Research Article

Age and Petrogenesis of the Gabbros from Tajik South Tianshan: Implications for Early Paleozoic Geodynamic Evolution of the Southwestern Central Asian Orogenic Belt

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Identification of slab window process is important for understanding the nature of the accretionary orogenesis. In this study, we report detailed petrological, geochronological, geochemical, Sr-Nd isotopic, and mineral chemical data for two dyke-like gabbroic intrusions from the South Tianshan belt of Tajikistan, southwestern margin of the Central Asian Orogenic Belt. Both intrusions are composed of coarse- and fine-grained gabbros. U–Pb zircon dating shows that they were emplaced at 431 ± 5 Ma. The gabbroic rocks show relatively large variation in elemental and isotopic compositions, with SiO₂ of 40.62–53.97 wt.%, Sr of 333–1261 ppm, and εNd(t) of +2.5 to +5.8. Especially, the fine-grained gabbros show lower SiO₂ and higher MgO but more evolved isotopes than the coarse-grained gabbros for each of the intrusions. All the rocks display OIB-like or transitional OIB-/E-MORB-like geochemical characteristics with no obvious Nb-Ta depletion, indicative of an intraplate affinity. Combined with their mineral chemical compositions, we suggest that these gabbroic rocks were generated by partial melting of asthenospheric mantle in the transitional spinel-garnet stability field, followed by different degrees of fractional crystallization of olivine, clinopyroxene, and plagioclase and mixing with carbonatitic melts. The available data indicate that roll-back of the subducting Turkestan oceanic slab occurred during the Late Ordovician to Early Silurian period. Asthenosphere upwelling due to the opening of slab window resulted from localized slab tearing during slab roll-back may have been responsible for the generation of the studied dyke-like gabbroic intrusions.
1. Introduction

The whole Wilson cycle for the formation of orogenic belt involves oceanic opening, subduction and closure, and collision between continents and/or arcs [1]. For the accretionary orogenic belts that underwent long-time subduction-accretion processes, the occurrences of slab window are common [2–4]. The opening of slab window provides a pathway for the upwelling of subslab asthenosphere materials, which will significantly affect the thermal structure of the overlying lithosphere and result in the extensive extension and uplift of the overriding plate, in particular the generation of geochemically unusual magmatism with a regular distribution in space. The typical products of slab window magmatism include adakites, high-Mg andesites and diorites, Nb-enriched basalts, A-type granites, and MORB- and OIB-like mafic rocks [3–7]. Considering the complexity of their sources, these slab window mafic rocks can provide a rare opportunity to investigate the chemistry of different mantle reservoirs and subducting oceanic slab and their interactions. The development of slab windows was always linked to some specific deep geodynamic processes, such as ridge subduction, slab tearing, and slab break-off [2, 4, 8–10]. However, slab windows associated with the slab roll-back are rarely reported and the responses and records of magmatism generated by this geodynamic process are still not well understood.

The Central Asian Orogenic Belt (CAOB, its southern part also known as the Altaiids or Altaiid Tectonic Collage), extending from the Urals, through the Kazakhstan, Uzbekistan, northern Tajikistan, Kyrgyzstan, northern China, and Mongolia to the southeastern Russian coast, is one of the largest accretionary belts on Earth [11–16] (Figure 1). It is bounded by the Siberia Craton to the north, the Baltica Craton to the northwest, and the Karakum–Tarim–North China cratons to the south (Figure 1). Numerous studies in the past decades have demonstrated that the CAOB formed by long-time (~1000–250 Ma) oceanic subduction and accretion of ophiolites, accretionary wedges, arcs (including island arcs and oceanic islands), seamounts, oceanic plateaus, and pre-Cambrian microcontinental blocks related to the closure of the Paleo-Asian Ocean and represents the largest site of Phanerozoic juvenile crustal growth in the world, although the controversies still exist about its detailed tectonic evolutionary history and the mechanisms of crustal growth [11–15, 17–25].

The Tianshan (or Tien Shan) orogenic belt occupies the southwestern margin of the CAOB and contains several ophiolitic belts and arcs (Figures 1 and 2). It marks the ultimate amalgamation of the southern accretionary margin of the Siberia Craton and the northern margin of the Karakum–Tarim cratons and thus records the final evolution history of the Paleo-Asian Tectonic Domain [16–18, 26–30]. As compared with those in the eastern part of the Tianshan orogenic belt, the orogenesis in the western part of the Tianshan orogenic belt (especially that in the Uzbekistan and Tajikistan parts) is less understood. In recent years, some geochronological and geochemical researches have been conducted on the granitic, sedimentary, ophiolitic, and metamorphic rocks in the western part of the Tianshan orogenic belt, and the Late Paleozoic tectonic evolution has been roughly constrained although some issues such as the closure time of the Turkestan Ocean (also termed the South Tianshan Ocean) neighboring the Karakum–Tarim cratons to the south are still debated [31–41]. However, the Early Paleozoic geodynamic evolution related to the subduction of the Turkestan Ocean was not yet well addressed, although Early Paleozoic arc magmatism has been identified by recent researches [31, 33, 36, 41, 42]. Moreover, the slab window magmatism, which was suggested to significantly contribute to the crustal growth of the CAOB [4, 6, 43, 44], was rarely reported in the western Tianshan of the Kyrgyzstan, Uzbekistan, and Tajikistan.

Here, we carried out an integrated study of mineral chemistry, zircon U–Pb dating, whole-rock major and trace element, and Sr–Nd isotopic geochemistry for the Early Paleozoic gabbros from the South Tianshan of the Tajikistan. The data allow us to discuss their sources, magma evolution, tectonic setting, and magma generation mechanism. The results suggest that the generation of these gabbros could be related to an Early Paleozoic slab window process during slab roll-back at the southwestern CAOB.

2. Geological Background and Sample Description

The western Tianshan forms the southwestern part of the CAOB, and it is bounded by the Karakum–Tarim craton to the south (Figure 1). Based on tectonic characteristics and lithological assemblages, the western Tianshan of the Kyrgyzstan, Tajikistan, and Uzbekistan can be divided into three east-west-trending tectonic units: the North Tianshan, the Middle Tianshan, and the South Tianshan [45, 46], which are cut by the NW-SE-trending Talas–Fergana strike-slip fault with a total offset of ~200 km (Figure 2).

The North Tianshan is separated from the Middle Tianshan by the Nikolaev Line, which is a strike-slip fault formed by voluminous Early Paleozoic granitoids (Figure 2). The pre-Cambrian basement is dominated by intermediate–acid magmatic rocks, and most of them have Mesoproterozoic formation ages [47, 48], except for a few with Late Neoproterozoic age [49]. The Early Paleozoic granitoids have U–Pb ages of ~520–420 Ma [47–53], and they were suggested to be the products of northward subduction and closure of the Terskey Ocean [49, 54]. In the northern part of the North Tianshan (Aktyz and Makhbal areas), Cambrian–Ordovician subduction-accretionary ophiolitic rocks and high-pressure/ultrahigh-pressure (HP/UHP) metamorphic rocks (e.g., garnet amphibolites and eclogites) are also exposed, and their formation was linked to the evolution of the Dzhahalir–Naiman oceanic basin in the north and the Terskey Ocean in the south [55–57]. An ophiolitic gabbro from the Kemin Complex in the northern North Tianshan gives a zircon U–Pb age of 531 ± 4 Ma [56], and the HP/UHP metamorphism was dated at ~500–470 Ma [55, 57]. The Early
Devonian (414 Ma) and Early–Middle Permian (292 Ma and 263 Ma) intrusions, which sporadically crop out in the North Tianshan, have also been reported by several researchers [40, 47, 51].

The Middle Tianshan is separated from the South Tianshan to the south by the northern South Tianshan ophiolite belt (Figure 2). It is considered a continental magmatic arc developed on a pre-Cambrian basement and is mainly composed of Early and Late Paleozoic intermediate–acid intrusive and volcanic rocks with minor Early and Late Paleozoic sedimentary strata (Figure 2). Geochronological studies show that the pre-Cambrian granitoids mainly formed in the Paleoproterozoic and Early Neoproterozoic [34, 58, 59]. The Paleozoic magmatic rocks were generated at two time intervals: 467–397 Ma and 338–279 Ma, and their generation could have been related to the subduction and closure of the Turkestan Ocean (or the South Tianshan Ocean) [31, 33, 36, 40, 60]. Recently, subduction-accretionary complexes including ophiolitic rocks and HP metamorphic rocks (e.g., retrogressed eclogites) have also been identified in the Chatkal Range of the Middle Tianshan, west of the Talas–Fergana fault [31, 61, 62].

The northward subduction and closure of the Turkestan Ocean were suggested to be responsible for the generation of the HP metamorphism on both sides of the Talas–Fergana fault [61, 62].

The South Tianshan is an accretionary complex belt, with complex rock compositions and structural deformations [16, 38]. It recorded the northward convergence of the Karakum–Tarim craton with the Kazakh–Kyrgyz continent during the Paleozoic to Early Mesozoic. The South Tianshan is mainly composed of Paleozoic ophiolitic rocks, (ultra-)high-pressure and medium-high temperature (M-HT) metamorphic rocks (e.g., blueschists, eclogites, and granulite facies paragneisses) and sedimentary strata and numerous Early Carboniferous–Middle Permian magmatic rocks, with sporadic exposure of Late Ordovician, Middle–Late Devonian and Mesozoic intrusive and volcanic rocks (Figure 2) [33, 35, 40–42, 63–65]. The ophiolitic gabbros and plagiogranite from the South Tianshan accretionary complex yielded formation ages of 505 ± 6 Ma, 448 ± 4 Ma, and 438 ± 6 Ma [33, 66], implying that the initial spreading of the Turkestan Ocean occurred no later than the Drumian. The occurrence of Cambrian fossil-bearing limestones in the South Tianshan also indicates that the Turkestan oceanic basin may have already existed located to the east of the Talas–Fergana fault [38, 61, 62].

![Figure 1: Geological sketch map showing main components of the Central Asian Orogenic Belt and its adjacent areas (modified from Xiao et al. [16] and Sengör and Natal' in [124]).](http://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/2020/1/1/5207938/7866431.pdf)
since the Cambrian [63, 65]. A microcontinent with pre-Cambrian basement was inferred to exist in the South Tianshan, according to the outcrop of Paleozoic shallow-marine limestones [27, 67, 68]. On the other hand, some Early Paleozoic and Late Paleozoic carbonate rocks (caps) and associated OIB-like rocks in the northern and central parts of the South Tianshan were linked to Paleozoic accretion of seamounts and/or oceanic plateau [37, 69, 70]. The HP/UHP metamorphic rocks related to the subduction and closure of the Turkestan Ocean were exposed in the Atbashi and Zeravshan areas. In the Atbashi area, the typical HP/UHP metamorphic rocks are Late Paleozoic blueschists and (coesite-bearing) eclogite, whose protoliths are HP metamorphic rocks of Late Paleozoic blueschist facies rocks with protoliths of oceanic complexes [38, 71].

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of dark gray coarse- and fine-grained gabbros, and the fine-grained gabbros commonly occur in the margins of the mafic bodies. The SDK fine-grained gabbro mainly consists of clinopyroxene (45–55 vol%), plagioclase (30–40 vol%), Fe–Ti oxides (~10 vol%), and apatite (~5 vol%), with tiny amounts of zircon (Figures 4(c) and 4(d)). Some clinopyroxene
crystals have been partially replaced by chlorite (Figures 4(c) and 4(d)). The SDK coarse-grained gabbro is mainly composed of clinopyroxene (40–45 vol%), plagioclase (50–55 vol%), Fe–Ti oxides (~5 vol%), and accessory minerals including apatite and zircon (Figure 4(e)). Some plagioclases are enclosed in clinopyroxenes. The NDK fine-grained gabbro comprises clinopyroxene (~44 vol%), plagioclase (~48 vol%), and Fe–Ti oxides (~8 vol%) (Figure 4(f)). Some clinopyroxene crystals have been partially altered to nontro-nite. Accessory phases include apatite and zircon. The NDK coarse-grained gabbro contains clinopyroxene (~40 vol%) and plagioclase (~60 vol%) and minor amounts of Fe–Ti oxides, apatite, K-feldspar, and zircon.

3. Analytical Methods

Mineral compositions for clinopyroxene and plagioclase were determined using a JEOL JXA-8230 electron microprobe at the Southwest Petroleum University, Chengdu, with an accelerating voltage of 15 kV, a beam current of 20 nA, a spot diameter of 5 μm, and a counting time of 30 seconds during the analyses.

Whole-rock geochemical analyses for representative (unaltered or least-altered) samples were performed at the Wuhan Sample Solution Analytical Technology Co., Ltd., Wuhan, China, after crushing all the selected samples into powder of less than 200 mesh size. Major element contents were determined by X-ray fluorescence (XRF). The measurement procedure and data quality were monitored by simultaneous analyses of repeated samples (one in ten samples) and the standard samples GBW07103, GBW07105, GBW07110, GBW07111, and GBW07112. The analytical uncertainties are generally less than 1% for most major elements. Trace element (including rare earth element) contents were determined by an Agilent 7700e ICP-MS. The compositions of repeated samples (one in ten samples) and the reference materials AGV-2, BHVO-2, BCR-2, and RGM-2 were also measured to monitor the data quality. The analytical uncertainties are better than 5% for most trace elements. The detailed analytical procedures are the same as those described by Liu et al. [81]. Sr–Nd isotopic compositions were analyzed by a multiple collector inductively coupled plasma mass spectrometry (Neptune Plus MC-ICP-MS). Details of analytical procedures are given in Lin et al.’s study [79]. The measured Sr and Nd isotopic ratios were normalized to \(^{88}\)Sr\(^{86}\)Sr = 8.375209 and \(^{144}\)Nd/\(^{144}\)Nd = 0.7219, respectively. During the analyses, the BCR-2 standard yielded a \(^{87}\)Sr/\(^{86}\)Sr ratio of 0.705007 ± 10 (2σ) and a \(^{143}\)Nd/\(^{144}\)Nd ratio of 0.512642 ± 2 (2σ), respectively, which were identical within an error to the previously reported values [80].

After crushing, zircon grains were extracted from the rock samples using conventional heavy-liquid and magnetic methods. The handpicked zircons were mounted in epoxy resin and then polished to one-half to two-thirds of their original thickness. The cathodoluminescence (CL) images and the transmitted and reflected light photomicrographs of zircons were obtained at the Wuhan Sample Solution Analytical Technology Co., Ltd., Wuhan, China, in order to guide the U–Pb dating analysis. Zircon U–Pb dating and trace element analyses for the sample TSY-26 were carried out at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, using an Agilent 7500a inductively coupled plasma mass spectrometry (ICP-MS) instrument in combination with an ArF excimer laser (\(\lambda = 193\) nm). The detailed instrumental operating conditions and analytical procedures are similar to those described in Liu et al. [81]. All analyses were performed with a laser spot size of 32 μm. A signal-smoothing and mercury-removing device was used in laser ablation system to obtain smooth signals and reduce the mercury signal [82]. Small amount of (4.1 mg min\(^{-1}\)) water vapor was added before the ablation cell to improve the analytical accuracy and precision [83]. Zircon 91500 was used as external standard to correct the Pb/U fractionation and instrumental mass discrimination, and the trace element compositions of zircons were calibrated using NIST 610 glass as an external standard in combination with \(^{29}\)Si as internal standardization. Off-line selection and integration of background and analyze signals and time-drift correction and quantitative calibration were performed by ICPMSDataCal [81]. Data correction and processing followed the methods similar to those in Yang et al. [10].

4. Results

4.1. Mineral Compositions.

Mineral compositions of representative clinopyroxenes from the SDK fine- and coarse-grained gabbros (TSY-22 and TSY-24) and plagioclase from the SDK coarse-grained gabbro (TSY-24) were analyzed in this study, and the results are listed in Supplementary Tables DR1 and DR2 and illustrated in the ternary Wo–En–Fs and An–Ab–Or plots, respectively (Figures 5(a) and 5(b)).

The clinopyroxene grains are dominantly augite with minor diopside (Wo\(_{42–46}\)En\(_{37–39}\)Fs\(_{17–21}\)) for the fine-grained sample TSY-22 and Wo\(_{42–43}\)En\(_{36–37}\)Fs\(_{20–29}\) for the coarse-grained sample TSY-24. The clinopyroxene grains from the fine-grained gabbro sample TSY-22 have moderately variable SiO\(_2\) (46.70–52.18 wt.%), TiO\(_2\) (1.02–3.40 wt.%), and Al\(_2\)O\(_3\) (1.25–5.30 wt.%), and relatively uniform FeO\(^\text{T}\) (9.67–11.94 wt.%), MgO (12.13–13.27 wt.%), CaO (19.69–21.12 wt.%), and Na\(_2\)O (0.41–0.61 wt.%) contents, with Mg\(^\#\) (100 Mg/(Mg + Fe\(^\text{T}\))) ranging from 64.9 to 70.4. The clinopyroxenes in the coarse-grained gabbro sample TSY-24 show a limited range of SiO\(_2\) contents (49.67–50.86 wt.%). Compared with those from the fine-grained sample, they possess similar CaO contents (19.60–21.14 wt.%), but lower TiO\(_2\) (0.61–1.16 wt.%), Al\(_2\)O\(_3\) (1.39–2.39 wt.%), MgO (8.76–12.73 wt.%), and Na\(_2\)O (0.21–0.46 wt.%) and higher FeO\(^\text{T}\) (11.88–16.91 wt.%) contents. Most clinopyroxenes from the fine-grained gabbro sample TSY-22 show reverse compositional zoning, which is characterized by increasing MgO contents, Mg\(^\#\) and Ca/Al ratios from cores to rims (Figures 5(c) and 5(d); Supplementary Table DR1). By contrast, clinopyroxene grains from the coarse-grained gabbro sample TSY-24 generally show normal compositional zoning with decreasing MgO contents and Mg\(^\#\) from cores to rims (Figures 5(e) and 5(f); Supplementary Table DR1).
Figure 5: Ternary classification diagrams for (a) Ca-Mg-Fe pyroxenes [125] and (b) feldspars [126]; (c, d) representative clinopyroxene grain in the fine-grained gabbro sample TSY-22 and its compositional variations; (e, f) representative clinopyroxene grains in the coarse-grained gabbro sample TSY-24 and their compositional variations; (g, h) representative plagioclase grain in the coarse-grained gabbro sample TSY-24 and its compositional variations. Red circles represent spots analyzed by EMPA. Cpx = clinopyroxene; Pl = plagioclase.
Seven analyses were obtained on one plagioclase grain from the coarse-grained gabbro sample TSY-24. Six of them, with anorthite portions (An contents) ranging from 56 to 64, plot in the field of labradorite (Figures 5(b), 5(g), and 5(h)). One analysis on the plagioclase rim shows lower An content (41) and falls into the andesine field (Figures 5(b), 5(g), and 5(h)).

4.2. Major and Trace Elements. Major and trace elemental results of this study are listed in Supplementary Table DR3. The gabbroic rocks in this study show large compositional variations (Figure 6). The SDK fine-grained gabbros have low SiO₂ (40.62–42.71 wt.%) and high MgO (6.06–6.66 wt.%) (Mg# = 43–44), CaO (8.94–9.14 wt.%), TiO₂ (4.68–4.80 wt.%), and P₂O₅ (1.98–2.01 wt.%) contents. Compared with them, the SDK coarse-grained gabbros show higher SiO₂ (48.82–49.09 wt.%) but lower MgO (4.21–4.31 wt.%), TiO₂ (3.11–3.33 wt.%), and P₂O₅ (0.32–0.35 wt.%), Mg# of 35–36. The NDK fine-grained gabbro possesses SiO₂ of 47.64 wt.%, MgO of 3.98 wt.%, CaO of 5.45 wt.%, TiO₂ of 3.85 wt.%, and P₂O₅ of 1.05 wt.%, with lower Mg# of 33. The NDK coarse-grained gabbro is high in SiO₂ (53.97 wt.%) and low in MgO (1.97 wt.%), CaO (2.64 wt.%), TiO₂ (1.90 wt.%), and P₂O₅ (0.68 wt.%), with low Mg# of 21. In the Zr/TiO₂ versus Nb/Y diagram (Figure 7(a)), all the samples fall into the field of alkaline basalt, except for the SDK coarse-grained gabbros, which show the composition of sub-alkaline basalt. In the K₂O versus SiO₂ plot (Figure 7(b)), most samples plot in the calc-alkaline and high-potassic calc-alkaline fields.

The gabbro samples in this study are characterized by variable trace elemental contents. Their Cr and Ni contents range from 0.26 to 27.6 ppm and from 0.91 to 42.3 ppm, respectively. All the samples are enriched in Nb (20.8–65.3 ppm) and Ta (1.33–3.93 ppm). They show positive or unapparent Na–Ta anomalies in the primitive mantle-normalized trace element patterns (Figures 8(a)–8(d)).

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Figure 7: (a) Zr/TiO₂ versus Nb/Y [127] and (b) K₂O versus SiO₂ diagrams [128]. Symbols as in Figure 6.

Figure 8: Primitive mantle-normalized trace element spider diagrams and chondrite-normalized REE patterns. Chondrite and primitive mantle normalized values are from Sun and McDonough [129]. Data sources for slab window-related mafic rocks are the same as in Figure 6.
4.3. Sr–Nd Isotopes. Whole-rock Sr–Nd isotopic data are listed in Supplementary Table DR4 and shown in Figures 9(a) and 9(b). The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios ($I_{\text{Sr}}$) and $\varepsilon_{\text{Nd}}(t)$ values of the gabbros are calculated back to 431 Ma.

The SDK fine-grained gabbros have relatively uniform Sr–Nd isotopic composition, with $I_{\text{Sr}}$ of 0.7044–0.7046, $\varepsilon_{\text{Nd}}(t)$ of +2.8 to +3.1, and depleted mantle Nd model ages ($T_{\text{DM}}$) ranging from 0.97 to 1.02 Ga. The SDK coarse-grained gabbro shows lower $I_{\text{Sr}}$ (0.7041), higher $\varepsilon_{\text{Nd}}(t)$ (+5.8), and younger $T_{\text{DM}}$ of 0.85 Ga.

The NDK gabbros possess more evolved Sr–Nd isotopic compositions than the SDK gabbros. The NDK fine-grained gabbro has $I_{\text{Sr}}$ of 0.7057 and $\varepsilon_{\text{Nd}}(t)$ of +2.5, with $T_{\text{DM}}$ of 1.06 Ga. The NDK coarse-grained gabbro shows $I_{\text{Sr}} = 0.7056$ and $\varepsilon_{\text{Nd}}(t) = +2.6$, with $T_{\text{DM}}$ of 1.02 Ga.

4.4. Geochronology. The SDK coarse-grained gabbro sample TSY-26 was selected for LA-ICP-MS U–Pb zircon dating, and the results are presented in Supplementary Table DR5 and plotted on concordia diagrams (Figure 10). Representative cathodoluminescence (CL) images are shown in Figure 10. The zircon grains from the sample TSY-26 are generally semitransparent, subhedral, and short prismatic, with crystal lengths varying from 40 to 110 µm and length to width ratios of 1 : 1–2.5 : 1. Most zircons show broad oscillatory zoning in CL images (Figure 10), consistent with the typical characteristic of igneous zircons from mafic rocks [84]. Sixteen analyses were obtained from 16 grains, which have variable U (462–3671 ppm) and Th (338–8431 ppm) contents, with high Th/U ratios of 0.8–4.3. Seven analyses give older $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 495 Ma to 453 Ma, interpreted to be captured during magma ascent. The remaining nine analyses yield $^{206}\text{Pb}/^{238}\text{U}$ ages between 443 and 423 Ma, with a weighted mean age of 431 ± 5 Ma (MSWD = 2.3) (Figure 10), which is in agreement with the Rb–Sr age (411 ± 27 Ma) obtained by Saidyganiev [77] within error and is interpreted as the magma crystallization age of the gabbro in this study.

5. Discussion

5.1. Petrogenesis

5.1.1. Fractional Crystallization and Magma Evolution. The gabbros under study are characterized by relatively low contents of $\text{SiO}_2$ (40.62–53.97 wt.%) (Supplementary Table DR3; Figure 6), indicating that they were derived dominantly from a mantle source. The concentrations of $\text{MgO}$, Mg#, Cr, and Ni (Supplementary Table DR3) are lower than in primitive basaltic lavas ($\text{MgO} = 8–11$ wt.%; Mg# = 63–71; Cr = 266–575 ppm, and Ni = 85–245 ppm) [85], implying that they were derived directly from evolved melts experienced fractionation of mafic minerals (e.g., olivine and clinopyroxene). The low values of Mg# (50–70)
in clinopyroxene from the coarse- and fine-grained rocks of the SDK intrusion (Supplementary Table DR1; Figures 5(c)–5(f)) also support this inference. Plagioclase from a coarse-grained gabbro sample of the SDK intrusion displays a low portion of anorthite (41-64) (Supplementary Table DR2), in particular, in rims (Figures 5(g) and 5(h)), suggesting fractional crystallization of plagioclase. Negative correlation between TiO2 and SiO2 in gabbro samples from each intrusion indicates fractionation of Fe-Ti oxides.

The coarse-grained gabbro samples from the both SDK and NDK intrusions all show lower MgO and Mg# and higher SiO2 than the fine-grained samples (Supplementary Table DR3), and the clinopyroxenes from the coarse-grained gabbros also show lower MgO and Mg# than those in the fine-grained samples (Supplementary Table DR1; Figures 5(c)–5(f)). Thus, it is possible that the coarse-grained gabbros could be the products directly evolved from the fine-grained gabbros. However, this inference is not supported by the isotopic evidence, because the coarse-grained gabbros show more depleted Sr and Nd isotopic compositions than the fine-grained gabbros for each of the intrusions (Supplementary Table DR4; Figure 9). Therefore, the coarse- and fine-grained gabbros for each intrusion can not be regarded readily as comagmatic products resulted from simple magma differentiation in a closed system but could have been formed by more complex open-system magmatic processes. It is apparent that the coarse-grained gabbros could experience stronger fractional crystallization processes, but the fine-grained rocks could involve more isotopically enriched components in their genesis (also see below).

5.1.2. Mantle Source and Magma Generation. The isotopically most depleted sample (the SDK coarse-grained gabbro) of the gabbros in this study shows Sr–Nd isotopes similar to those of the Paleozoic OIB-like rocks and some of E-MORB-like rocks in the OPS (Ocean Plate Stratigraphy) sections of the South Tianshan (Figure 9) [37], indicating that their parent magmas were probably derived from relatively enriched asthenosphere.

However, they display relatively large variation in Sr–Nd isotopic compositions (Supplementary Table DR4; Figure 9). The systematically correlative variations of the elemental and isotopic compositions for the coarse- and fine-grained gabbros of each intrusion (Figure 11) and the observation that majority of samples show relatively evolved isotopes

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Figure 11: Plots of (a–c) Nb/Th, \( I_{\text{Sr}} \), and \( \epsilon_{\text{Nd}}(t) \) versus MgO; (d) Nb/Th versus \( I_{\text{Sr}} \); (e) Ta/Th versus \( \epsilon_{\text{Nd}}(t) \); (f) Nb/La versus MgO; (g) Ta/Sm versus MgO; (h) Zr/Sm versus Hf/Sm; and (i) P2O5 versus Ba/Zr. Symbols as in Figure 6.
(Figure 9) suggest that other components apart from the asthenosphere were also involved in their genesis. Continental crustal and lithospheric mantle materials were suggested to be the common contaminants during the evolution of most asthenosphere-derived mafic magmas [9, 86–88]. The positive correlation between Nb/Th and MgO (Figure 11(a)) seems consistent with the contamination of continental crust. However, for each intrusion, the lower MgO samples also show lower $I_{Sr}$ and higher $\varepsilon_{Nd}(t)$ (Figures 11(b) and 11(c)), contradicting significant crustal contamination. Moreover, the decrease of Nb/Th with decreasing $I_{Sr}$ and the decrease of Ta/Th with increasing $\varepsilon_{Nd}(t)$ for each of intrusions (Figures 11(d) and 11(e)), disagree with gradual involvement of continental crust or lithospheric mantle materials, considering the relatively low Nb/Th, Ta/Th, Nb/La, and Ta/Sm and relatively enriched isotopic compositions of the continental crust and lithospheric mantle as compared with those of asthenosphere [89, 90]. As shown in Figures 12(a)–12(d), unlike the Eocene and Miocene OIB-type and transitional OIB-/arc-type basaltic rocks in the southern South America which were generated dominantly by interactions between asthenosphere and lithosphere [9, 87, 91, 92], there is no clear similarity between the gabbros in this study (especially the samples with enriched isotopes) and the typical arc-related rocks in the major and trace elements, precluding significant contribution from the lithospheric mantle metasomatized by subduction-related processes or crustal components in their petrogenesis. The relatively high Ta/La ratios of the studied gabbros are also not in line with important input of slab fluid/melt (Figure 13).

Previous studies have suggested that the carbonatitic components were also involved in the formation of some
mafic alkaline rocks [93–96], which plays an important role in deep carbon-recycling. Relative to the silicate melts, the carbonatitic melts, although with complex compositions, show pronounced enrichment in light rare-earth elements (LREE), Ba and Sr, and relative depletions in HREE and HFSE, with high Ca/Al [93, 94, 97, 98]. If the carbonatite is dolomite-enriched, then, the relatively high MgO contents for it would be predicted [97, 98]. The MgO and Sr increase and SiO$_2$, Zr/Sm, and Hf/Sm decrease, coupled with $I_{Sr}$ increase and $\epsilon_{Nd}(t)$ decrease, from the coarse-grained gabbros to fine-grained gabbros for each studied intrusion (Supplementary Tables DR3 and DR4; Figures 6(a), 11(b), 11(c), and 11(b)), consistent with involvement of carbonatitic melts in the fine-grained gabbros. On the other hand, considering the high solubility of apatite in carbonate-rich melts [99], the addition of carbonatitic melts would drive the magma composition toward higher P$_2$O$_5$. Compared with the coarse-grained gabbros from the two intrusions (P$_2$O$_5 = 0.32$–0.68 wt.%), all the fine-grained samples with relatively evolved isotopes show relatively high P$_2$O$_5$ (1.05–2.01 wt.%) (Supplementary Table DR3; Figure 11(i)), in accord with the involvement of carbonatitic components. In the Hf/Sm versus Ta/La diagram (Figure 13), the fine-grained gabbros also show similarity with the alkaline basalts formed from mantle sources that experienced carbonatite metasomatism. Moreover, unlike the clinopyroxenes from the SDK coarse-grained gabbro (sample TSY-24) which show normal compositional zoning with decrease of MgO and Mg$^\#$ from core to rim (Figures 5(c) and 5(f)), the clinopyroxenes from the SDK fine-grained gabbro (sample TSY-22) show reverse zoning with increase of MgO and Mg$^\#$ as well as Ca/Al from core to rim (Figures 5(c) and 5(d)), also indicative of addition of carbonatitic melts into the host magma. Therefore, the involvements of carbonatitic melts were significant during the formation of the fine-grained gabbros in the SDK and NDK dyke-like intrusions. It should be noted that the coarse-grained gabbro from the NDK intrusion also shows obviously higher $I_{Sr}$ and lower $\epsilon_{Nd}(t)$ than the SDK coarse-grained gabbros and the Paleozoic OIB- and E-MORB-like rocks in the OPS sections of the South Tianshan (Figure 9) [37], although this sample displays no subduction (or arc-related) imprint (Figures 12 and 13). Considering its relatively high P$_2$O$_5$, Ba, and Ba/Zr (Figure 11(i); Supplementary Table DR3), we suggest that parent magma of the NDK coarse-grained gabbro could also contain minor carbonatitic components.

The REE distributions of mafic rocks are sensitive to the mineralogy of their magma sources and can be used to constrain the depth of partial melting and melting degrees. As shown in Figures 14(a) and 14(b), the SDK coarse-grained gabbro samples (TSY-24 and TSY-26), which possess most depleted Sr–Nd isotopic compositions (Supplementary Table DR4) and were not significantly influenced by later addition of carbonatitic melts in their genesis, can be generated by low degrees (2–5%) of partial melting of mantle peridotite in the transitional spinel-garnet stability field (~70–80 km, 87, 100, 101) according to the results of geochemical modeling using batch equilibrium melting and nonmodal melting equations. Therefore, we suggest that the Early Paleozoic gabbros in this study were derived by partial melting of spinel-garnet transitional facies asthenospheric mantle (at ~70–80 km), followed by different degrees of fractional crystallization of olivine, clinopyroxene, and plagioclase and mixing with carbonatitic melts. In other words, the coarse-grained gabbros from each of the SDK and NDK intrusions represent the least isotopically evolved rocks which underwent strong fractional crystallization during magma evolution, and their parental magmas were mixed with carbonatitic melts to form the fine-grained gabbros of each intrusion.

**Figure 14:** (a) Sm/Yb versus La/Sm diagram for the gabbroic rocks in this study. Batch melting trends are taken from [91]; (b) Gd/Yb versus La/Yb plot. Also shown in (b) are nonmodal batch melting curves calculated for spinel lherzolite (with mode and melt mode of O$_{5.5}$ + Opx$_{0.33}$ + Cpx$_{0.17}$ + Sp$_{0.03}$ and O$_{5.06}$ + Opx$_{0.28}$ + Cpx$_{0.67}$ + Sp$_{0.11}$, respectively) [133], spinel-garnet lherzolite (with mode and melt mode of O$_{5.59}$ + Opx$_{0.25}$ + Cpx$_{0.14}$ + Gt$_{0.02}$ + Sp$_{0.09}$ and O$_{5.15}$ + Opx$_{0.05}$ + Cpx$_{0.30}$ + Gt$_{0.28}$ + Sp$_{0.32}$, respectively) [134], and garnet lherzolite (with mode and melt mode of O$_{6.6}$ + Opx$_{0.26}$ + Cpx$_{0.10}$ + Gt$_{0.16}$ and O$_{6.83}$ + Opx$_{0.16}$ + Cpx$_{0.38}$ + Gt$_{0.90}$, respectively) [135]. Composition of mantle source was assumed to be the same as those of primitive mantle [129]. Partition coefficients are from Mckenzie and Onions [100]. The numbers on each curve (or line) correspond to degrees of partial melting.
5.2. Identification of Early Silurian Intraplate-Type Mafic Magmatism along the Northwestern Margin of the Central Asian Orogenic Belt. Relative to the widespread magmatic rocks of Late Paleozoic age, the Early Paleozoic magmatic rocks are less exposed in the Kyrgyz, Uzbek, and Tajik South Tianshan. Mirkamalov et al. [66] reported SHRIMP U–Pb ages for a ~448 Ma metagabbro from the Madzherum ophiolitic complexes of the South Tianshan, but no available geochemical data for them. Dolgopolova et al. [33] reported a 505 Ma ophiolite-related plagiogranite from the Kakhralaysai intrusion and a 438 Ma gabbro from the Teskuduk ophiolite, both of which show transitional geochemical characteristics between ocean ridge and volcanic arc rocks, with relatively flat chondrite-normalized REE patterns [(La/Yb)N = 1.04–1.27] and apparent depletion of Nb (<0.5–2.3 ppm), Ta (<0.1 ppm), TiO2 (0.18–0.21 ppm), and P2O5 (0.03–0.05 ppm). Worthington et al. [41] identified a Paleozoic greenrich-facies meta-andesite in the Fan Karategin belt, which has a zircon U–Pb age of 450 ± 5 Ma, and a zircon εHf(t) values ranging from −4.7 to −1.6. The OIB- and E-MORB-like rocks in the South Tianshan ophiolitic complexes have been reported by Safonova et al. [37] (Figures 8 and 12), and their formation ages were constrained between the Late Silurian and the Middle Devonian based on the stratigraphic data. Recently, Early Paleozoic granitoids and volcanic rocks with arc-like geochemical characteristics, which occur as bluffs in the mélanges on the northern slopes of the Alai Range, were identified by Alexeiev et al. [42]. The granitoids were dated at 472 ± 4 Ma, and the volcanic rocks that have no accurate formation age were suggested to form in the Early Silurian according to the palaeontological and stratigraphic data. Therefore, Early Paleozoic intraplate-type magmatism with accurate formation age has not been reported in the western South Tianshan.

The gabbros in this study occur as dyke-like intrusions and have magma crystallization age of 431 ± 5 Ma (Figure 10), indicating that they formed in the Early Silurian. They are relatively enriched in Nb (20.8–65.3 ppm), Ta (1.33–3.93 ppm), and TiO2 (1.90–4.80 wt.%), and none of them show obvious Nb–Ta depletion (Figures 8(a) and 8(c)), indicative of their affinity with intraplate basaltic rocks [1, 102]. They are LREE-enriched and exhibit OIB-like and transitional OIB/E-MORB-like geochemical characteristics (Figures 8(a)–8(d)). In the Th/Yb versus Nb/Yb diagram (Figure 12(a)), the gabbros plot along the MORB-OIB array and cluster towards relatively enriched compositions, with no clear subduction-related imprints. In the diagram of TiO2/Yb versus Nb/Yb, they mainly lie within the OIB array, except for the NDK coarse-grained gabbro that falls into the MORB array (Figure 12(b)). As shown in Figure 12(c), the Zr/Nb and La/Nb ratios of the gabbros are also lower than those of typical arc basalts but similar to those of the within-plate alkaline basalts. Moreover, the gabbros in this study also have relatively high Zr (146–454 ppm) and plot in the field of within-plate basalts in the Zr/Y–Zr diagram (Figures 12(d)). Therefore, the SDK and the NDK gabbros were the newly discovered Early Paleozoic intraplate-type mafic magmatic rocks in the western South Tianshan, southwestern margin of the Central Asian Orogenic Belt.

5.3. Tectonic Implications. As mentioned previously, the early evolution of the western South–Middle Tianshan has not been well constrained, mainly because of less studies on the Early Paleozoic rocks as compared with the Late Paleozoic rocks. The gabbros in this study, which show OIB-like or transitional OIB/E-MORB-like geochemical characteristics, have been dated to the Early Silurian. Previous researches have demonstrated that the intraplate-type mafic rocks with OIB-like or E-MORB-like affinities can form in various tectonic settings, such as mantle plume-related oceanic-islands/seamounts [24, 37], continental rifts [86] and large igneous province [88], and slab window settings associated with ridge subduction [4] and slab tearing [9, 103] during oceanic subduction stage and slab break-off at post-collision stage [104].

First, we will constrain the occurrence environment of the studied gabbros. The tectonic nature of the South Tianshan remains debated. For example, some researchers suggested that the South Tianshan contains pre-Cambrian microcontinents and is dominated by passive marginal sediments derived from the southern microcontinents or cratons [27, 28, 64, 67], while others argued that the South Tianshan is an accretionary complex belt that contains Paleozoic OPS units [30, 37, 39]. In fact, determining the location of the terminal suture zone is not easy for the accretionary orogenic belt, especially for those belts that experienced long-time subduction-accretion processes accompanied by formation of vast accretionary wedges [16]. As exemplified by the Japan and Makran accretionary wedges and the Franciscan Complex [105–108], a typical accretionary wedge or accretionary complex often consists of melange unit and coherent unit. The ultimate location of the terminal suture zone should be determined by the basal surface of the accretionary wedge [109], rather than the site of sole exposure of ophiolitic melange, especially considering that the coherent unit commonly occurs much more widely than the melange unit. The gabbroic rocks in this study intrude the Llandovery strata dominated by shales, sandstones, and limestones, and the coeval mafic dykes and sills in Uzbekistan have also been reported to intrude the Llandovery turbidites [76]. These Llandovery wall rocks are similar to the typical components of accretionary wedges (or complexes) [105–108]. Based on the studies on the sedimentology and stratigraphy and combined with petrographic and paleocurrent data, Pickering et al. [110] suggested that some Silurian–Devonian deep-marine clastic (turbidite-dominated) strata on the northern slope of the Alai Range formed in an accretionary prism and their clastic materials were mainly sourced from the continental margin of the Kazakhstan continent (Middle–North Tianshan). This implies that the northern part of the South Tianshan contains a significant proportion of accretionary wedge materials. Recently, Biske et al. [32] also identified a large number of Paleozoic accretionary complexes that are continuously exposed from the northern to central parts of the South Tianshan belt and suggested that these accretionary complexes belonged to the hanging-wall of the subduction system related to the northward subduction of the Turkestan Ocean. It should be noted that our studied dyke-like mafic intrusions share similar latitude position with
these accretionary complexes including the ophiolitic mélanges and turbidites. In addition, other researchers have also identified many ophiolitic mélanges, OPS-bearing mélanges, and coherent unit rocks to the south of our studied dyke-like intrusions [33, 70, 111, 112], which are also parts of the huge South Tianshan accretionary complex [30, 37]. Therefore, our samples are far away from the real terminal suture to the south, which lies along the bottom of the South Tianshan accretionary complex. Thus, the gabbroic rocks in this study that crop out in the north of the South Tianshan intruded an accretionary complex rather than the passive continental margin of the Karakum–Tarim cratons.

The oceanic-island- or seamount-related OIB- and E-MORB-like mafic rocks in the OPS units or ophiolitic mélanges of the accretionary wedge are always regarded as accreted seamount fragments [24, 37]. In these cases, they are always coexisted with oceanic fragments and deep-marine or slope facies sediments such as carbonate cap, chert, and volcanic clastics and can occur as blocks within the matrix consisting of the sedimentary rocks. The relatively simple rock composition and the long-distance dyke-like occurrence of the gabbroic intrusions in this study (Figure 3) are not consistent with their formation in oceanic-island- or seamount-related settings. The plume-related continental rifts were commonly generated due to the break-up of the supercontinents and formed before the opening of the oceanic basin [86, 113]. The gabbroic intrusions in this study occur in the South Tianshan accretionary complex belt, and their formation time was much later than the opening time of the Turkestan Ocean (probably before the Middle Cambrian) [33]. Thus, their generation could not be linked to the plume-related continental rifting. The large igneous province has also been identified in the Tarim Craton adjacent to the South Tianshan, which is characterized by the outcrop of kimberlites, flood basalts, mafic–ultramafic intrusions (and/or dykes), and alkaline intermediate-felsic magmatic rocks [88, 114]. However, the formation time of the Tarim large igneous province was constrained to the Permian [88, 114], which was much later than the magma crystallization of the gabbros in this study. Therefore, the SDK and NDK dyke-like gabbroic intrusions could not form in the mantle plume-related settings. Considering the dyke-(and sill)-like occurrence of the SDK, NDK, and coexisted gabbroic intrusions which strike nearly east-west and extend discontinuously from Tajikistan to Uzbekistan for a long distance (Figures 2 and 3) and the similarity between the gabbroic rocks in this study and the slab window-related mafic rocks in the circum-Pacific orogenic belts and the North Chinese Tianshan (Figures 7, 8, 12, and 13) [9, 87, 91, 92, 103, 115], we suggest that the SDK and NDK gabbroic rocks could be generated in a slab window setting.

The structure and composition of the accretionary materials in the South Tianshan belt, the results of paleogeography reconstruction, and the occurrence of Early Paleozoic arc magmatism in the Middle Tianshan indicate that the Turkestan oceanic slab was subducted northward (present-day coordinates) beneath the Middle Tianshan during the Early Paleozoic [12, 14, 16, 30, 35, 36], which was accompanied by a general southward and oceanward growth of the accretionary wedge. Thus, the SDK and NDK gabbros resulted from subduction-related rather than continental collision-related processes. Ridge subduction was suggested to be common in modern and ancient accretionary orogenic belts [3, 14], and it would result in the opening of slab window and generation of strong magmatism and metamorphism in near-trench position, with characteristic products including adakites, high-Mg andesitic rocks, tholeiitic and alkaline basalts, high-Ca boninites, and A-type granites and associated low-pressure/high-temperature metamorphic rocks. However, except for the dyke-like gabbroic intrusions, most of the magmatic and metamorphic products mentioned above are lacking in the study area (Figures 2 and 3). Therefore, the generation of the SDK and NDK gabbroic rocks could not be related to the ridge subduction-related process.

As shown in Figure 2, the Early Paleozoic magmatism in the Middle Tianshan of the west of the Talas-Fergana fault shows regular temporal and spatial variation, with clear magmatic migration from the northeast to the southwest from ~450 Ma to ~430 Ma: in the Bozbuta Mountain (northeastern part of the western Middle Tianshan), the Middle to Late Ordovician felsic arc-related volcanic, and subvolcanic rocks, which are associated with basaltic andesites and andesites, were dated at 467–445 Ma [31]. To the west of the Bozbuta Mountain, the Early Paleozoic granites and dacites exposed in the southeastern Chatkal Range show magma crystallization ages of ~450 Ma [31]; in the west of the Chatkal and Kurama Ranges (Figure 2), the Early Paleozoic granites and granodiorites recovered recently were dated at 429–425 Ma [33, 36]. This south-westward-younging trend for the arc magmatism in the western Middle Tianshan is interpreted here as the result of south-westward roll-back of the subducted Turkestan oceanic slab. Previous studies have shown that the slab roll-back is a common process during the formation and evolution of the accretionary orogens, which can account for the generation of oceanward-younging arc magmatism and can also contribute to the formation of orocline bending of arcs or continental margins [22, 116]. Moreover, slab roll-back would induce asthenosphere upwelling and arc-related extension [117, 118], which could be accompanied by extensive crustal melting and generation of voluminous granitic rocks (especially the strongly peraluminous S-type granites) [119]. The 467–445 Ma felsic volcanic and granitic rocks and associated andesites in the Bozbuta Mountain and southeastern Chatkal Range are metaluminous to peraluminous in composition [31], while the ~430 Ma granites and granodiorites in the west of the Chatkal and Kurama Ranges all show strongly peraluminous characteristics [33, 36] (Figure 2). We suggest this transition of magma series is also consistent with the slab roll-back and heat transfer toward the southwest. During the roll-back of subducting oceanic lithosphere, slab tearing (or fracturing) can occur due to differential motion of different parts of the subducting slab, concave-upwards bending of the slab, subduction of aseismic ridges, or collision between ridge (and/or arcs or continental terranes) and trench [9, 103, 120–122]. Considering the nearly linear distribution of the dyke-like gabbroic intrusions (Figures 2 and 3), relatively uniform lithology of them (gabbros with alkaline-dominated characteristics) and their
intraplate affinity, we suggest that localized slab tearing during roll-back of the subducted Turkestan slab could occur and lead to the formation of these intrusions. In this scenario (Figure 15), as the slab window opened due to slab tearing, decompression melting of upwelled asthenosphere followed by fractional crystallization and mixing with minor carbonatic melts produced the OIB-like and transitional OIB-/E-MORB-like gabbros in this study. Similarly, the processes of slab window opening during slab roll-back have also been used to explain the generation of some magmatism in other convergent settings, such as the Sindreth and Punagarh basalts in the NW India [123]. Thus, our study not only highlights the importance of identifying OIB- and/or E-MORB-like rocks that are not associated with ophiolitic rocks in the accretionary belts, which could be used as a potential indicator of slab window process in convergent settings, but also proves that the slab windows can form during roll-back of subducting oceanic slab.

6. Conclusions

The dyke-like mafic intrusions, located to the northeast of the Ayni town in northwestern Tajikistan, were emplaced in the Early Silurian (~431 Ma). They show OIB-like and transitional OIB-/E-MORB-like geochemical characteristics with an intraplate affinity. Elemental, isotopic, and mineral chemical data indicate that they were derived by partial melting of the asthenospheric mantle in the transitional spinel-garnet stability field, followed by different degrees of fractional crystallization of olivine, clinopyroxene, and plagioclase and mixing with minor carbonatic melts. Combined with the available data, we suggest that the subducting Turkestan oceanic slab experienced roll-back towards the southwest from ~450 to ~430 Ma. During the slab roll-back, a slab window probably formed due to the localized slab tearing, which then resulted in the upwelling and decompression melting of the asthenosphere and the generation of the dyke-like gabbroic intrusions in this study.

Data Availability

Data generated during this study are available in the supplementary materials provided with it.

Disclosure

This study is a contribution to IGCP 662.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

Table DR1: electron microprobe analyses for clinopyroxenes and formulae in atoms per formula unit (apfu) based on four cations. Table DR2: electron microprobe analyses for plagioclase and formulae in atoms per formula unit (apfu) based on five cations. Table DR3: major and trace elemental data. Table DR4: whole-rock Sr–Nd isotopic data. Table DR5: zircon LA-ICP-MS U–Pb isotopic data. (Supplementary Materials)

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