys tectonic was transferred to the Neo-Tethys tectonic evolution stage. Compared with the Proto-Tethys and the Paleo-Tethys, the bulk of the Neo-Tethys Ocean has been moved to the Bangong-Nujiang-Yalutsangpo area. The influence of the new Tethys on the East Kunlun had become remote.

This is considered to be a hard or rigid block of crystalline basement, consisting of advanced metamorphic rocks of the Paleoproterozoic Jinshuikou Group [23]. The basement is exposed on the western and southern margins of the block. The exposed strata include the Paleoproterozoic Jinshuikou Group, the Mesoproterozoic Xiaomiao Group, the Neoproterozoic QiuGuerDonggou Group, the Cambrian-early Silurian Qimantage Group, and the late Devonian Maoniushan Group. Granites are mainly Silurian-Devonian and late Permian-late Triassic in age. The SKB is located between the CEKF and the SEKF, with E-W orientation. The block contains few intrusive rocks, including late Paleozoic-early Mesozoic granitic rocks and a small number of early Paleozoic intrusive rocks. Early Paleozoic strata are strongly deformed and have been metamorphosed to granulite facies.

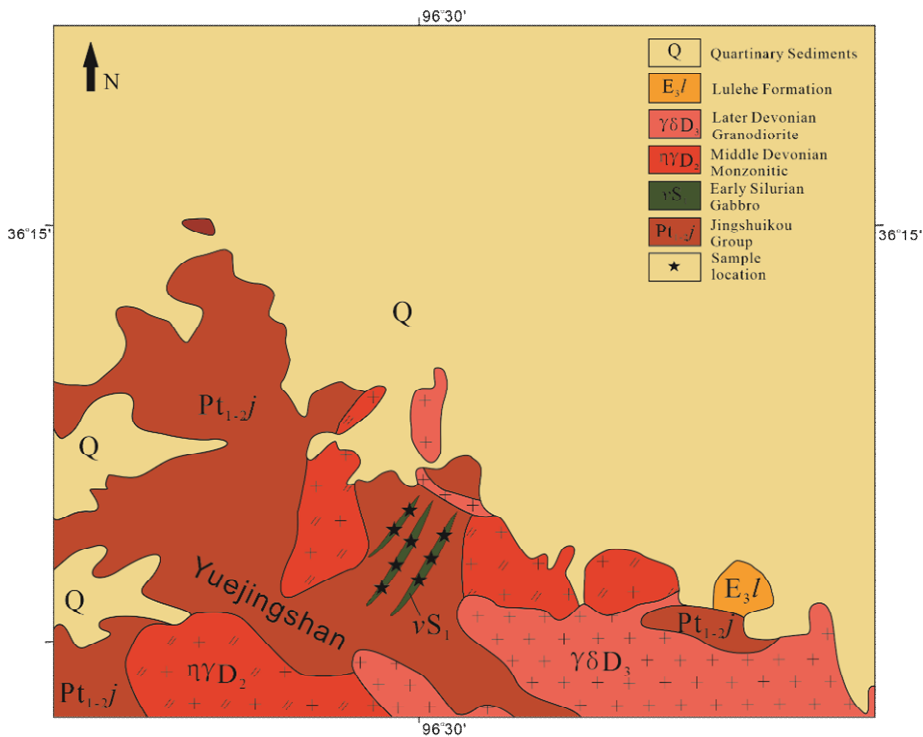


Figure 2. Simplified geological map of the Yuejingshan area.

The Yuejinshan gabbro assumes a veinlike form, intrudes into the Jinshuikou rock group, and the boundary with the surrounding rock mostly appears as an undulating curve. Phenomena of contact thermal metamorphism at the boundary are obvious, and occasionally hornfelization may be found (Figure 3a). Except for the rocks at the contact boundary showing a medium-fine grain texture (Figure 3b), all rocks in the center have a coarse grain texture (Figure 3c). Observed under a microscope, the main minerals of the rocks are plagioclase, pyroxene, and biotite. Pyroxene and plagioclase have similar granularity, and are interwoven to form the gabbro texture. The pseudomorph left after pyroxene alteration and the hornblende reaction rim on the periphery of pyroxene can be seen locally (Figure 3d).

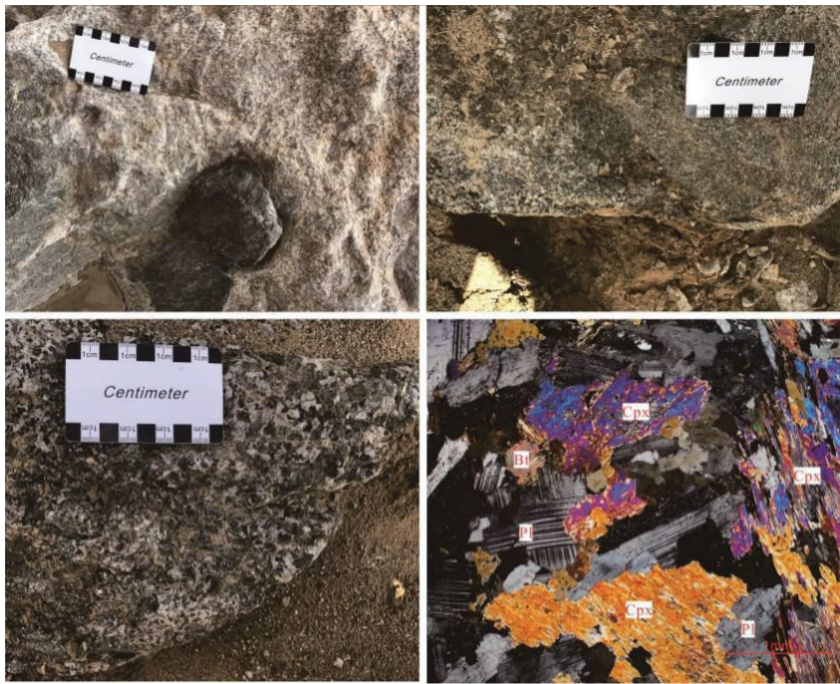


Figure 3. Outcrops and Photomicrographs of Early Silurian Yuejingshan Gabbro in the EKOB. a) The boundary with the surrounding rock mostly follows an undulation curve. b) The rocks at the contact boundary show a medium-fine grain texture. c) The rocks inside have a coarse grain texture. d) Photomicrographs of gabbro (cross-polarized light). Abbreviations: Cpx, Clinopyroxene; Bt, biotite; Pl, plagioclase.

3. Analytical methods

3.1. Zircon U–Pb dating

Zircon crystals were extracted from whole-rock samples by a combination of magnetic and heavy liquid separation, and finally by handpicking under a binocular microscope at the Langfang Regional Geological Survey, Hebei Province, China. All samples were examined by optical microscopy, using both transmission and reflection light microscopes. To identify their internal structures, cathodoluminescence (CL) images were obtained by a JEOL scanning electron microscope. Grains of transparent, euhedral, unfractured, and inclusion-free zircons were chosen for isotopic analyses. Zircon U–Pb dating and trace element analysis were conducted by the Sample Solution Analysis Laboratories Ltd. The analyses used a beam diameter of 30 μm and an ablation depth of 20–40 μm . Helium was used as carrier gas to transport the ablated material from the standard laser-ablation cell. Zircon 91500 was used as external standard for age calibration, and Nist 610 and GJ-1 were used as external standards to calculate concentrations. 29Si was used as internal standard element. Analytical methods are available in the literature [36]. Common Pb was corrected using the method proposed by Andersen [37]. The ICP–MS–DATECAL program was used to calculate isotopic ratios and element contents (Liu et al. 2008, 2010) The age calculations and Concordia plots were made using Isoplot version 3.0 [38].

3.2. Major and trace elements

For geochemical analysis, after removal of altered surfaces, whole-rock samples were crushed and milled to $\sim 75\ \mu\text{m}$. After acid digestion of samples in Teflon bombs, X-ray fluorescence (XRF; PW1401/10) with fused-glass disks and ICP–MS (Agilent 7500a with a shield torch) were used to measure the compositions of major and trace elements, respectively. These measurements were conducted at the Testing Center of Jilin University, China. The analytical results for BHVO-1 (basalt), BCR-2 (basalt), and AGV-1 (andesite) standards indicate that the analytical precision for the detection of major elements exceeds 5%, generally exceeds 5% ($\sim >10\ \text{ppm}$) for trace elements, and is often better than 10% ($\sim <10\ \text{ppm}$). The analytical results of major and trace elements are listed in Table 2.

3.3. Zircon Hf isotopic analyses

Zircon Hf isotopic analyses were conducted using a NewWave UP213LA–MC–ICP–MS at the Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing, China. The instrument conditions and data acquisition methods followed Wu et al.[39]. During Hf isotope analyses, a laser repetition rate of 7 Hz was used and the spot size was 45 μm . The original counting rates of ^{172}Yb , ^{173}Yb , ^{175}Lu , $^{176}\text{ (Hf+Yb+Lu)}$, ^{177}Hf , ^{178}Hf , ^{179}Hf , ^{180}HF , and ^{182}W were collected, and the isobaric interference correction of ^{176}Hu and ^{176}Yb on ^{176}HF was accurately determined. The zircon Hf isotopic data obtained in this study are presented in Table 3.

4. Analytical results

4.1. Whole-rock geochemistry

The test results for the major and trace elements of the whole rock and the related parameters are listed in Table 1. Diagrams related to the main, rare earth, and trace elements are all drawn using GEOKIT software [40].

The Yuejingshan gabbros have low SiO₂ (48.05–55.56 wt.%), MgO (6.58–8.41 wt.%), total Fe₂O₃ (2.87–3.39 wt.%), and ALK (0.73–3.51 wt.%), and high Al₂O₃ (13.95–16.73 wt.%) contents (Table 1). On a total alkali vs. silica (TAS) classification diagram of Wilson (1989), the plot falls into the gabbro field (Figure 4a). Geochemically, they belong to subalkaline series with calc-alkaline affinity (Figure 4b,c). Their A/CNK ratios are 0.57–0.72, showing peraluminous characteristics ((K₂O + Na₂O) < Al₂O₃ < (CaO + K₂O + Na₂O)).

On a PM-normalized trace element spider diagram (Figure 5b; Sun and McDonough, 1989), the samples show enrichment in light rare earth elements (LREEs) and large ion lithophile elements (LILEs; e.g., Sr, Rb, Ba, U, and K), but depleted in heavy rare earth elements (HREEs) and high field strength elements (HFSEs; e.g., Nb, Ta, Ti, and P) (Figure 5a; Boynton 1984). They have (La/Yb)_N ratios of 2.66–5.77 and Eu/Eu* values of 0.23–1.91.

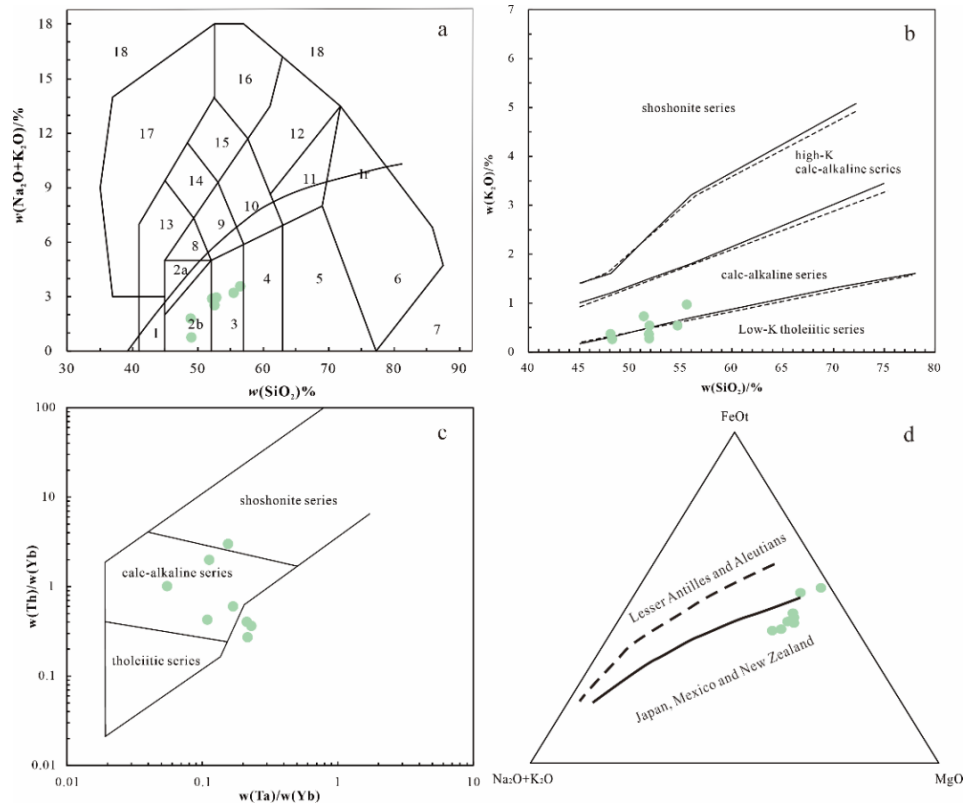


Figure 4. Total alkali vs. silica (TAS) diagrams (a, after Middlemost [41]), K₂O vs. SiO₂ (b, after Winchester and Floyd [42]) Th/Yb vs. Ta/Yb (c, after Pearce [43]), and AFM Classification diagrams (d, after Coleman [44]) of Yuejingshan gabbro.

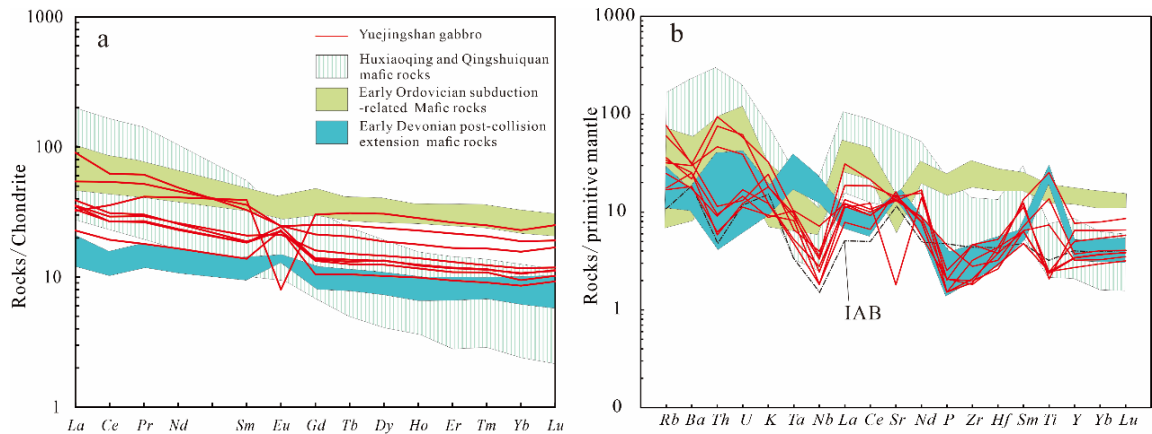


Figure 5. Chondrite-normalized rare-earth element distribution patterns (a, normalization values after Taylor and McLennan [45]) and primitive mantle-normalized trace element spider diagrams (b,

normalization values after Sun and McDonough [46] of Yuejinshan gabbro. IAB data are from Niu and O'Hara [47]; data of early Ordovician subduction-related mafic rocks are from Cui, Meng [48]; data of Huxiaoqing mafic rocks are from Liu, Ma [10]; data of Early Devonian post-collision extension mafic rocks are from Liu, Ma [49].

4.2. Zircon U-Pb ages

The Yuejingshan gabbros were selected for zircon LA-ICP-MS U-Pb dating. Zircon U-Pb age results are presented in Table 2 and Figure 6a.

Zircons from the Yuejingshan gabbro (YJHC-1) are mostly colorless to pale brown, euhedral, or subhedral crystals (100-200 μm long) with aspect ratios of 1:1–2:1. They display clear oscillatory zoning and annulus zoning (Figure 7). These features, together with increased Th/U ratios (most exceed 0.4; see Table 2), indicate a magmatic origin [50-53]. The $^{206}\text{Pb}/^{238}\text{U}$ ages of 27 analytical spots range from 428 to 443 Ma, yielding a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 435 ± 2 Ma (MSWD = 0.03, Figure 6b).

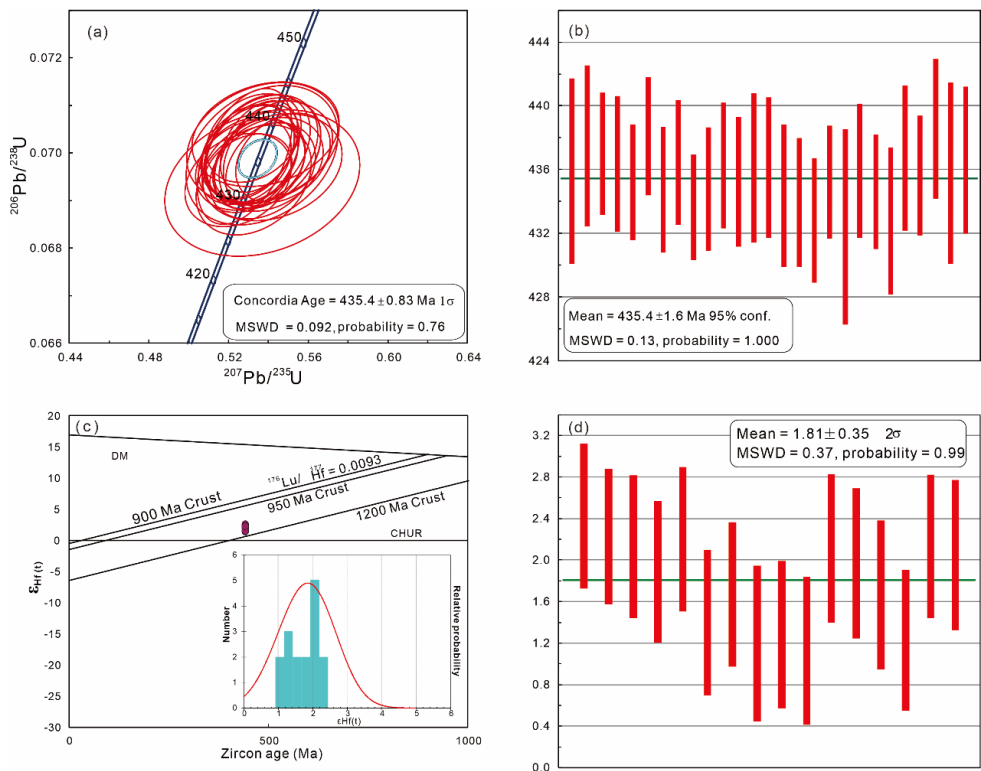


Figure 6. U-Pb Concordia diagrams (a), weighted average ages (b), $\epsilon_{\text{Hf}}(t)$ crust evolution diagrams and weighted average $\epsilon_{\text{Hf}}(t)$ values of Yuejingshan gabbro.

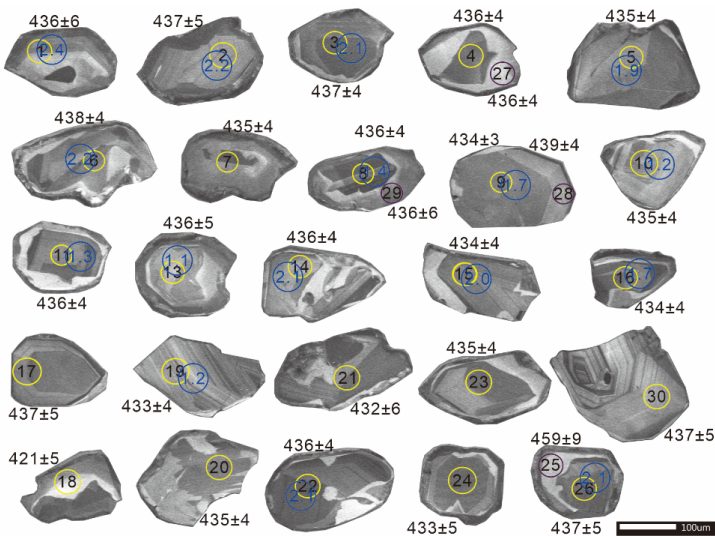


Figure 7. Zircon CL images of Yuejingshan gabbro. Yellow circles and black numbers represent U-Pb test spots and ages. Blue circles and numbers represent Lu-Hf tested spots and related $\epsilon_{\text{Hf}}(t)$ values.

4.3. Zircon Lu-Hf isotopic compositions

The results of Hf isotopes are presented in Table 3 and Figure 6c. The spot locations on the zircons grains are indicated with blue circles in Figure 7. All tested spots showed a low ratio of $^{176}\text{Lu}/^{177}\text{Hf}$ (0.000358-0.001035, Table 3), which indicates no significant radioactivity. Hf are accumulated after zircon had formed. The measured $^{176}\text{Hf}/^{177}\text{Hf}$ ratio may represent the composition for the zircons forming stage[54]. The $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of 16 measuring spots are relatively concentrated, and distributed between 0.282534-0.282570. The $\epsilon_{\text{Hf}}(t)$ values are positive, ranging from 1.13 to 2.45 (with an average of 1.81). In addition, the 16-point two-stage model ages (T_{DM2}) range from 1.16 to 1.23 Ga, which is much older than the crystallization age (435 ± 2 Ma). This indicates origin from the enriched mantle source area or contamination by crustal materials during the magmatic evolution process.

5. Discussion

5.1. Fractional crystallization and crustal contamination

The contents of $\text{Mg}^\#$, Cr, and Ni in the Yuejinshan gabbro samples are relatively stable. The contents of $\text{Mg}^\#$ range from 58 to 65, those of Cr from 89 to 157 ppm, and those of Ni from 13.0 to 25 ppm. These characteristics indicate that the fractional crystallization of this gabbro is not obvious before the final emplacement. The binary diagram, with $\text{Mg}^\#$ as abscissa, shows that only Cr and Ni are very weakly positively correlated with $\text{Mg}^\#$ (Figure 8), indicating that fractional crystallization of clinopyroxene and olivine did not occur in the formation of the magma or that the fractional crystallization was not obvious [55-57]. P_2O_5 , FeO_t , and TiO_2 exhibit significant negative correlations with $\text{Mg}^\#$, indicating that the magma possibly experienced fractional crystallization of apatite and iron-titanium oxide. $(2\text{CaO}+\text{Na}_2\text{O})/\text{TiO}_2$ shows clear negative correlation with $\text{Al}_2\text{O}_3/\text{TiO}_2$ (Figure 9) and part of the samples display obvious Eu negative anomaly. This suggests that the magma underwent the fractional crystallization of plagioclase [58]. In summary, the Yuejinshan gabbro magma likely experienced mainly fractional crystallization of apatite, iron, titanium oxide, and plagioclase during its formation.

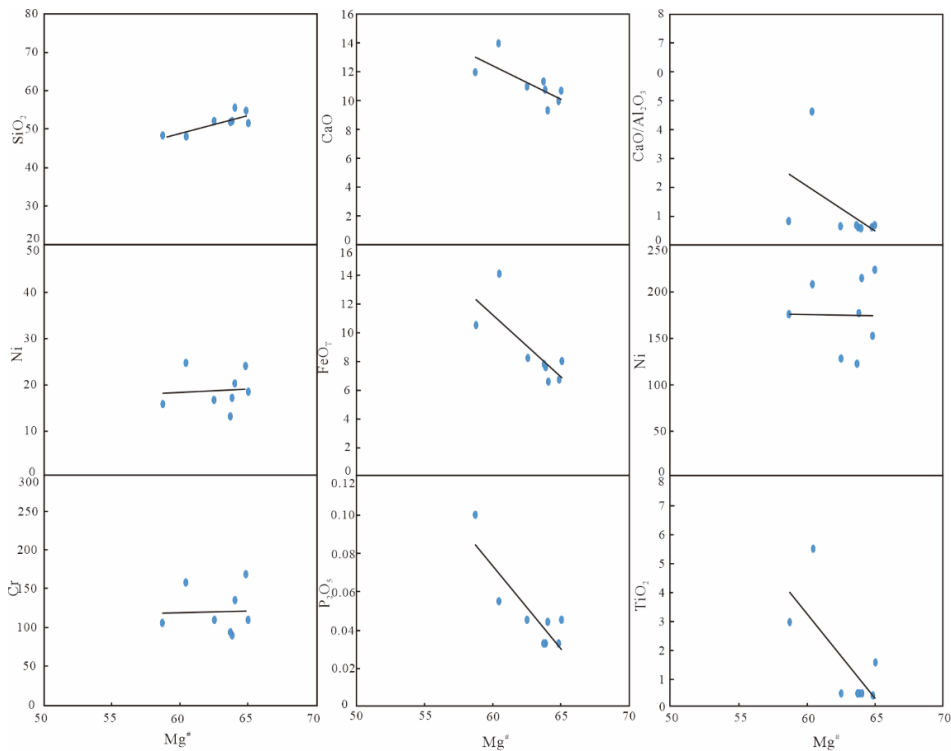


Figure 8. Variation diagrams of SiO₂, TiO₂, FeO_T, CaO, P₂O₅, Cr, Ni, CaO/Al₂O₃, and Sc/Y versus Mg[#] for Yuejingshan gabbro.

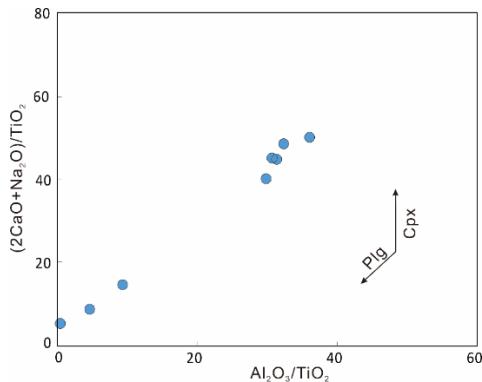


Figure 9. CaO+Na₂O)/TiO₂ versus Al₂O₃/TiO₂ diagrams of Yuejingshan gabbro (after Dessureau et al. [58]).

Studies have shown that crustal contamination and crystallization differentiation often occur simultaneously in the process of magmatic evolution and emplacement [59-61]. Crustal contamination commonly increases LILE, K₂O, and Na₂O, while decreasing P₂O₅ and TiO₂ [61, 62]. The binary diagram, constructed with Mg[#] as abscissa, shows that as Mg[#] decreases, P₂O₅ and TiO₂ gradually increase (Figure 8). This is inconsistent with the characteristics of the mafic magma formed under the involvement of crustal contamination. The Yuejinshan gabbros have relatively lower Nb/La and Nb/Ce ratios (ranging from 0.12 to 0.31 and from 0.07 to 0.29, respectively), which are lower than the Nb/La and Nb/Ce ratios of the primitive mantle, the average crust, and the average lower crust (1.02, 0.4; 0.69, 0.33; and 0.83, 0.39, respectively) [45]. This suggests that mafic magma may not form by mixing a certain proportion of crustal and mantle material. In addition, a few inherited zircons and a slightly enriched $\epsilon_{\text{Hf}}(t)$ values (1.13-2.45) were found in the gabbros, indicating that a small amount of crustal contamination occurred once. Therefore, it may be concluded that the Yuejinshan gabbros were contaminated to a lesser extent by the crust during their formation process.

5.2. Nature of the mantle source

Mafic rocks, e.g., gabbro, usually derive from the lithospheric mantle or asthenospheric mantle [62, 63]. Compared with the primitive mantle, rocks derived from the lithospheric mantle are generally enriched in LILE and LREE and depleted in HFSE (e.g., Nb, Ta, and Ti). However, materials from the asthenospheric mantle are normally enriched in LILE and HFSE and possess isotopic compositions characterized by the depletion mantle. The gabbro samples from Yuejinshan all have relatively low TiO_2 (ranging from 0.45% to 2.97%), are rich in LILE (i.e., Rb, Ba, Th, and U), and show obvious depletion of HFSE (i.e., Nb, Ta and Ti) compared with the primitive mantle (Figure 5b). Moreover, they show a slightly enriched Hf isotope composition ($\epsilon_{\text{Hf}}(t)$ values between 1.13 and 2.45); t_{DM2} (in scope from 1.16 to 1.23 Ga) is much earlier than its crystallization age (~435 Ma), indicating that the mafic rocks may derive from the lithospheric mantle. The Yuejinshan gabbros have a relatively low Ce/Y ratio (ranging from 0.62 to 1.67, with an average value of 1.10), indicating that it may derive from the spinel-garnet facies stable area with a depth ranging from 60 to 80 km [64]. The low (Tb/Yb)_N ratio (ranging from 1.22 to 1.35, with an average of 1.29) of the rocks further confirms that the mafic rocks were derived from the partial melting of spinel-bearing peridotite [65].

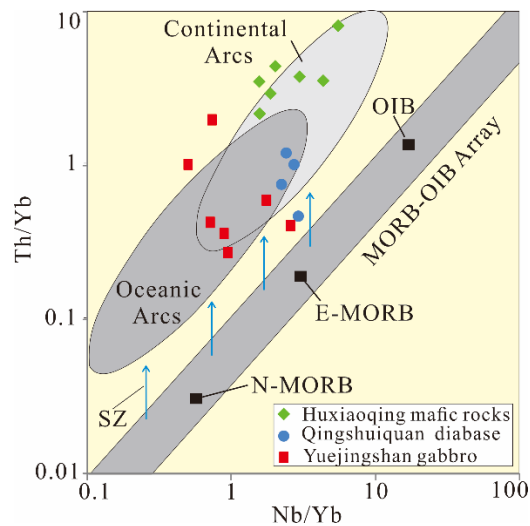


Figure 10. Th/Yb versus Nb/Yb diagram for Yuejinshan gabbro (after Pearce [66]).

Compared with Huxiaoqing mafic rocks, Yuejinshan gabbro samples have a relatively lower Th/Yb ratio (ranging from 0.27 to 2.00). The points plotted in Th/Yb-Nb/Yb diagrams all deviate clearly from the MORB-OIB evolution line (Figure 10), suggesting its formation is significantly affected by the subduction component [67]. The transformation of the mantle source area through plate subduction is mainly realized through the interaction between fluid or melt derived from altered oceanic crust or subduction zone sediments and mantle peridotite [68-70]. Mafic magma ultimately formed by the interaction between mantle peridotite and slab melt, which generally contains relatively high Na_2O , P_2O_5 , and TiO_2 levels, and shows positive anomalies of elements Nb, Ta, and Ti compared with the primitive mantle [68, 71]. The Yuejinshan gabbro samples have lower TiO_2 and P_2O_5 contents, and show obvious negative anomalies of elements Nb, Ta, and Ti compared with the primitive mantle. Basically, the interaction between mantle peridotite and slab melt can be excluded. Trace element ratios (Ba/Th, Th/Nb, Ba/La, and Th/Yb) may identify hydrous fluid or subduction zone sediments. All Yuejinshan gabbro samples have relatively stable Th/Nb and Th/Yb ratios (in the ranges of 0.29-3.20 and 0.27-3.02, respectively), and a wider variation range of Ba/Th and Ba/La ratios (in the ranges of 23.73-356.16 and 10.06-27.26, respectively) (Figure 11). These data imply that a large amount of hydrous fluid enters the mantle source area [69, 70, 72]. Moreover, most rock samples have a wider variation range of Sr/Nd ratios and relatively stable Th/Yb ratios (in the ranges of 2.00-43.96 and 0.27-3.02, respectively), suggesting that the hydrous fluid mainly originates from the altered oceanic crust [73].

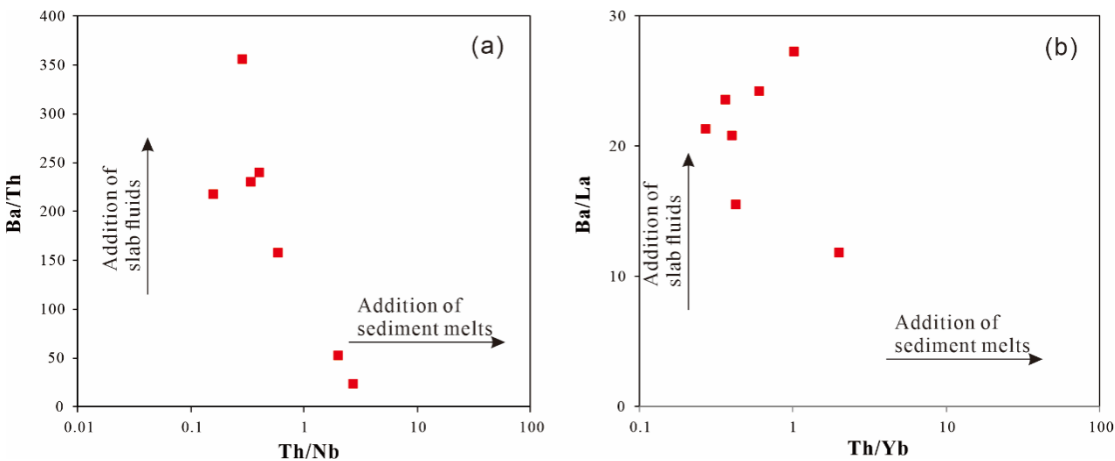


Figure 11. Ba/Th vs. Th/Nb (a, after Hanyu et al.,[69]) and Ba/La vs. Th/Yb (b, after Woodhead et al., [72]) diagrams for Yuejingshan gabbro.

In summary, it may be concluded that the genesis of Yuejinshan gabbros is related to the partial melting of spinel-bearing peridotite replaced by slab fluid. Moreover, their formation underwent fractional crystallization of clinopyroxene, olivine, and plagioclase.

5.3. Implications for the Early Silurian tectonic nature of the EKOB

Based on the studies of Qingshuiquan, Kekesha, and Nuomuhong ophiolites from the Early Cambrian to the Early Ordovician, the existence of an Early Paleozoic ocean was identified [3, 74, 75]. Many high-temperature peraluminous - strong peraluminous granites (the saturation temperatures of most zircons exceed 800 °C), magnesium-rich diorite ($Mg^\#$ all exceed 45), and a small number of HFSE-enriched gabbros (such as Nb, Ta, and Ti) have been identified to belong to the age from the Late Silurian to the Early Devonian [10, 49, 76, 77]. This indicates that the East Kunlun region had begun the post-collision extension during this period. However, there is still much controversy over the final closure of the Early Paleozoic ocean basin in East Kunlun and when collision orogeny began. Mo et al. [31] suggested that the emergence of Late Ordovician amphibole schist and its associated gabbro (Ar-Ar age is 445 ± 2 Ma) in the southwest of Tumulus, Qimantag, could be regarded as a sign of the end of subduction and the beginning of collision. However, Ren et al. [78] and Gao et al. [79] considered that in the Late Ordovician-Early Silurian, the oceanic basin had still not been closed, the East Kunlun region was in a stage of partial back-arc extension, and the final closing time of the ocean basin was in the Middle Silurian [80]. The findings on Wanbaogou rapakivi granite reported by Wang et al. [81] suggested that the continental collision had ended and had entered the post-orogenic extensional stage in the Late Ordovician. The Yuejinshan gabbro reported in this paper may provide crucial petrology evidence for further investigations of the specific tectonic evolution history of the East Kunlun region from the Late Ordovician to the Early Silurian. This evidence may be used to determine the conversion time between the oceanic crust subduction and collision orogeny during the Early Paleozoic in the East Kunlun region.

Compared with the primitive mantle, Yuejinshan gabbro samples are rich in LILE (e.g., Rb, Ba, Th, and U) and LREE, and are clearly depleted in HFSE (e.g., Nb, Ta, and Ti). These characteristics are similar to the distributional characteristics of island arc basalt and Early Ordovician Eastern Kunlun mafic rocks with island arc characteristics (Figure 12). However, they obviously differ from the mafic rocks related to the post-collision extension during the Early Devonian in Eastern Kunlun (Figure 5), indicating that it is closely related to subduction. Moreover, previous analyses on its petrogenesis also confirmed that the subduction components (especially from hydrous fluid) contributed more to the mantle source area. These characteristics suggest that the Yuejinshan gabbros most likely formed in a subduction-related environment. However, two studies have also shown that mafic rocks that formed in the post-collision extension period tend to have a similar geochemical composition to island arc basalt because they inherited mantle source areas modified by paleo-slab subduction [82, 83]. The crystallization age of Yuejinshan gabbros belongs to Early

Silurian (435 ± 2 Ma), which is clearly earlier than the metamorphic age (428 Ma) of the collision-related eclogite facies[24] and the peak metamorphic age (427 Ma) [80] of medium pressure (epidotization) amphibolite facies in the EKOB. This indicates that it could not have formed during the post-collision extensional stage. Ren et al.[78] and Liu et al.[10] reported Qingshuiquan diabase (438 ± 1 Ma) and Huxiaoqin mafic rocks (438 ± 2 Ma), respectively, which also possess Early Silurian subduction magmatic characteristics and are situated in the middle Kunlun suture zone. Both are similar to the Yuejingshan gabbros reported in this paper in terms of age, spatial distribution, and geochemical composition (Figure 1 and Figure 10). These similarities indicate that these three sets of mafic rocks could have formed in an identical tectonic setting.

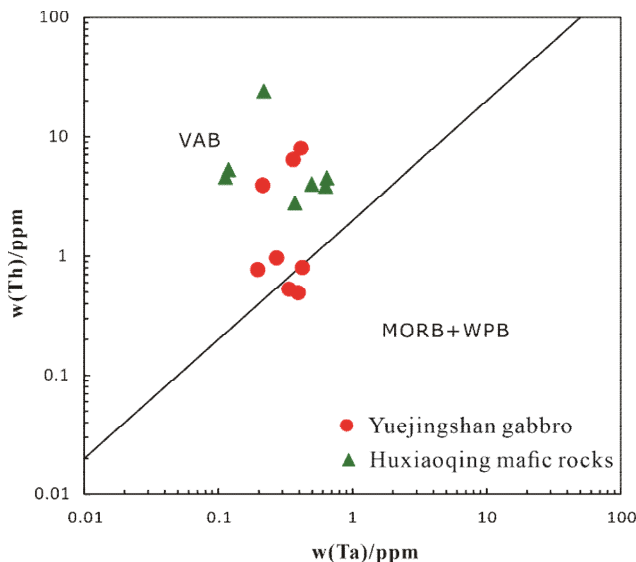


Figure 12. Th vs. Ta diagram for Yuejingshan gabbro (after Pearce *et al.*, 1980).

Subduction-related intrusive rocks with ages of 515–436 Ma (e.g., Qingshuiquan, Kekesha, and Huxiaoqing) were found in the Northern and Middle Kunlun Area. These include cal-calkaline gabbro, dabise, diorite, quartz diorite, and granodiorite, which have been reported in the southern part of the Qingshuiquan–Nuomuhong ophiolites [6, 10, 84, 85]. Additionally, granulite with a metamorphic age of 508 ± 8 Ma, as well as gneisses and amphibolites with ages of 517–482 Ma have been reported, thus confirming the connections of the tectonic thermal events to oceanic crust subduction [86, 87]. All previous research implied that the Early Paleozoic Ocean opened at least at the Early Cambrian and the subduction lasted from the Ordovician to the Early Silurian [88-90].

6. Conclusions

- (1) LA-ICP-MS zircon U–Pb dating dated Yuejingshan gabbro at ~435 Ma.
- (2) Yuejingshan gabbro formed by the plate and partially melted fluid-containing spinel account related peridotite, and were subjected to a Clinopyroxene during their formation, as well as the fractional crystallization of olivine and plagioclase mineral.
- (3) The geochronology and geochemical characteristics of the Yuejingshan gabbro indicate that the EKOB was in a post-collisional extensional environment during the Early Silurian, which was triggered by slab break-off.
- (4) The gabbro represents magmatic records of the latest period of the Early Paleozoic oceanic crust subduction in the Eastern Kunlun which witnessed the final closure of the Proto-Tethyan Ocean and the beginning of collisional orogeny, occurred before the Early Silurian.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Table S1: Major (wt%) and trace element (ppm) data for Yuejingshan gabbro, Table S2: U–Pb isotopic ratios and apparent ages of zircons for Yuejingshan gabbro, Table S3: LA-MC-ICP MS zircon Lu–Hf isotope data for the zircons from Yuejingshan gabbro.

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