Research Article

Triassic-Jurassic Granitoids and Pegmatites from Western Kunlun-Pamir Syntax: Implications for the Paleo-Tethys Evolution at the Northern Margin of the Tibetan Plateau

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The Western Kunlun-Pamir-Karakorum (WKPK) at the northwestern Tibetan Plateau underwent long-term terrane accretion from the Paleozoic to the Cenozoic. Within this time span, four phases of magmatism occurred in WKPK during the Early Paleozoic, Triassic-Jurassic, Early Cretaceous, and Cenozoic. These voluminous magmatic rocks contain critical information on the evolution of the Tethys Oceans. In this contribution, we provide field observations, petrography, ages, whole-rock elemental and Sr-Nd isotopic compositions, and zircon in situ Lu-Hf isotopes of the Triassic-Jurassic granitoids and pegmatites from the Dahoonglutian in Western Kunlun and Turuke area at the Pamir Plateau, in an attempt to constrain their petrogenesis and to decipher a more detailed Paleo-Tethys evolution process. The Dahoonglutian pluton is composed of diorites (ca. 210 Ma) and monzogranite (ca. 200 Ma). The diorites have moderate SiO₂ (56.77–62.22 wt. %), variable Mg⁰ (46–49), and low Cr (34.4–50.6 ppm) and Ni contents (7.0–14.5 ppm). They show LREE-enriched patterns ([La⁰/Yb⁰] = 4.3 – 17), with variable negative Eu anomalies (0.63–0.91) and variable ratios of Nb/La (0.27–0.97). Isotopically, the diorites display enriched whole-rock εNd(t) (−5.43 to −7.67) and negative to positive zircon εHf(t) values (−6.6 to 0.4). They were most likely generated by melting of a subduction-modified mantle source with subsequent assimilation and fractional crystallization. The Turuke monzogranites (ca. 202–197 Ma) have S-type granite characteristics and are characterized by high SiO₂ (70.36–76.12 wt. %) and A/CNK values (1.19–1.36), variable LREE-enriched patterns ([La⁰/Yb⁰] = 8.87 – 14.40), negative Eu anomaly (0.07–0.56), relatively uniform whole-rock εNd(t) (−10.49 to −11.22), and variable negative zircon εHf(t) values (−10.7 to −1.3). They were probably generated by muscovite-dehydration melting of dominantly metapelitic sources. The widespread pegmatites (ca. 195 Ma) at the Dahoonglutian area record an extensional setting after the collision of Karakorum with the South Kunlun-Tianshuihai terrane. Combining our new data with the previous studies, we propose a divergent double-sided subduction of the Paleo-Tethys Ocean (243–208 Ma) and a gradual closure of the Paleo-Tethys Ocean from east (ca. 200 Ma) to west (ca. 180 Ma) to explain the Triassic-Jurassic tectono-magmatism in the WKPK.

1. Introduction

The Western Kunlun-Pamir-Karakorum (WKPK) in the northwestern margin of the Tibetan Plateau adjoins the Tarim Block to north and the Kohistan-Ladakh Arc to the south and is offset from the East Kunlun Orogen and the Tibetan Plateau to the east by the Altyn Tagh Fault (Figure 1(a)). The WKPK underwent long-term history of terrane drifting, slab subduction, and accretion during the Paleozoic to the Mesozoic [1–4] and subsequent extension after the India-Asia collision in the Cenozoic (e.g., [5, 6]). The WKPK records critical geological information for the
Figure 1: (a) Simplified tectonic map of the Himalayan-Tibetan Orogen showing major tectonic terranes and sutures (modified after [15]). (b) Geological map of the Western Kunlun-Pamir-Karakorum (WKPK) showing the major tectonic terranes and related granitoids (modified from Li et al., [16]). The so-called basement of Tashkorgan terrane and South Kunlun terrane, locally known as the Bulunkuole Group and Saitula Group, are an early Paleozoic accretionary wedge. TSZ: Tanymas Suture Zone; RPSZ: Rushan-Pshart Suture Zone; SSZ: Shyok Suture Zone; ITSZ: Indus-Tsangpo Suture Zone; KKF: Karakorum Fault; NKT: Northern Kunlun terrane; SKT: Southern Kunlun terrane; MZ-TSHT: Mazar-Tianshuihai terrane; KQS: Kudi-Qimanyute Suture; MKF: Mazar-Kangxiwa Fault; HQS: Hongshanhu-Qiaoertianshan Suture; WTBZ: Wakhan-Tirich Boundary Zone.
evolution history of the Tethys Oceans (e.g., [7]). Particularly, the Late Paleozoic to Triassic (Paleo-Tethys) evolution of the WKPK is important for better understanding the assemblage process of the Pangea. Nevertheless, owing to the inaccessible, harsh natural conditions, fundamental geological knowledge of the Late Paleozoic to Triassic evolution of the WKPK is limited (e.g., [8]). For example, the closure time of the Paleo-Tethys Ocean in the WKPK is still under debate and has been proposed as the Late Permian (e.g., [9]), Middle Triassic (e.g., [10, 11]), Late Triassic (e.g., [12, 13]), or Late Jurassic (e.g., [14]).

Four main phases of magmatic rocks were emplaced in the Tethyan Realm during the Paleozoic, Triassic to Early Jurassic, Early Cretaceous, and Cenozoic (Figure 1(b), [17]). Among them, the Triassic-Jurassic granitoids are considered products of the late-stage evolution of Paleo-Tethys Ocean [9]. Precise geochronological results show that these Triassic-Jurassic granitoids were emplaced 243 Ma to 195 Ma (Figure 1(a), [10, 11, 18–21] and this study). However, previous studies mainly focused on the granitoids along the Chinese-Pakistan Road and Xinjiang-Tibet Road [10, 11, 18, 19, 21], and granitoids from other areas have received little attention. Furthermore, although most studies argued that northward subduction occurred since ca. 240 Ma and the amalgamation of Southern Pamir-Karakorum terrane to Southern Asia broadly took place at ca. 200 Ma, the detailed assembly process is still little known. In this study, we provide field observations, petrography, mineral compositions, zircon and monazite U-Pb ages, whole-rock elemental and Sr-Nd isotopic compositions, and zircon in situ Lu-Hf isotopes from the Triassic-Jurassic granitoids at Dahongliutan and newly identified Triassic monzogranite at the Chinese Wakhan Corridor, WKPK. Our data not only shed new light on the petrogenesis of these rocks but also provide new information for a better understanding of the Paleo-Tethys evolution in the WKPK.

2. Geologic Background

The WKPK is comprised of the Pamir-Karakorum to the west and Western Kunlun Orogenic Belt (WKOB) to the east. The Pamir Plateau has been subdivided into three tectonic units, i.e., the North Pamir, Central Pamir, and South Pamir-Karakorum, by the Tanyamas Suture Zone, Rushan-Pshart Suture Zone, and Shyok Suture Zone (Figure 1(a), [2, 3, 22–24]). The North Pamir is a Paleoaoice accretionary complex associated with southward subduction of Proto-Tethys [2, 3, 25]. The Central Pamir and South Pamir-Karakorum are continental fragments rifted from the northern margin of Gondwana during the Late Carboniferous to Early Permian [1, 23] and then drifted across the Paleo-Tethys and finally amalgamated with the North Pamir in the Triassic or later [1, 4]. The South Pamir-Karakorum, though separated by the Wakhan-Tirich Boundary Zone (Figure 1(b)), was generally interpreted to be continuous (e.g., [26]). The South Pamir (north part of the South Pamir-Karakorum) is dominated by the occurrence of crustal-scale extensional detachment system, which can be subdivided into two distinct regions by a system of Cenozoic extensional detachments, i.e., the SE Pamir and SW Pamir [3, 27]. The SE Pamir consists of thick Permian to Cretaceous sedimentary sequences with minor exposures of Precambrian basement, while the SW Pamir is dominated by a gigantic Precambrian basement dome [3, 27]. The Karakorum is a fragment with Gondwana affinity [28, 29] and consists mainly of highly deformed and metamorphosed Precambrian basement as well as Paleoaoice and Mesozoic sedimentary sequences [4, 30, 31].

The WKOB contains three main tectonic units, i.e., the North Kunlun terrane, the South Kunlun terrane, and the Mazar-Tianshuihai terrane, which is bounded by the Paleoaoice Kudi-Qimanyute Suture and Mazar-Kangxiwa Fault, respectively (Figure 1(a), [13, 14, 32]). The North Kunlun terrane is an uplifted terrane of the Tarim Block that is composed of pre-Cryogenian basements and Cryogenian-Cambrian sedimentary sequences [33, 34]. The South Kunlun terrane, composed mainly of the Saitula Group, is a metamorphosed Cambrian-Ordovician accretionary wedge equivalent to the coeval metamorphic volcano-sedimentary sequence at the North Pamir (Figure 1(a), [8, 35]). The Mazar-Tianshuihai terrane is composed of Archean Mazar complex and the Neoproterozoic Tianshuihai Group and Late Paleozoic to Triassic sedimentary sequences, which may be a microcontinent rifted from the north of Gondwana [8, 36]. The Qiangtang terrane, separated from the WKOB to the south by the Hongshanhui-Qiaotienhsan Suture (HQS in Figure 1(a)), is a Gondwana-derived fragment correlative to both Central Pamir and South Pamir-Karakorum in the Pamir-Karakorum (e.g., [2]), as evidenced by similarity in Permian fauna [1] and limited displacement of the Karakorum Fault [37, 38].

Four main phases of magmatism were identified in the WKPK, including (1) the early Paleoaoice, (2) the Triassic-Jurassic, (3) the Cretaceous, and (4) the Cenozoic (Figure 1(b), [8, 10, 11, 18, 19, 25, 35, 36, 39–44]). Those Triassic-Jurassic magmatic rocks, generally considered to be associated with the evolution of the Paleo-Tethys Ocean, are widespread along the Mazar-Kangxiwa Fault in the WKOB (Figure 1(b)) and at the south part of North Pamir and along the Rushan-Pshart Suture Zone in the Pamir. These Triassic-Jurassic magmatic rocks in the WKOB emplaced during 243 Ma to 195 Ma (Figure 1(b), [10, 11, 18–21] and this study). These rocks are composed of both I- and S-type granites. Microgranular mafic enclaves are commonly seen in some granitoids [10, 11, 18]. Apart from the granitoids, plenty of granitic pegmatites dykes emplaced at the east of the magmatic belt, some of which are genetically associated to the rare-metal mineralization in this region [45–47].

The studied granitoids and pegmatites outcrop at the west end of the Dahongliutan area (Mazar-Tianshuihai terrane) and the Chinese Wakhan Corridor (SE Pamir) (Figure 1(b)). The basement in the Dahongliutan area is the Late Neoproterozoic Tianshuihai Group, which occurs at the southwest of the studied area (Figure 2(a), [8, 48]). The Paleoaoice strata in the Dahongliutan area include the Silurian clastic sedimentary sequence locally known as Wenquanguo Group and Permian clastic-limestone sequence.
Figure 2: Simplified geologic maps around the (a) Chinese Wakhan Corridor and the (b) Dahongliutan area, WKPK.
Huangyangling Group (Figure 2(a)). The Triassic sedimentary rocks in this region were termed as the Bayan Har Mountain Group and consist mainly of metamorphosed sedimentary clastic rocks and carbonates (Figure 2(a)). In the field, those sedimentary sequences exhibit broad recumbent fold structures (Figure 3(a)), indicating an extensional setting. Magmatic rocks in the Dahongliutan area consist of the Early Cambrian and the Late Triassic intrusions and Early Jurassic pegmatites (Figure 2(b), [20, 42, 48] and this study). The Triassic Dahongliutan pluton is a NW-trending intrusion, extending from Sanshiliyingfang to Dahongliutan with an outcrop area of >300 km² (Figure 1(a)). The pluton mainly...

**Figure 3:** Field photographs and microphotographs of the granitoids from Turuke and Dahongliutan areas, WKPK. Mineral abbreviations: Hb: hornblende; Pl: plagioclase; Mus: muscovite; Bt: biotite; Q: quartz; Ap: apatite; Af: alkali-feldspar; Spd: spodumene.
intruded into the Triassic Bayan Har Mountain Group, and produced a 3–10 m wide hornfels belt along the margins of the pluton [20]. Granitic pegmatite dikes commonly occur in the Bayan Har Mountain Group and the Dahongliutan intrusion [45, 46]. These dykes are usually a dozen meters wide and several to hundreds of meters long, dominantly NW striking, with a few N–S- or E–W striking (Figure 2(a)). There are several Li-rich rare-metal pegmatite deposits in this region [45, 46]. Generally, the Li-barren pegmatites are distributed both in the Dahongliutan pluton and in the Triassic Bayan Har Mountain Group, while almost all Li-rich pegmatites intruded into the Triassic Bayan Har Mountain Group (Figure 2(a)).

The Archean Mazar complex (ca. 2.5 Ga), the oldest Precambrian basement in the WKPK, is located east of the Chinese Wakhan Corridor (Figure 2(b), [35, 49]). The complex is intruded by ca. 840 Ma granitic and 500 to 490 Ma mafic intrusions [35, 42]. North of the Archean Mazar complex is the Cambrian Bulunkuole Group, which was identified as an accretionary complex formed by southward subduction of Proto-Tethys Ocean [36]. Large-scale magmatic rocks are widespread in this region. Previous work suggested that they were emplaced during the Early Cretaceous [50] and Mesozoic. Our new zircon U-Pb dating results reveal that the Turuke intrusion located at the most west end of Chinese Wakhan Corridor was emplaced during the latest Triassic (ca. 200 Ma). The pluton intrudes the Silurian clastic-sedimentary sequence and the Carboniferous carbonate (ca. 200 Ma). The pluton intrudes the Silurian clastic-sedimentary sequence and the Carboniferous carbonate.

### 3. Petrography and Sampling

Our field work and thin section observations reveal that the Dahongliutan pluton consists of quartz diorite (Figure 3(b)) and monzogranite. In the field, these two distinct lithologies intermingled with each other. The quartz diorites (Figure 3(c)) consist of quartz (5–7 vol. %), plagioclase (40–52 vol. %), alkali-feldspar (11–16 vol. %), hornblende (20–23 vol. %), biotite (4–12 vol. %) and minor muscovite (<5 vol. %). The monzogranites (Figure 3(d)) consist of alkali-feldspar (22–33 vol. %), plagioclase (18–23 vol. %), quartz (27–38 vol. %), and muscovite (2–5 vol. %). Accessory minerals include garnet, zircon, and monazite. The Li-barren pegmatite in the Dahongliutan intrusion (2018KL02) is composed of variable contents of quartz, albite, microcline, muscovite, and tourmaline. The Li-rich pegmatite from the Dahongliutan rare-metal deposit (2018KL09-1) consists of quartz, albite, muscovite, and spodumene (Figures 3(e) and 3(f)).

The Turuke pluton in the Chinese Wakhan Corridor is mainly composed of two-mica monzogranite (Figures 3(g) and 3(h)). They usually have massive structure and medium-to-coarse-grained textures and consist of quartz (22–32%), plagioclase (18–26%), K-feldspar (27–33%), muscovite (4–12%), and minor biotite. The detailed textures and mineralogy of the samples in this contribution are summarized in Table 1, and the sample locations are illustrated in Figure 2. Most selected samples are relatively fresh and a few samples underwent slight chloritization and/or sericitization.

### 4. Analytical Procedures

Three granitoids were chosen for zircon U-Pb dating and a monzogranite and two granitic pegmatites were chosen for monazite U-Pb dating. Mineral separations were carried out using conventional magnetic and density techniques to concentrate the non-magnetic, heavy fractions. Representative selections of zircon and monazite were then extracted by handpicking under a binocular microscope. The grains were cast into an epoxy mount and polished to section the crystals in half for analysis. Zircons were documented with transmitted and reflected light microphotographs and cathodoluminescence (CL) images to reveal their inner structures. U-Pb isotopic data were determined using the LA-MC-ICPMS method at Tianjin Institute of Geology and Mineral Resources, Chinese Geology Survey, where a Neptune MC-ICPMS coupled with a 193 nm excimer laser ablation system was used to determine zircon U-Pb isotope. The detailed analytical procedures can be found in Geng et al. [51]. Zircon U-Pb isotopic data is listed in Supplementary Table 1.

Monazites were documented with transmitted and reflected light microphotographs and back-scattered electron (BSE) images to reveal their inner structures. The analyses were carried out on those homogenous grains. Monazite U-Pb ages were determined using the LA-MC-ICPMS method at the same laboratory with the same instrument at the

### Table 1: Summary of the lithologies and sample locations of the granitoids and pegmatites.

| Pluton/area | Sample No. | Locality | Lithology | Mineralogy | Age (Ma) |
|------------|------------|----------|-----------|------------|----------|
| Dahongliutan | 2018KL05 | N:35°51'.61' E:79°04'.68' | Diorite | Pl+Am+Kfs+Bt+Qtz+Mu | 209.9 ± 1.3 |
|             | 2018KL04-2 | N:35°53'.11' E:79°07'.52' | Monzogranite | Kfs+Qtz+Pl+Mu±Grt | 198.9 ± 1.0 |
|             | 2018KL02 | N:35°54'.72' E:79°10'.54' | Pegmatite | Qtz+Pl+Kfs+Mus±Grt | 196.1 ± 1.0 |
|             | 2018KL09-1 | N:35°53'.11' E:79°07'.52' | Pegmatite | Qtz+Ab+Kfs+Mus+Am+Spd | 195.2 ± 1.5 |
| Turuke | 2018KL11 | N:37°09'.40' E:74°39'.64' | Monzogranite | Qtz+Pl+Kfs+Mus±Bt | 201.9 ± 1.5 |
|             | 2018KL12 | N:37°09'.51' E:74°39'.62' | Monzogranite | Qtz+Pl+Kfs+Mus±Bt | 197.4 ± 2.1 |

Pl: plagioclase; Kfs: K-feldspar; Qtz: quartz; Bt: biotite; Mus: muscovite; Am: amphibole; Grt: garnet; Ab: albite; Spd: spodumene.
Tianjin Institute of Geology and Mineral Resources, Chinese Geology Survey. The detailed analytical procedures can be found in Cui et al. [52]. Isoplot [53] was used for data processing for both zircon and monazite U-Pb dating. Monazite U–Pb isotopic data is listed in Supplementary Table 2.

Mineral compositions were determined on thin sections at Nanjing Institute of Geology and Mineral Resources, Chinese Geology Survey, using an automated Shimadzu EPMA-1720H electron microprobe equipped with 5 wavelength spectrometers. The operating conditions during analyses

Figure 4: Concordia plots of U-Pb results of Triassic-Jurassic granitoids. (a) Zircon age of the Dahongliutan diorite, (b) monazite age of Dahongliutan monzogranite, (c, d) zircon ages of Turuke monzogranites, (e) monazite, and (f) zircon U-Pb results Dahongliutan pegmatite. MSWD: mean square of weighted deviates.
were 15 keV accelerating voltage and 20 nA beam current with 20 s counting time and 5 μm beam size. The analytical precision was better than 5% for all elements. The analytical results of hornblende and plagioclase were listed in Supplementary Tables 3 and 4, respectively.

Thirty-two granitoids were chosen for whole-rock elemental analysis. Whole-rock major elements were measured by X-ray fluorescence spectroscopy at the ALS Laboratory Group, an Australian ICP-MS analytical lab in Guangzhou, China. Before the final analysis, samples (2 g) were fused with a Li2B4O7 flux at a sample-to-flux ratio of 1:5 and a temperature of 1150-1250°C to generate glass fusion discs for XRF analysis. The analytical precision for the major oxides was better than 1%. Trace elements were analysed using a PE Elan 600 ICP-MS at the Chinese Institute of Geochemistry, Chinese Academy of Science, following procedures similar to those described by Li et al. [54]. In-run analytical precision for most elements was generally better than 2–5%. The analytical results of major and trace elements are listed in Supplementary Table 5.

Sr-Nd isotopes were determined using a Micromass Isoprobe MC-ICPMS at Tianjin Institute of Geology and Mineral Resources, Chinese Geology Survey, following the procedure described by Li et al. [54]. Measured 87Sr/86Sr and 143Nd/144Nd ratios were normalized to 86Sr/88Sr = 0.1194 and 146Nd/144Nd = 0.7219, respectively. The reported 87Sr/86Sr and 143Nd/144Nd ratios were adjusted to the NBS SRM 987 standard 87Sr/86Sr = 0.71025 and the Shin Etsu JNdi-1 standard 143Nd/144Nd = 0.512115, respectively. Sr-Nd isotope results are listed in Supplementary Table 6.

Zircon in situ Lu-Hf isotopic compositions were determined using a New Wave 193 nm ArF excimer laser-ablation system linked to a Neptune MC-ICP-MS at Tianjin Institute of Geology and Mineral Resources, Chinese Geology Survey. Zircon standard GJ-1 was used for external calibration. The analyses were conducted with a beam diameter of 50 μm and 8 Hz repetition rate with a laser power of 15 J/cm². Details of the operating conditions for the laser ablation system, the MC-ICP-MS instrument, and the analytical method are documented in Geng et al. [51]. The isotopic results are listed in Supplementary Table 7.

5. Analytical Results

5.1. Geochronology of the Granitoids. Zircons from the Dahongliutan diorite (2018KL05) are euhedral, 100–200 μm long, with length/width ratios ranging from 3:2 to 3:1. In the CL images, most grains exhibit oscillatory or blurry zoning. A total of 30 analyses yield concordant 206Pb/238U and 207Pb/235U ages, with a weighted mean 206Pb/238U age of 209.9 ± 1.3 Ma (MSWD = 1.16, Figure 4(a)). Monazite grains from the Dahongliutan monzogranite (2018KL04-2) are euhedral to semieuhedral and are 80–250 μm long. In the BSE images, most grains are homogenous with some showing bright and dark domains. A total of 40 analyses yield concordant 206Pb/238U and 207Pb/235U ages with a weighted mean 206Pb/238U age of 198.9 ± 1.0 Ma (MSWD = 2.2, Figure 4(b)) (Supplementary Table 2).
Two monzogranite samples from Turuke (2018KL11 and 2018KL12) are chosen for zircon U-Pb dating. Zircons are euhedral to semieuhedral and are 60–200 μm long, with length to width ratios ranging from 3 : 2 to 3 : 1. Most grains exhibit oscillatory zoning, typical of magmatic-derived zircons. Among the 30 analyses of sample 2018KL11, two spots (2018KL11-14 and 2018KL11-29) yield Paleozoic ages (456 ± 6 Ma and 405 ± 11 Ma) and one spot (2018KL11-21) yield 213 ± 4 Ma age, likely to be xenocrysts. Except for these four spots with significantly younger 206Pb/238U ages than others (183 ± 2 Ma and 405 ± 11 Ma) and one spot (2018KL11-21) yield 213 ± 4 Ma age, likely to be xenocrysts. Except for these four spots with significantly younger 206Pb/238U ages than others (183 ± 2 Ma and 405 ± 11 Ma) and one spot (2018KL11-21) yield 213 ± 4 Ma age, likely to be xenocrysts. Except for these four spots with significantly younger 206Pb/238U ages than others (183 ± 2 Ma and 405 ± 11 Ma) and one spot (2018KL11-21) yield 213 ± 4 Ma age, likely to be xenocrysts. Except for these four spots with significantly younger 206Pb/238U ages than others (183 ± 2 Ma and 405 ± 11 Ma) and one spot (2018KL11-21) yield 213 ± 4 Ma age, likely to be xenocrysts. Except for these four spots with significantly younger 206Pb/238U ages than others (183 ± 2 Ma and 405 ± 11 Ma) and one spot (2018KL11-21) yield 213 ± 4 Ma age, likely to be xenocrysts. Except for these four spots with significantly younger 206Pb/238U ages than others (183 ± 2 Ma and 405 ± 11 Ma) and one spot (2018KL11-21) yield 213 ± 4 Ma age, likely to be xenocrysts. Except for these four spots with significantly younger 206Pb/238U ages than others (183 ± 2 Ma and 405 ± 11 Ma) and one spot (2018KL11-21) yield 213 ± 4 Ma age, likely to be xenocrysts. Except for these four spots with significantly younger 206Pb/238U ages than others (183 ± 2 Ma and 405 ± 11 Ma) and one spot (2018KL11-21) yield 213 ± 4 Ma age, likely to be xenocrysts. Except for these four spots with significantly younger 206Pb/238U ages than others (183 ± 2 Ma and 405 ± 11 Ma) and one spot (2018KL11-21) yield 213 ± 4 Ma age, likely to be xenocrysts. Except for these four spots with significantly younger 206Pb/238U ages than others (183 ± 2 Ma and 405 ± 11 Ma) and one spot (2018KL11-21) yield 213 ± 4 Ma age, likely to be xenocrysts.

A total of 29 analyses have been carried out on sample 2018KL12. Among them, four spots (2018KL12-4, 2018KL12-11, 2018KL12-19, and 2018KL12-24) yield discordant 206Pb/238U and 207Pb/235U ages. Four spots (2018KL12-3, 2018KL12-15, 2018KL12-20, and 2018KL12-27) yield Paleozoic and Neo-
total of 18 analyses have been carried on the zircon grains of the spodumene-bearing pegmatite. Apart from two discordant analyses, the other 16 spots yield weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of $195.2 \pm 1.5$ Ma (Figure 4(f)).

5.3. Mineral Compositions. The hornblendes from Dahongliutan diorite have variable Si (6.79–7.12) and Ca (1.69–1.91) apfu (atoms per formula unit) and are thus calcic amphibole following the classification scheme of Leake et al. [55]. They exhibit variable Mg# ($0.53–0.74$, Mg#/Mg + Fe$^{2+}$/C$_{138}$) and have (Na+K) A (occupancy of Na+K in A-site) ranging from 0.14 to 0.35 and belong to magnesiohornblende (Figure 5(a)). Their high Mg# and low alkaline features show arc affinities (Figure 5(b), [56]). The plagioclases from the Dahongliutan diorite show complex chemical zoning and record the evolutionary history of the magma. The EMPA data show that they are mainly andesite and labradorite with subordinate bytownite (Figure 5(c)).

5.4. Whole-Rock Elemental Geochemistry

5.4.1. The Dahongliutan Diorites. The Dahongliutan diorites show intermediate SiO$_2$ contents (56.77–62.22 wt. %), low total alkaline (Na$_2$O±K$_2$O, 3.62–4.89 wt. %), and high CaO (5.57–6.68 wt. %) and plot in the diorite field in the TAS diagram (Figure 6(a)). Their major elements exhibit calcic signature (Figure 6(b)) and high-K calc-alkaline series (HKCK, Figure 6(c)). Their Al$_2$O$_3$ contents range from 15.92 to 17.80 wt. %, and the A/CNK values (0.88–1.03) define their metaluminous feature. MgO contents of the diorite range from 3.06 to 4.17 wt. % with Mg$^\#$ ranging from 46 to 49, consistent with their low contents of Cr (34.40–50.60 ppm) and Ni (7.00–14.50 ppm). As for the trace elements, they have total rare earth elements (REEs) concentrations ranging from 91 ppm to 221 ppm, with weak to moderate negative Eu anomaly ($\text{Eu}/\text{Eu}^*$ = 0.63 – 0.91). All samples show arc-like trace element signatures, such as enrichment of LREEs ($\text{La/Yb}_N$ = 4.3–17, Figure 7(a)) and Rb, Th, U, and Pb and depletion in high field strength elements (HFSEs) such as Nb, Ta, P, Zr, and Hf (Figure 7(b)).

5.4.2. The Turuke Monzogranites. The Turuke monzogranites have variable SiO$_2$ (70.36–76.12 wt. %) and relatively high total alkali (6.36–7.80 wt. %). They are plotted within the granite field on the TAS diagram (Figure 6(a)) and are associated with the alkalic-calcic to calcic-alkalic series and high-K calc-alkaline series on the SiO$_2$ vs. K$_2$O±Na$_2$O–CaO and SiO$_2$ vs. K$_2$O diagrams, respectively (Figures 6(b) and 6(c)). These monzogranites are all peraluminous (A/CNK = 1.2 – 1.4, Figure 6(d)). As for the trace elements, the Turuke monzogranites have low but variable contents of REEs (34–146 ppm) and exhibit significant negative Eu anomaly (0.07–0.56, Figure 7(a)). Normalized to the primitive mantle (Figure 7(d)), those granites are enriched in Rb, U, Ta, Pb, and P and depleted in Ba, Nb, La, Ce, Sr, and Eu.

As shown in the Harker diagram (Figure 8), the samples show a decrease in TiO$_2$, FeO$^*$ (total Fe as FeO), MgO, and CaO with increasing SiO$_2$, while Na$_2$O and Al$_2$O$_3$ are
relatively constant with increasing SiO$_2$, P$_2$O$_5$ of the Turuke monzogranites is positively correlated with SiO$_2$ content, typical of S-type granite [65].

5.5. Sr-Nd Isotopic Compositions. Whole-rock Sr-Nd isotopic compositions of the Dahongliutan diorite and Turuke monzogranite are listed in Supplementary Table 6. Six samples from the Dahongliutan diorites yield a range of measured $^{143}$Nd/$^{144}$Nd ratios from 0.512140 to 0.512280, with negative $\varepsilon_{\text{Nd}}(t)$ values (-5.43 to -7.67) and Mesoproterozoic two-stage model age (1.42–1.60 Ga). Their analysed $^{87}$Sr/$^{86}$Sr ratios range from 0.7104 to 0.7131 with age-corrected initial $^{87}$Sr/$^{86}$Sr ($t$) values ranging from 0.7079 to 0.7097. Three samples from the Turuke monzogranites yield measured $^{143}$Nd/$^{144}$Nd ratios ranging from 0.511976 to 0.512017 and exhibit relatively uniform $\varepsilon_{\text{Nd}}(t)$ values (-10.49 to -11.22), with two-stage model ages ranging from 1.83 to 1.89 Ga. For the strontium isotopes, the Turuke monzogranites have high measured $^{87}$Sr/$^{86}$Sr ranging from 0.7547 to 0.7566 and variable initial $^{87}$Sr/$^{86}$Sr ($t$) values (0.7082–0.7177). The initial $\varepsilon_{\text{Nd}}(t)$ values of the Turuke monzogranites are similar to those of the Dahongliutan monzogranites [20].

5.6. Zircon in Situ Lu-Hf Isotopes. In situ Lu-Hf isotopes were determined on zircons that were previously dated, and the initial isotopic compositions were calculated to the weighed mean U-Pb ages of each sample. Zircons from the Dahongliutan diorite (2018KL05) yielded $\varepsilon_{\text{Hf}}(t)$ values ranging from -6.6 to 0.4, which formed a broad Gaussian distribution with a peak at about -3 (Figure 9(a)), corresponding to two-stage model ages ($T_{\text{DM2}}$) ranging from 1.12 to 1.50 Ga. Zircons from Turuke monzogranites (samples 2018KL11 and 2018KL12) yield large range of initial $\varepsilon_{\text{Hf}}(t)$ values from -10.7 to -1.3, which formed a nearly Gaussian distribution with a peak at about -6 (Figure 9(b)), corresponding to $T_{\text{DM2}}$ ranging from 1.20 to 1.72 Ga, reflecting a heterogeneous source region.
mixing or assimilation and fractional crystallization process in generating the chemical composition of the Dahongliutan diorite. The massive feature (Figure 3(b)) and the absence of compositional disequilibrium textures, such as MMEs and oscillatory or reverse zoning of early crystallizing phases (e.g., [67]), rule out the magma mixing between mantle- and crustal-derived melt as the mechanism in generating the Dahongliutan diorite. This conclusion is also supported by the broad Gaussian distribution of its $\varepsilon_{Hf}(t)$ values (peak at about -3, Figure 10(a)). In addition, a simple mixing calculation of two endmembers is tested on the Dahongliutan diores using the most mafic magmatic MMEs in the Triassic granitoids from WKOB [10, 11, 21] and the Dahongliutan monzogranites [20]. The result illustrates a very high portion of (90–70%) basaltic components (Figure 10(b)), which is inappropriate for magma mixing. In contrast, this ratio probably reflects the assimilation and fractional crystallization (AFC) process of the diores. However, the assimilation hypothesis is not supported by the positive correlations between SiO$_2$ and $\varepsilon_{Nd}(t)$ (Figure 10(a)). Therefore, the variable whole-rock Sr-Nd and zircon Hf isotopes (Supplementary Tables 4 and 5, Figures 10(b) and 10(c)) of the Dahongliutan diorite likely record the source features. The negative correlations of MgO, CaO, FeO*, and TiO$_2$ with SiO$_2$ and the constant Na$_2$O and Al$_2$O$_3$ on the Harker diagram (Figure 8) indicate crystal fractionation of olivine, clinopyroxene, and Fe-Ti oxide in the magma chamber. The crystal fractionation of olivine and clinopyroxene is also supported by the low concentrations of Cr (34.40–50.60 ppm) and Ni (7.00–14.50 ppm).

Although the Dahongliutan diores exhibit crust-like trace element distribution patterns, such as the enrichments of LREEs and LILs, depletions in HFSEs, and enriched Sr-Nd-Hf isotopic compositions (Figures 7, 10(b), and 10(c)), their Mg$^+$ values (46–49) are higher than these melts derived from pure crustal sources under variable P-T conditions (Figure 8(i), [62–64]), demonstrating that they were not derived from partial melting of pure crustal sources. As mentioned above, the high Mg$^+$ of the diorite could not be generated by magma mixing between mantle- and crustal-derived melts. Alternatively, the high Mg$^+$ values can be generated by partial melting of subducted oceanic slab [71, 72] or by melting of delaminated lower crust in the mantle depth [73, 74]. The negative $\varepsilon_{Nd}(t)$ values (-5.43 to -7.67) indicate that the Dahongliutan diores were not derived from partial melting of depleted oceanic slab. Due to interaction with the mantle peridotite, partial melts from the delaminated lower crust in the mantle depth [73, 74] and slab-derived adakites [75] would have high Mg$^+$ as well as high Cr and Ni, which are distinct from the low contents of Cr (34.40–50.60 ppm) and Ni (7.00–14.50 ppm) for the Dahongliutan diorite.

6. Discussion

6.1. Spatial and Temporal Distribution of the Triassic-Jurassic Magmatism in the Western Tibetan Plateau. Zircon and monazite dating results of the Dahongliutan diorite and Turke monzogranite reveal that they were emplaced at ca. 210–200 Ma. Our age data are slightly younger than those in the Qiangtang terrane (e.g., [15, 66]). Coeval magmatism has been also reported in the Bulunkoule Group at the NE Pamir (ca. 195 Ma) in the WKOB, such as those in the Arkarz, Bulunkou, Muztage, and Taer pluton [10, 11, 18, 21]. Two pegmatitic samples from Dahongliutan area yield crystallization ages of ca. 195 Ma, which is the youngest age of the Triassic-Jurassic magmatism (ca. 243–195 Ma) in the WKOB. The crystallization of the granitic pegmatites occurred earlier than the amphibolite-facies metamorphism identified in the Bulunkuole Group at the NE Pamir (ca. 200–180 Ma, [25]). Therefore, the Triassic-Jurassic magmatic rocks in the WKOB are mainly distributed along the Mazar-Kangxiwa Fault (Figure 1), with emplacement ages at ca. 243–195 Ma. While in the Pamir, they are distributed in the south part of North Pamir along the Rushan-Pshart Suture Zone (Figure 1(b)). Coeval magmatism has been also reported in the Qiangtang terrane (e.g., [15, 66]).

6.2. Petrogenesis of the Dahongliutan Diorite. The significant linear correlations between the Dahongliutan diorite and the mafic microgranular enclaves (MMEs) in the Triassic plutons on the Harker diagrams (Figure 9) demonstrate magma

![Figure 9: Histogram of initial Hf isotopes of zircons for the Triassic granitoids from the Turuke and Dahongliutan areas, WKPK.](http://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/2020/1/7282037/5213543/7282037.pdf)
Experimental studies on reactions between silicic melts and mantle peridotites show that a small number of slab-derived melts with low Mg# can be completely consumed by peridotites to form pyrope-rich garnet and orthopyroxene [79], generating enriched mantle with “marble-cake” structure (e.g., [80]). An experimental study also demonstrated

**Figure 10:** (a) SiO₂ vs. εNd(t), (b) whole-rock Sr-Nd, (c) zircon U-Pb age (t) vs. εHf(t), and (d) whole-rock εNd(t) vs. zircon εHf(t) diagrams for the Triassic granitoids from Turuke and Dahongliutan pluton in the WKPK. In (b), the whole-rock Sr-Nd isotopes of the Triassic granitoids and mafic microgranular enclaves (MMEs) in the WKPK are from Zhang et al. [21], Liu et al. [11], Jiang et al. [10] and Zhang et al. [20]; Area of the Late Triassic S-type granites in Qiangtang terrane is from Lu et al. [66]; Nd isotopes of the Late Triassic slate in Songpan-Ganzi are from Zhang et al. [33, 68]; Jinsha Ophiolite is from Xu and Castillo [69]. In (c), data sources for the Triassic granitoids and MMEs are from Wang et al. [18], Jiang et al. [10], and Zhang et al. [20]; data source for the Triassic flysch from Songpan-Ganzi is from Zhang et al. [70].
that partial melting of a hybrid silica-excess pyroxenite can produce andesitic melts with compositions similar to the Dahongliutan diorite (SiO$_2$ ≥ 60 wt. %, MgO < 5 wt. %, and Mg$^\#$ < 55; [81]). Recently, some scholars have proposed a SARKSH (subduction, anatexis, reaction, storage, and heating) model to interpret the Cretaceous continental arc andesites in the Lower Yangtze Valley, Southeast China [82, 83]. In this process, a metasomatized mantle source was generated by the reaction of the mantle wedge peridotite with the subducted sediment-derived hydrous melts at slab-mantle interface. Melting of such mantle source in a proper tectonic setting would generate variable andesitic rocks [84]. The arc affinities of the hornblende from the Dahongliutan diorite (Figure 6(b), [56]) suggest that its magma source could be modified by the subduction process. More importantly, the variable Nb/La ratios (0.27–0.97) of the Dahongliutan diores reflected variable injection of crustal components, which also argue for a subduction process. The subducted slab includes the seafloor sediments and altered oceanic basalts, both of which exhibit distinct geochemical features. These two components can be presented as hydrous melts and aqueous fluids, which are produced by metamorphic dehydration and partial melting of the subducted seafloor sediments and altered oceanic basalts. The relative contribution of these two crustal components to the oceanic and continental arc magmatism can be identified by using ratio diagrams between particular elements. As illustrated in the Th/Nd vs. Ba/La and (La/Sm)$_N$ vs. Ba/Th diagrams (Figure 11), the mantle source of the Dahongliutan diorite could be most possibly metasomatized by seafloor sediment-derived melts. Therefore, we conclude that the Dahongliutan diores most likely originated from melting of enriched mantle sources metasomatized by seafloor sediment-derived melts, with subsequently fractional crystallization.

6.3. Petrogenesis of the Turuke and Dahongliutan Monzogranites. Magmatic muscovites are commonly seen in the monzogranites from both the Turuke and Dahongliutan intrusions (Figures 3(d) and 3(e)). Chemically, the Turuke and Dahongliutan monzogranites exhibit high silicate, alkali and P$_2$O$_5$, and peraluminous (A/CNK > 1.1) signatures, typical of S-type granites [65, 85]. Experimental studies demonstrated that apatite has very low solubility in metaluminous to weakly peraluminous magma system and apatite crystallized early in the magmatic system, which result in a negative relationship between P and SiO$_2$. While in the strong peraluminous magma, apatite shows an opposite behavior and leads to a positive or remains unchanged as the SiO$_2$ increasing [86, 87]. As illustrated in Figure 9(h), the high P$_2$O$_5$ contents and positive correlation between P$_2$O$_5$ and SiO$_2$ reveal S-type feature of those monzogranites. On the other hand, Th and Y have different behaviors in strong peraluminous and metaluminous to weakly peraluminous magma, which can be used for distinguishing the S- and I-type granites [88]. In a peraluminous magma system, Th and Y will enter minerals rich in Th and Y (e.g., monazite) preferentially. The fractionated S-type granites (Rb > 200 ppm) usually have a low concentration of Th and Y and show a negative correlation with the increasing Rb (e.g., [89]). As for a metaluminous magma system, Th- and Y-rich minerals do not crystalize at the early stage of magma evolution, which leads to a positive correlation between Rb vs. Th and Y in magmas. The negative correlations in Th vs. Rb and Y vs. Rb diagrams support the S-type affinity of these monzogranites (Figures 12(a) and 12(b)).

S-type granite is usually considered a product of the partial melting of dominantly metasedimentary protoliths, generally with an insignificant contribution of mantle-derived components (e.g., [66, 90]). Sedimentary rocks will lose components of CaO and Na$_2$O during the formation of clay from feldspar through weathering, which produces the low concentrations of CaO and Na$_2$O for S-type granite [65]. Previous studies proposed pelite-derived peraluminous granites tend to have lower CaO/Na$_2$O ratios (<0.3) than those psammitic-derived counterparts [91]. The CaO/Na$_2$O ratio ranges of the Turuke granite (0.10–0.43, averagely 0.25) and Dahongliutan monzogranite (0.14–0.33, averagely 0.26) are similar to those melts derived from pelite-rich sources. On the other hand, the psammitic-derived melts tend to have lower Rb/Sr and Rb/Ba than pelite-derived peraluminous granitic melts [91]. The overwhelming majority of the peraluminous granites in this contribution are plotted into the clay-rich sources with lower plagioclase contents, which coincide with the pelite-derived melts (Figure 12(c)). A similar conclusion can be reached from the diagram of CaO/(MgO+FeO$^\text{III}$)$_{\text{molar}}$ vs. Al$_2$O$_3$/(MgO+FeO$^\text{III}$)$_{\text{molar}}$.

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**Figure 11:** (a) Th/Nd vs. Ba/La and (b) (La/Sm)$_N$ vs. Ba/Th diagrams, suggesting that subducted sediment-derived melts were added to the source of the Dahongliutan diorite.
A potential source for the Turuke and Dahongliutan monzogranites is the Triassic flysch in the Songpan-Ganzi terrane, northern Tibet Plateau (Figures 8(b) and 8(c)), as evidenced by the whole-rock Nd [68, 92] and zircon Hf isotopes [70].

Two types of anatexis, i.e., the dehydration melting and water-fluxed melting (or hydrated melting), could occur during partial melting of crustal rocks. Melting experiments revealed that hydrated melting of the K-rich metasedimentary rocks would generate trondhjemitic melts due to dissolving of plagioclase+quartz at the stability fields of muscovite, while dehydration melting of the same rocks generated granitic melts as a result of the breakdown of micas [93, 94]. Rb, Sr, and Ba variations in the granitic melt are mainly controlled by mica, plagioclase, and orthoclase, which are used as possible indicators of the melting reaction (Figure 13, [95, 96]). Geochemical modeling on melting of variable metasedimentary rocks reveals that low-degree partial melting involving mica breakdown can cause Rb/Sr enhancement and Ba depletion in the melt, whereas water-fluxed melting typically results in melts with low Rb/Sr ratios (<3.5, [95]). The high Rb/Sr ratios of Dahongliutan (average of 3.89, mostly higher than 3.5) and Turuke (2.28 to 27.61, average of 8.91) monzogranites indicate that dehydration melting is mainly responsible for their melt generations. Inger and Harris [96] modeled the behavior of Rb/Sr versus Sr and Ba for three different melting reactions, i.e., the muscovite dehydration, biotite dehydration, and aqueous fluid-saturated muscovite dehydration. The Dahongliutan and Turuke monzogranites exhibit distinct trends of vapour-present muscovite-dehydration melting on the Rb/Sr vs. Ba and Rb/Sr vs. Sr diagrams (Figure 13).

The Turuke monzogranites have negative whole-rock $\varepsilon_{\text{Nd}}(t)$ and zircon $\varepsilon_{\text{Hf}}(t)$ values (Figures 8(b) and 8(c)) and exhibit slightly decoupled Nd-Hf isotopic compositions (Figure 8(d)), with two-stage Hf model ages ranging from 1.12 Ga to 1.72 Ga and whole-rock Nd model age ranging from 1.83 Ga to 1.89 Ga. Previous studies have attributed the decoupling of Nd-Hf isotopes in the granites to the disequilibrium melting processes or inheritance from the magma source [98, 99]. The mineral residual effect is an important mechanism to explain the anomalous behavior of Hf isotopes during disequilibrium melting [100]. Zircon is the main Hf-Zr bearing mineral with very low Lu/Hf ratios. Residual zircons in the source region during crustal anatexis would generate partial melts with higher $^{176}$Hf/$^{177}$Hf ratios.
relative to the source region, due to low Lu/Hf and $^{176}$Hf/$^{177}$Hf ratios in zircon (e.g., [101]). The absence of Zr-Hf trough on the primitive mantle normalized trace element spider diagram (Figure 7(b)) indicates little zircon residual in the magma source. Therefore, the Nd-Hf decoupling of the Turuke monzogranite was more likely inherited from their magma source. During weathering and sedimentary processes, rare earth elements tend to quickly become part of fine-grained materials, either much-abraded primary grains or more likely adsorbed onto clay minerals and organic particles, while Hf trends to remain in resistant zircon [102]. Thus, changes in the extent of zircon fractionation of source materials may influence sedimentary compositions through time [103].

To sum up, we conclude that the Turuke and Dahongliutan monzogranites were generated by vapour-absent muscovite melting of dominantly metapelitic protoliths, probably the Triassic flysch in the Songpan-Ganzi terrane.

6.4. The Closure Time of the Paleo-Tethys. As mentioned in the Introduction section, the final closure time of the Paleo-Tethys Ocean in the WKPK still remains controversial [9–14]. It has been proposed that rare-metal mineralized pegmatites are related to orogenic event (e.g., [104]) and can be used to constrain the tectonic evolution [105]. The Jurassic rare-metal mineralized granitic pegmatites (ca. 195 Ma) are the youngest magmatic record of the Triassic-Jurassic magmatism (243–195 Ma) in the WKOB, which is helpful for better understanding the Paleo-Tethys tectonic evolution in this region.

Some studies show that a stable tectonic setting favors the concentration of rare-metal elements and thus promotes ore formation (e.g., [106, 107]). Wang et al. [108] proposed that large-scale rare-metal mineralized pegmatites in the Chinese Altai were mainly emplaced in a postcollisional environment. Zagorsky et al., [109] suggested that the large-scale spodumene-bearing pegmatites in the Central Asian fold belt were associated with regional lithosphere extension. They proposed that those large-scale spodumene-bearing pegmatites in the world occur either at tectonic settings of a long-term active deep fault margin or at the postcollisional region where shear and tensile dislocations exist. Our compilations of geochronological data reveal that these pegmatites (ca. 195 Ma) are the youngest in the Triassic-Jurassic magmatism (ca. 243–195 Ma), which may postdate the collision between the Qiangtang and MZT-TSHT. This conclusion is supported by the broad recumbent fold structure identified in the Bayan Har Mountain Group, which strongly argues for an extensional setting. The granitic pegmatites in the Dahongliutan area were crystallized slightly later than the
Dahongliutan monzogranite, which was identified as S-type granite with high radiogenic Pb isotopic compositions and high $\delta^{18}O$ (10.5–11.6‰, [20]). Those strongly peraluminous S-type granites are mainly derived from partial melting of crustal sources from syn- or postcollisional tectonics (e.g., [91]). Therefore, we propose that the final closure of the Paleo-Tethys Ocean basin in the WKOB was at least no later than ca. 200 Ma. This conclusion is also supported by the high-greenschist- to amphibolite-facies metamorphic ages (ca. 210–200 Ma) of the Kangxiwa Group along the Mazar-Kangxiwa Fault and the lower Jurassic molasse unconformably overlying the pre-Jurassic sequences in the Tianshuihai terrane [8].

According to the rock associations, those volcanic-sedimentary sequences in the Cambrian Bulunkuole Group might be the accretionary complex probably formed by the southward subduction of the Proto-Tethys Ocean (Figure 1(b), [8, 25]). The Bulunkuole Group had undergone intensive amphibolite-facies metamorphism during the Jurassic (ca. 200–180 Ma), which may witness the collision between the Central Pamir and northeastern Pamir [25], i.e., the Paleo-Tethys Ocean in the northeast of Pamir was finally closed at ca. 180 Ma. The amphibolite-facies metamorphism of Bulunkuole Group occurred earlier than the final closure of the Paleo-Tethys Ocean in the WKOB. Therefore, we propose that the Paleo-Tethys Ocean basin gradually closed from east (WKOB) to west (Pamir) follows 200–180 Ma. Emplacement of the Turuke monzogranite in this contribution took place earlier than amphibolite-facies metamorphism of the Bulunkuole Group. More importantly, the pluton has a large exposed area (>300 km² in Chinese part), which may be generated by southward subduction of Rushan-Pshart Oceanic slab, a branch of the Paleo-Tethys Ocean (e.g., [17]).
6.5. Paleo-Tethys Evolution in the WKPK. Geochronological data reveal that the Triassic-Jurassic igneous activities in the eastern section of the WKOB occurred between 243 Ma and 195 Ma (Figure 14), coeval with those igneous rocks in the Qiangtang terrane [15, 66, 68]. According to the geochemical characteristics, most of the 243–208 Ma magmatic rocks show typical arc-like features and might represent the arc magmatism as a result of the northward subduction of the eastern extension of the Tanymas Ocean [10, 11, 18, 21]. A relatively quiet period (ca. 208–200 Ma) in the WKOB after the arc magmatism may record the closure of the eastern extension of the Tanymas Ocean, as evidenced by the metamorphic age (210–200 Ma) of the Kangxiwa Group in the South Kunlun terrane (Figure 1(b), [8]). Those ca. 195 Ma rare-metal pegmatites in the Dahongliutan area represent a regional extension in the eastern section of the WKOB. Combining our petrogenetic study with those previous studies about the Triassic granitoids in the WKPK, a remarkable progression in the evolution of the magma source can be summarized as follows. The continuous southward subduction and rollback of the Paleo-Asia Oceanic slab beneath the Tarim Block [110] led to the dispersal of Gondwana in the Carboniferous, as evidenced by the Carboniferous rift-related magmatism at the north of the South Kunlun terrane [40, 111], which triggered the initial opening of the Paleo-Tethys Ocean. The initial subduction of the Paleo-Tethys Ocean may have started at least earlier than 243 Ma, when the earliest subduction-related magmatism occurred [10]. The subduction polarity of the Paleo-Tethys Ocean should trend initially northward, generating those ca. 243–208 Ma magmatic rocks, including the Dahongliutan diorite, with arc signatures along Kongur Mountain in the northeast Pamir, the southern South Kunlun terrane, and the northern Mazar-Tianshuihai terrane (Figure 15(a)). Previous studies have demonstrated the presence of a double-sided subduction during the closure of the Paleo-Tethys Ocean in the Pamir [17]. The Turuke monzogranite might result from the southward subduction of the Paleo-Tethys Ocean. In the eastern section of the WKOB, the final closure of the Paleo-Tethys Ocean occurred at ca. 200 Ma, as evidenced by the monazite ages of the metamorphic rocks along the Mazar-Kangxiwa Fault (Figure 15(b), [8]). A short period later, the tectonic setting in the WKOB quickly turned into an extensional setting due to postcollision collapse as demonstrated by abundant recumbent folding. This extensional process was intimately related to the formation of the rare-metal mineralized pegmatites in the Dahongliutan area (Figure 15(c)). While in the Pamir, it was not until the Jurassic (ca. 180 Ma) that the Paleo-Tethys Ocean finally closed (Figure 15(d)).

7. Conclusions

(1) The Dahongliutan diorite, Turuke and Dahongliutan monzogranites, and Dahongliutan rare-metal pegmatites in the Western Kunlun-Karakorum-Pamir were emplaced at ca. 210 Ma, ca. 200 Ma, and ca. 195 Ma, respectively

(2) The Dahongliutan diorites were generated by melting of enriched mantle sources metasomatized by seafloor sediment-derived melts, with subsequent assimilation and fractional crystallization. The Turuke and Dahongliutan monzogranites are S-type granites and were generated by muscovite-dehydration melting of dominantly metapelitic sources

(3) The Triassic granitoids in the Western Kunlun-Pamir-Karakorum indicate that the northward subduction of the Paleo-Tethys Ocean began before ca. 243 Ma. The continuous subduction of the Paleo-Tethys during the 243–208 Ma generated the coeval arc magmatism in the WKOB. The newly identified Turuke monzogranite in the Karakorum Orogen reveals a southward subduction polarity of the western section of Paleo-Tethys Ocean before ca. 200 Ma. The Paleo-Tethys oceanic basin was closed gradually from the Western Kunlun Orogenic Belt (eastern section, ca. 200 Ma) to the Pamir Plateau (western section, ca. 180 Ma)

Data Availability

All data supporting this contribution can be found in the Supplementary material.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Supplementary Materials

Supplementary 1. Supplementary Table 1: zircon U-Pb dating results of the Triassic granitoids.

Supplementary 2. Supplementary Table 2: monazite U-Pb dating results of the monzogranite and pegmatites from Dahongliutan pluton.

Supplementary 3. Supplementary Table 3: amphibolite compositions of the Dahongliutan diorite in the Tianshuihai terrane.

Supplementary 4. Supplementary Table 4: plagioclase compositions of the Dahongliutan diorite in the Tianshuihai terrane.

Supplementary 5. Supplementary Table 5: whole-rock major and trace element result the Triassic-Jurassic granitoids.
Supplementary 6. Supplementary Table 6: whole-rock Sr-Nd isotopic compositions of the Triassic granitoids.

Supplementary 7. Supplementary Table 7: zircon in situ Lu-Hf isotopic compositions of the Triassic granitoids.

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