Geophysical Research Letters

RESEARCH LETTER
10.1029/2021GL095192

Key Points:

- There is no record of a magmatic arc during oceanic basin closure in the Mazar-Kangxiwa suture zone between ca. 300–250 Ma
- This Paleo-Tethyan oceanic basin opened at ca. 340 Ma and closed by ca. 250 Ma
- Oceanic crust underthrusting was a potential mechanism to account for oceanic basin closure and the absence of a magmatic arc

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

G.-J. Tang,
tanggj@gig.ac.cn

Citation:

Tang, G.-J., Cawood, P. A., Wyman, D. A., Dan, W., Wang, Q., & Yang, Y.-N. (2021). The missing magmatic arc in a long-lived ocean from the western Kunlun- Pamir Paleo-Tethys Realm. *Geophysical Research Letters*, *48*, e2021GL095192. https://doi.org/10.1029/2021GL095192

Received 14 JUL 2021
Accepted 27 OCT 2021

Author Contributions:

Conceptualization: Gong-Jian Tang
Data curation: Gong-Jian Tang
Investigation: Gong-Jian Tang
Writing – original draft: Gong-Jian Tang
Writing – review & editing: Gong-Jian Tang, Peter A. Cawood, Derek A. Wyman, Wei Dan, Qiang Wang, Ya-Nan Yang

The Missing Magmatic Arc in a Long-Lived Ocean From the Western Kunlun- Pamir Paleo-Tethys Realm

Gong-Jian Tang[1,2], Peter A. Cawood[3], Derek A. Wyman[4], Wei Dan[1,2], Qiang Wang[1,2], and Ya-Nan Yang[1]

[1]State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China, [2]CAS Center for Excellence in Deep Earth Sciences, Guangzhou, China, [3]School of Earth, Atmosphere and Environment, Monash University, Melbourne, VIC, Australia, [4]School of Geosciences, Division of Geology and Geophysics, The University of Sydney, Sydney, NSW, Australia

Abstract The evolution of the western Kunlun-Pamir region involved the opening and closing of several branches of the Paleo-Tethys Ocean, although the specific timing of these events is poorly constrained. Here, we present a synthesis of sedimentary, magmatic, and metamorphic records associated from the Mazar-Kangxiwa suture zone in the western Kunlun-Pamir that is generally regarded as the main Paleo-Tethys Ocean suture. These data show that the Paleo-Tethyan oceanic basin opened at ca. 340 Ma and closed by ca. 250 Ma, and there is no record of a magmatic arc between ca. 300–250 Ma. The absence of a magmatic arc was a result of oceanic crust underthrusting, rather than oceanic subduction, which is consistent with a narrow back-arc basin. Our study provides an important example of how an oceanic basin opened and closed without oceanic subduction, and highlights a potential mechanism to account for the absence of a magmatic arc.

Plain Language Summary The closure of oceanic basins is generally believed to result from oceanic subduction associated with development of arc magmatism. However, there are no magmatic arcs associated with the closure of some oceanic basins in the Paleo-Tethys realm. In order to understand the detailed history of ocean basins in the Paleo-Tethys oceans, we carry out an integrated in situ analysis of zircon U-Pb age and Hf-O isotopes, along with whole-rock geochemistry for sedimentary, magmatic, and metamorphic records from the Mazar-Kangxiwa suture zone in the western Kunlun-Pamir that is widely regarded as the main Paleo-Tethys Ocean suture. Our data reveals that there is no record of a magmatic arc associated with Paleo-Tethys Ocean closure during the Permian (ca. 300–250 Ma). This Paleo-Tethyan oceanic basin was closed by oceanic crust underthrusting, rather than oceanic subduction. Thus, not all Paleo-Tethyan oceanic basins were closed by subduction with development of arc magmatism. We propose that widespread oceanic crust underthrusting accounts for the common absence of a magmatic arcs in oceanic basins of the Paleo-Tethys realm.

1. Introduction

Oceanic crust is created from the mantle at mid-ocean ridges and is recycled back into the mantle at subduction zones. Oceanic subduction provides a driving force for ocean closure, generally associated with development of arc magmatism and high pressure/low-temperature metamorphism (Grove et al., 2012; Stern, 2005). However, not all oceanic basins, especially narrow basins such as those in a back-arc region, are closed by oceanic subduction and therefore they can be devoid of arc magmatism. For example, some back-arc basins closed through underthrusting and/or obduction of oceanic crust (Klepeis et al., 2010; Maloney et al., 2011). In such cases, it can be difficult to fully understand the timing and style of closure of paleo-oceans based on the surviving rock record.

The Himalayan-Tibetan orogen is a huge composite terrain that records multiple subduction and collisional events. Its development was associated with the growth and consumption of a number of Tethys oceans along the southern margin of Asia during the Paleozoic–Mesozoic prior to the collision with India during the Cenozoic (e.g., Chung et al., 2005; Metcalfe, 2021; Yin & Harrison, 2000). The western Kunlun-Pamir lies at the northwestern end of the Himalayan-Tibetan Plateau, and its evolution involved the opening and closure of several branches of the Proto- and Paleo-Tethys Oceans as recorded by remnant oceanic and subduction-related fragments (Li, Robinson et al., 2020; Robinson, 2015; Robinson et al., 2012; Xiao et al., 2002; Yuan et al., 2002). Although numerous structural, geochronological and geochemical studies have been conducted throughout the western Kunlun-Pamir to constrain the Paleo-Tethys Ocean evolution within this region, several important questions remain in dispute: (a) the timing of opening and closing of Paleo-Tethys Ocean; (b) the identity of the main suture zone of the Paleo-Tethys Ocean; and (c) the nature of oceanic basin closure. Among the several suture zones of the Paleo-Tethyan Ocean in the western Kunlun-Pamir, the Mazar-Kangxiwa suture zone is the most important but remains poorly understood in terms of its formation. Numerous studies have argued that the Mazar-Kangxiwa suture zone represents the main closure boundary of the Paleo-Tethyan Ocean, which extends to the Tanymas suture in northern Pamir (Li, Robinson et al., 2020; Robinson, 2015; Robinson et al., 2012; Xiao et al., 2002; Yang et al., 2010). However, other researchers have argued that the Mazar-Kangxiwa suture zone represents the remnants of the Proto-Tethyan Ocean rather than Paleo-Tethyan Ocean (Xu et al., 2005; Yuan et al., 2002). The disparate interpretations have significant implications for the fundamental geodynamic processes that drove tectonic evolution of Paleo-Tethys Ocean, and the correlation and continuity of suture zones and tectonic terranes between the Pamir and Tibetan Plateau (Robinson et al., 2012). Here, we present a synthesis of sedimentary, magmatic, metamorphic records associated with the Mazar-Kangxiwa suture zone and show that there is a magmatic gap in the process of Paleo-Tethys Ocean closure during the Permian (ca. 300–250 Ma). On the basis of these data, we discuss the timing of initiation and closure, along with associated processes, for the Paleo-Tethys Ocean in the western Kunlun-Pamir, and then propose a potential explanation for the missing record of a magmatic arc.

2. Geological Background and Samples

The western Kunlun-Pamir forms a high plateau, geographically, bound to the west by the Tajik Basin, to the north by the Alai Basin and Tarim Basin, to the south by the Wakhan Corridor and Karakoram Mountains, and to the east by the left-slip Altyn Tagh fault (Figure 1a). The west Kunlun section is subdivided from north to south by the Kudi, Mazar-Kangxiwa, and Dahongliutan- Guozha Co suture zones into the northern Kunlun, southern Kunlun, Songpan-Ganzi-Hoxil, and Tianshuihai terranes, respectively (Matte et al., 1996; Xiao et al., 2002) (Figure 1b). The Kudi suture zone represents the remnants of the Proto-Tethyan Ocean that subducted southward beneath the westeren Kunlun-Pamir and closed at ca. 440 Ma (Yin et al., 2020; Yuan et al., 2002; Zhang et al., 2018). The Qiaoertianshan suture zone is probabaly the western extension of the Longmu Co-Shuanghu suture zone, and represents the remnants of the main Paleo-Tethyan Ocean (Metcalfe, 2021), and the Mazar-Kangxiwa and Dahongliutan- Guozha sutures zones represent the remnants of the back-arc basins within the Paleo-Tethyan Ocean. All of the western Kunlun terranes are intruded by Paleozoic and Mesozoic igneous rocks (Figure 1b). The Pamir terrane is divided from north to south by the Tanymas and Rushan-Pshart suture zones into the Northern Pamir, Central Pamir, and Southern Pamir, respectively (Burtman & Molnar, 1993). Northern Pamir is bound by the Main Pamir thrust in the north and the Tanymas suture in the south. It includes the Darvaz-Oytag-Kunlun terrane in the north and the Karakul-Mazar terrane in the south. Central Pamir comprises Paleozoic–Jurassic platform rocks (Burtman & Molnar, 1993; Modzalevskaya et al., 2017). The Southern Pamir and Karakoram terranes are separated by the Wakhan-Tirich Boundary Zone but are generally interpreted to be continuous (Zanchi et al., 2000) and consist of Paleozoic–Mesozoic metasedimentary rock and Cretaceous-Cenozoic granitoids (Chapman et al., 2018; Robinson et al., 2012; Schmidt et al., 2011).

There is an extensive Carboniferous magmatic belt, from Davaz to Oytage in the Darvaz-Oytag-Kunlun terrane, and to Taxkorgan and Waqia within the Mazar-Kangxiwa suture zone. It includes basalt, gabbro and dolerite and coeval tonalite and trondhjemite granitoids (Figure S1 in Supporting Information S1). A granulite and gneiss facies metamorphic belt dominated by garnet-biotite gneiss and garnet-amphibole gneiss has been recognized in the Mazar-Kangxiwa suture zone (Liu et al., 2013; Yang et al., 2010) (Figure S1 in Supporting Information S1). Furthermore, many Triassic garnet-bearing leucogranite dikes intrude into the high-grade metamorphic belt and an early Paleozoic granite pluton in the Mazar-Kangxiwa suture zone (Figure S1 in Supporting Information S1). Representative samples were collected from the western Kunlun-Pamir for zircon U-Pb dating and Hf-O isotopes and whole-rock geochemical analyses. Analytical methods and results are included in Supporting Information S1. Whole-rock geochemical and zircon

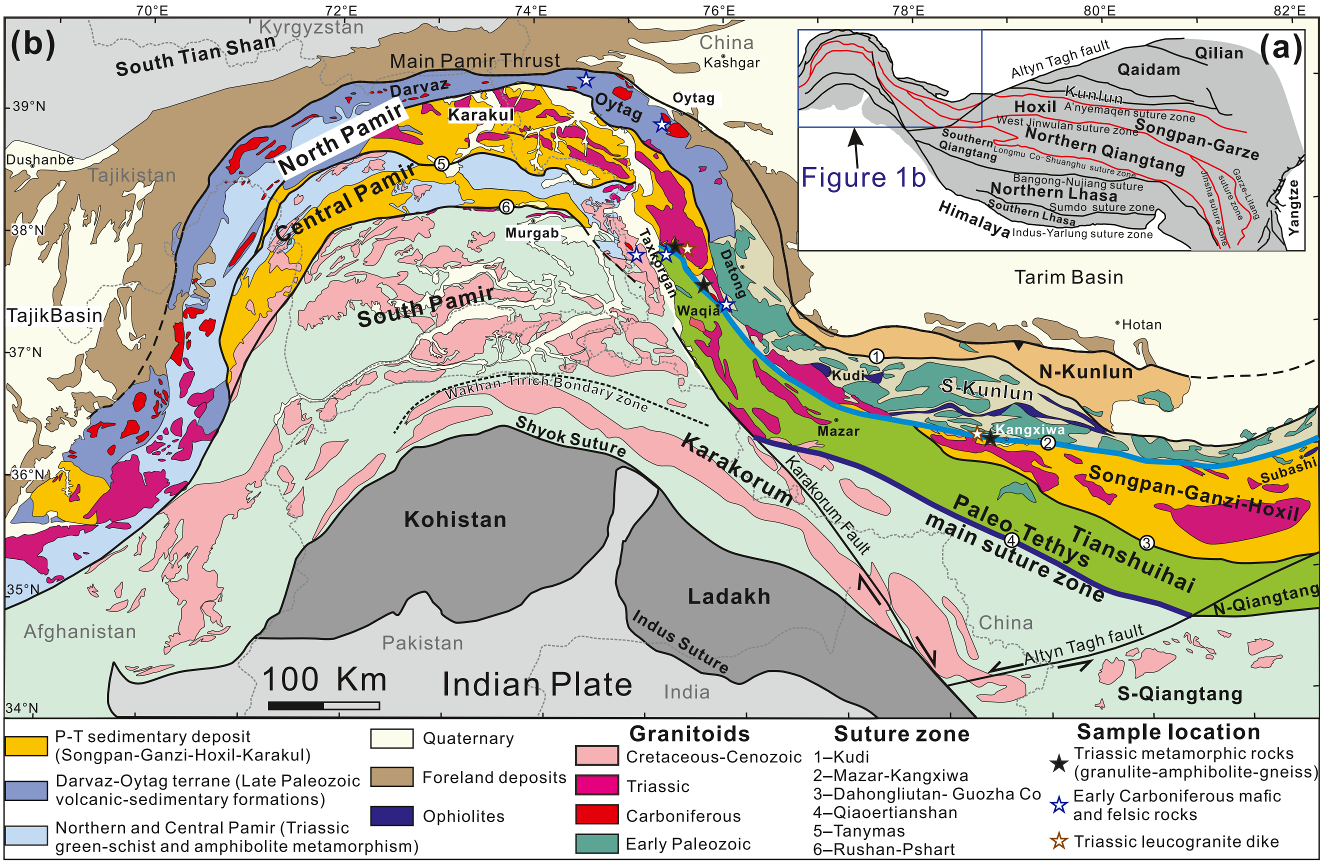

Figure 1. (a) Tectonic sketch map of Tibetan Plateau showing the major suture boundaries and tectonic fragments, and the red sutures represent Paleo-Tethys Ocean remnants. (b) Simplified geologic map of the western Kunlun-Pamir.

Hf isotopic data for the Carboniferous igneous rocks and Triassic metamorphic rocks are shown in Figure 2. Magmatic, metamorphic and sedimentary records in the western Kunlun-Pamir are summarized in Figure 3.

3. From Opening to Closure of the Paleo-Tethyan Oceanic Basin

There are three magmatic episodes in the region of the Mazar-Kangxiwa suture that range from the Cambrian to the end Triassic (Figure 3). The oldest (ca. 530–400 Ma) and youngest Triassic magmatic episodes are distributed in the western Kunlun and northern–central Pamir terranes (Figure 1b). The former is related to southward subduction of the Proto-Tethys Ocean and subsequent collisional events (Yin et al., 2020), whereras Triassic I- and S-type granitoids are interpreted to have formed in collisional or post-collisonal setting after Paleo-Tethyan Ocean closure (Yang et al., 2010). We focus on the Early Carboniferous magmatic episode from the northern Pamir to the Mazar-Kangxiwa suture zone, which, as noted, includes basalt, gabbro and dolerite and felsic rocks of tonalite and trondhjemite that occur as large plutons and dikes. Zircon U-Pb dating results indicate these rocks were formed in the Early Carboniferous during 340–320 Ma (Figure S1 in Supporting Information S1; Jiang et al., 2008; Tang et al., 2020). Whole-rock elemental geochemical data show that both mafic and felsic rocks have flat chondrite-normalized rare earth element (REE) patterns with negligible Eu anomalies (Figure 2c). On a N-MORB-normalized multi-element diagram, both the mafic and felsic samples show negative or no Nb, Ta and Ti anomalies (Figure 2d). In addition, both the mafic and felsic samples have depleted zircon Hf isotope compositions with $\varepsilon_{Hf}(t)$ values ranging from +14.4 to +16.7, and from +13.8 to +17.5, respectively (Figure 2b). Elemental and isotopic data suggest that these felsic rocks were produced by fractional crystallization of mafic melts at shallow depth (Figure 2c and Figure S3 in Supporting Information S1). A previous study suggested that the Northern Pamir tonalite

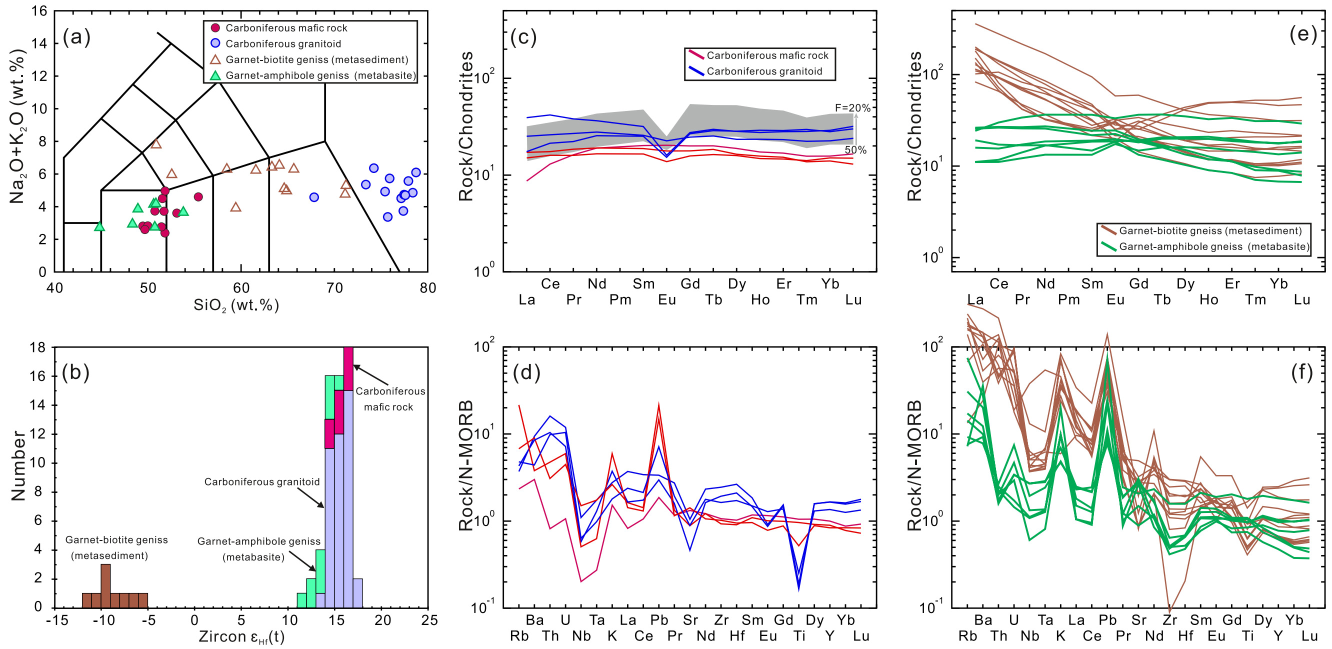

Figure 2. Whole-rock geochemical characteristics of representative samples. (a) Total alkalis vs SiO_2 (TAS) diagram (Le Maitre, 2002). (b) Zircon $\varepsilon_{Hf}(t)$ histogram (c–f) Chondrite- and N-MORB-normalized (Sun & McDonough, 1989) REE and trace element variation diagrams. In (c), fractional crystallisation of a mafic rock is shown for comparision. Mineral proportions of crystallization and partitioning coefficients are from Marien et al., (2019).

and trondhjemite formed in an oceanic island arc setting (Jiang et al., 2008), as evidenced by occurrence of similar felsic rocks in some intra-oceanic arcs, such as Izu–Bonin–Mariana (IBM) arc (Johnson et al., 2014). However, the volume of felsic rocks in intra-oceanic arcs is limited and similar to the volumes of plagiogranite in ophiolite, in contrast to the large volume of Northern Pamir tonalite and trondhjemite (ca. 1,000 km^2). In addition, there are no associated subduction-related rocks in the Northern Pamir, such as fore-arc basalt, boninite, or high-Mg andesite for intra-oceanic arcs (Ishizuka et al., 2014). No other older rift-related magmatism besides the Early Carboniferous rocks occur in the Mazar-Kangxiwa suture zone. Thus, these Carboniferous MORB-BABB (backarc basin basalt)-like mafic rocks and oceanic plagiogranite-like felsic rocks indicate opening of the Mazar-Kangxiwa suture zone-related oceanic basin starting at ca. 340 Ma. These data argue that the Mazar-Kangxiwa suture zone cannot be a remnant of the Proto-Tethyan Ocean since that ocean basin closed by ca. 440 Ma (Zhang et al., 2018).

In order to constrain the time of oceanic basin closure, zircon grains from garnet-plagioclase gneiss in the Mazar-Kangxiwa suture zone from Kangxiwa were selected for zircon U-Pb dating and Hf-O isotope analyses. Zircons yield apparent $^{206}Pb/^{238}U$ ages ranging from 511.3 ± 7.5 Ma to 185 ± 2.9 Ma (Figure 3), along with a few Precambrian ages. These zircon domains were divided into four groups based on CL imaging, U-Pb ages and Th/U ratios (Figure 3 and Figure S2 in Supporting Information S1). Group I and II domains have Cambrian-Devonian and Carboniferous apparent $^{206}Pb/^{238}U$ ages, respectively (Figure 3a). These two domains generally have clear oscillatory zoning showing light luminescence, and high Th/U ratios, indicating they are igneous grains. Their ages are broadly similar to the western Kunlun-Pamir Cambrian to Carboniferous magma age distribution, and this likely constitutes the source for these zircons. The Group III zircon domains yield apparent $^{206}Pb/^{238}U$ ages ranging from 255.4 ± 3.8 Ma to 225.9 ± 2.3 Ma, with Th/U ratios of 0.05–0.59. They are characterized by overgrowth rims around Group I and II domains and appear gray with patchy zoning in CL imaging, indicating that they are associated with anatectic melts (Xu et al., 2005). This Late Permian to Late Triassic anatectic event likely occurred during collisional or post-collisional tectonism after the oceanic basin closure (Zi et al., 2013). This interpretation is consistent with the presence of Triassic I- and S-type granitoids within the western Kunlun-Pamir, some of which intruded into the suture zone (Figure 1b), indicating that they formed after oceanic basin closure. Furthermore, the hypothesized post-basin closure Early Triassic anatectic event is also supported by the intrusion of the Triassic garnet-bearing leucogranite dikes into the Kangxiwa high-grade metamorphic gneiss and the early

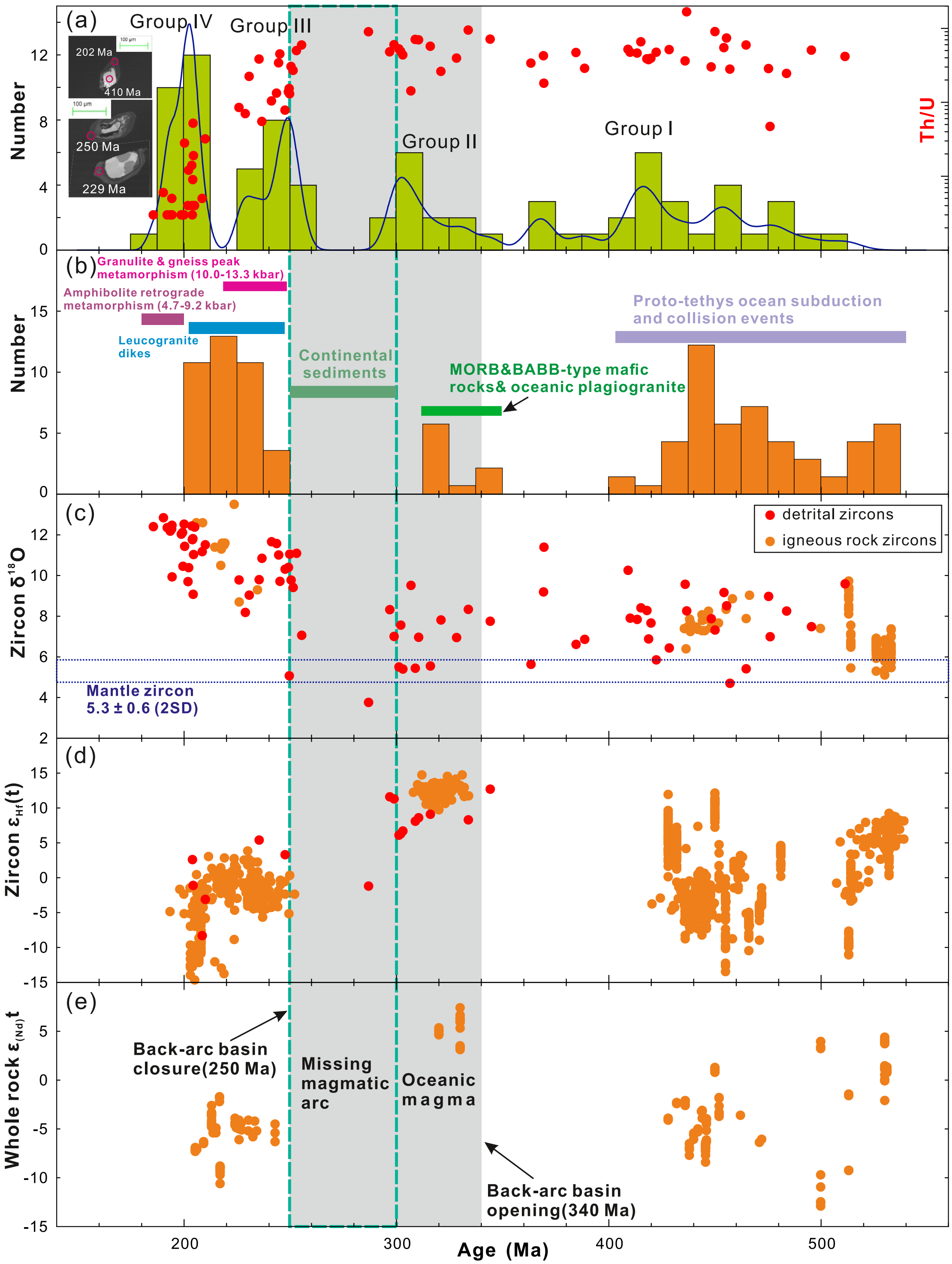

Figure 3. (a) Age distribution and Th/U ratios of zircons from the Kangxiwa gneiss, showing representative zircon CL images. (b) Age distribution of the igneous rocks from the western Kunlun-Pamir, showing time durations and conditions of metamorphism (c, d) Zircon $\varepsilon_{Hf}(t)$ and $\delta^{18}O$ values vs. age diagrams. (e) Whole-rock $\varepsilon_{Nd}(t)$ values vs. age diagram for igneous rocks.

Paleozoic Datong granite pluton in the Mazar-Kangxiwa suture zone (Figure S1 in Supporting Information S1), both of which were produced by melting of metasedimentary rocks during prograde metamorphism under granulite facies. The zircon grains from two leucogranite dikes yield concordia ages of 221.4 ± 1.2 Ma and 247.0 ± 1.9 Ma, which are consistent with Triassic granitoids ages (Figure S2 in Supporting Information S1). These zircon domains are overgrowth rims around early Paleozoic cores that appeared dark in CL images (Figure 3). In addition, zircon U-Pb dating suggested that high pressure granulites in the Mazar-Kangxiwa suture zone underwent peak metamorphism between 250 Ma and 220 Ma (Figure 3) (Yang et al., 2010). In summary, the sedimentary, metamorphic and magmatic records indicate that the Paleo-Tethyan oceanic basin in the Mazar-Kangxiwa suture zone was closed by ca. 250 Ma.

The Group IV zircon domains yield apparent $^{206}Pb/^{238}U$ ages ranging from 210.0 ± 3.3 Ma to 185.6 ± 2.9 Ma, with low Th/U ratios of 0.003–0.05 (Figure 2a and Figure S2 in Supporting Information S1). They are also characterized by overgrowth rims around Group I and II domains with low luminescence. The Group IV zircon ages overlap with U-Pb geochronology ages of metamorphic zircons from the garnet gneiss in the Mazar-Kangxiwa suture zone, which yield apparent $^{206}Pb/^{238}U$ ages ranging from 200.5 ± 3.2 Ma to 173.6.0 ± 3.3 Ma with a concordia age of 182.5 ± 2.7 Ma (Figure S2 in Supporting Information S1), and both zircon populations show flat HREE patterns with low HREE contents (Figure S4 in Supporting Information S1). It is worth noting the Group IV zircon have no Eu anomalies, reflecting that plagioclase was not stable during their formation. Thus, the Group IV zircon ages are thus interpreted as the time of peak metamorphism or the early stage of retrograde metamorphism during post-collisional extension.

4. Missing Record of a Magmatic Arc

The Paleo-Tethyan oceanic basin in the Mazar-Kangxiwa suture zone opened at ca. 340 Ma and closed at ca. 250 Ma (Figure 3). However, there is no record of a magmatic arc between ca. 300 to 250 Ma in the western-Kunlun-Pamir (Figure 3). In addition, zircon populations in garnet-plagioclase gneiss in the Mazar-Kangxiwa suture zone also lack magmatic zircon populations for this time interval. The absence of any field evidence of Late Carboniferous and Permian magmatism in the western-Kunlun-Pamir may result from erosion events and thus a lack of preservation of volcanic and intrusive edifices. The volcanic and intrusive products of magmatic arcs, however, are rapidly remobilized and redeposited in nearby basins (Cawood et al., 2012), which is in contrast to the lack of detrital magmatic zircons record in this case. In oceanic-continental subduction zones, if the continental lithosphere has a thickness of 150 km, the asthenospheric mantle is encountered by subducting oceanic slabs at sub-arc depths of ≥150 km. As such, only ca. 200 km of ocean basin crust was needed to subduct at a slab dip angle of 60° to generate subduction zone magmatism (Grove et al., 2012). Thus, the Paleo-Tethyan oceanic basin in the Mazar-Kangxiwa suture zone was likely to have been a narrow back-arc basin in order to account for the missing record of a magmatic arc.

Several hypotheses have been proposed to explain the lack of magmatism during oceanic subduction including "dry" lithospheric slab, flat-slab and spreading ridge subduction. McCarthy et al., (2018) proposed that the lack of magmatism in the Alps during subduction was induced by subduction of a "dry" lithospheric slab, where exposed oceanic remnants composed of oceanic sediments, trench deposits (flysch), serpentinite, sparse gabbro and basalt, and continental fragments were mainly isolated in an unsubducted orogenic wedge. Within the Alpine domain, the inefficient deep subduction of hydrous rocks may explain the absence of arc magmatism. Alpine high-pressure rocks reached >25 kbar in the process of deep subduction of the "dry" lithospheric slab during the arc gap (McCarthy et al., 2018). In contrast, there are no hydrous serpentinites and blueschist-to eclogite-facies rocks in the Mazar-Kangxiwa suture zone. Moreover, thermobarometric studies show that the granulite and gneiss only reached <13.3 kbar after the magmatic gap (Figure 3) and therefore, these metamorphic rocks only reached lower crustal depth after oceanic basin closure. In addition, there is no metamorphic record synchronous with the timing of oceanic basin closure. Consequently, the absence of Permian magmatic arc in the western-Kunlun-Pamir is unlikely to result from the subduction of a "dry" lithospheric slab.

Flat-slab subduction processes, where the descending slab approaches the horizontal at some depth, is common in Andean type subduction zones (Gutscher et al., 2000; Huangfu et al., 2016; Li & Li, 2007). In this scenario, subduction of the flattened slab would gradually exclude the asthenospheric mantle wedge, which sufficiently cools the thermal structure of the subduction zone, leading to a magmatic gap or the migration of arc magmatism away from the trench (Axen et al., 2018; Cawood et al., 2009; DeCelles et al., 2009; Gutscher et al., 2000). It should be noted that the narrow back-arc basin could have only resulted in a few million years of subduction, and initial subduction is likely to have been fairly shallow. Thus, there exists a possibility that the magmatic gap resulted from transient flat-slab subduction (Schellart & Strak, 2021), although in some cases of tens of million years of flat-slab subduction have been documented (DeCelles et al., 2009; Wu et al., 2015). Subduction of a spreading ridge would produce a "slab window", which is the gap between the subducted parts of the diverging oceanic plates mid-ocean spreading ridge subduction (Thorkelson, 1996). The "blowtorch effect" (DeLong et al., 1979) resulting from the upwelling of asthenospheric mantle through the slab window can generate a wide variety of magmatic rocks (Sisson et al., 2003; Tang et al., 2012). It is noteworthy, however, that a magmatic gap is probabaly formed above slab window when no more oceanic sediments/lithosphere are available to dehydrate and thus asthenosphere is too dry to produce magma (Sisson et al., 2003), as occurred on the NE Asian margin during the Paleocene (Liu, Zhang et al., 2020) and the Chile Triple Junction in the Patagonian Andes during the Cenozoic (Ramos, 2005). There is no record in the vicinity of the Mazar-Kangxiwa suture zone for magmatic arc migration that would be predicted for flat-slab subduction, and no evidence for ridge subduction or its typical magmatic rocks. In addition, flat subducted slab should return to a normal subduction angle after a few million years of subduction, and the resultant incursion of asthenosphere into the mantle wedge could promote a magma flare-up (DeCelles et al., 2009). Most importantly, both flat-slab subduction and ridge subduction models can only account for transient or local magma gaps, which are inconsistent with the missing magmatic arc over the life span of oceanic basin closure across the Mazar-Kangxiwa suture zone (ca. 300–250 Ma).

5. A Long-Lived Oceanic Basin Closed by Underthrusting

Oceanic basins, including back-arc basins, are generally closed via oceanic subduction (Cowgill et al., 2016; Wang et al., 2018), which generates arc magmatism and high pressure and low-temperature metamorphism (Grove et al., 2012). However, these characteristics are inconsistent with the missing record of a Permian magmatic arc and related metamorphism in the western-Kunlun-Pamir. In order to resolve these discrepancies, we propose that the Paleo-Tethyan oceanic basin in the Mazar-Kangxiwa suture zone was closed by underthrusting of oceanic crust, rather than oceanic subduction (Figure 4). Underthrusting of oceanic crust is supported by whole-rock elemental and isotopic data (Figure 2). For example, the garnet-amphibole gneiss mainly displays flat chondrites-normalized REE patterns without Eu anomalies and, on a

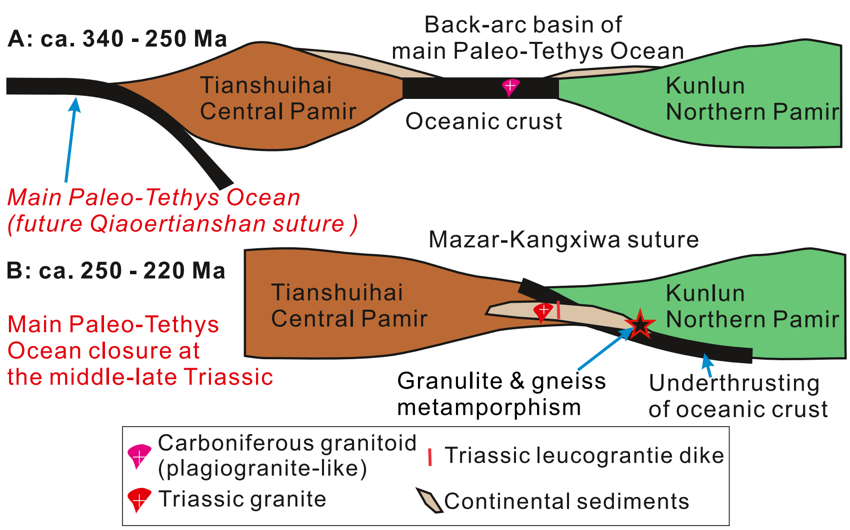

Figure 4. Cartoon summarizing Carboniferous to Triassic evolution of Mazar-Kangxiwa back-arc basin. (a) 340–250 Ma: opening the Paleo-Tethyan oceanic basin of the Mazar-Kangxiwa suture zone at ca. 340 Ma. There is no record of a magmatic arc between 300 Ma and 250 Ma, and the oceanic basin was closed by ca. 250 Ma. (b) 250–220 Ma: the back-arc basin was closed by oceanic crust underthrusting.

N-MORB-normalized multi-element diagram, they show negligible Nb, Ta and Ti anomalies. In addition, they have depleted zircon Hf isotopic compositions with $\varepsilon_{Hf}(t)$ values ranging from +11.3 to +15.7. Thus, these metabasites are geochemically broadly similar to the Early Carboniferous mafic rocks, suggesting that their protolith was a fragment of the Paleo-Tethyan oceanic crust in the Mazar-Kangxiwa suture zone. Furthermore, zircon U-Pb dating and thermobarometric studies show that the metabasites and metasedimentary rocks experienced granulite facies peak metamorphism under 13.3–10.0 kbar between ca. 250–220 Ma and subsequent amphibolite facies retrograde meta morphism at 9.2–4.7 kbar between ca. 200–180 Ma (Figure 3). These thermobarometric results indicate that the oceanic crust and continental materials were only underthrust to lower crustal depths. Therefore, underthrusting of oceanic crust without oceanic subduction best resolves the issue of oceanic closure and a missing magmatic arc.

Only a few narrow back-arc basins are recognized to have closed through oceanic crust underthrusting rather than oceanic subduction. Some of best documented examples are the Jurassic-Cretaceous back-arc basins along the western South American margin (Klepeis et al., 2010; Maloney et al., 2011). They were formed by large trench retreat events where rollback of the slab is greatest close to lateral slab edges (Schellart et al., 2007). Among these, the Rocas Verdes back-arc basin in southernmost South America was closed due to the relative motion of a microplate against the South American Plate (Eagles, 2016). There was no consumption of oceanic crust by subduction, but continental underthrusting and obduction of basaltic crust occurred during closure of the back-arc basin (Klepeis et al., 2010). Continental crust was underthrust beneath lower crust and experienced metamorphism at 12–9 kbar that was followed by thrusting-controlled exhumation at 9–6 kbar induced by continental collision related to closure of the back-arc basin (Maloney et al., 2011). These metamorphic conditions are broadly similar to the Triassic metamorphic complex in the Mazar-Kangxiwa suture zone. Thus, the sedimentary, magmatic, metamorphic records associated with the Mazar-Kangxiwa suture zone show that the absence of a magmatic arc can be attributed to the occurrence of oceanic crust underthrusting rather than oceanic subduction (Figure 4). It is important to note that the back-arc oceanic basin in the Mazar-Kangxiwa suture zone was long-lived from ca. 340 Ma to 250 Ma, but the initial spreading and final convergence phases of the basins were likely to be transient lasting for only a few million years because of its narrow width. For example, a spreading rate of 5 cm per year will close a 500 km wide ocean basin in 10 million years.

This oceanic crust underthrust model further supports the possibility that the Paleo-Tethyan oceanic basin, in the Mazar-Kangxiwa suture zone, was a narrow back-arc basin, one of a series that was developed during subduction of the main Paleo-Tethyan Ocean (Metcalfe, 2021; Wang et al., 2018). The Longmu Co-Shuanghu suture zone, to the south of the Mazar-Kangxiwa suture zone (Figure 1a), has generally been regarded as the remnants of the main Paleo-Tethyan Ocean in Tibet (Li et al., 2006). Previous studies constrained the timing of subduction initiation to the late Devonian and continental collision to the middle-late Triassic (Dan et al., 2018; Zhai et al., 2018). Thus, the opening time of the Mazar-Kangxiwa back-arc basin is younger than that of subduction initiation for the main Paleo-Tethyan Ocean, but the closure time is older than that of the main ocean. Therefore, the life cycle of the basin in entirely consistent with an origin linked to subduction of the main Paleo-Tethyan Ocean.

6. Conclusions

1. A belt of Early Carboniferous magmatic rocks that extends from the northern Pamir to the Mazar-Kangxiwa suture zone, includes basalt, gabbro and dolerite mafic rocks, and tonalite and trondhjemite as large plutons or dikes. Their formation is attributed to opening of a Paleo-Tethyan oceanic basin at ca. 340 Ma.
2. Sedimentary, metamorphic and magmatic records indicate that the Paleo-Tethyan oceanic basin of the Mazar-Kangxiwa suture zone was closed by ca. 250 Ma.
3. There is no record of a magmatic arc associated with Paleo-Tethyan oceanic basin closure preserved in the suture zone between ca. 300–250 Ma.
4. The absence of a magmatic arc linked to the Mazar-Kangxiwa back-arc basin is a result of oceanic crust underthrusting, rather than oceanic subduction. The opening and closing of the Mazar-Kangxiwa back-arc basin were probably related to subduction of the main Paleo-Tethyan Ocean, which lay to the south.

Data Availability Statement

Supporting data are provided in Texts S1, S2, Figures S1–S3 and Tables S1–S4 in Supporting Information S1, which can be found at website https://figshare.com/s/6db2bfb4d2dda597795d.

Acknowledgments
We thank Editor-in-Chief Valerie Trouet, Kai Liu, and two anonymous reviewers for their constructive and helpful reviews on the manuscript. This study was supported by the National Natural Science Foundation of China (grants 41722205 and 41673033), the Second Tibetan Plateau Scientific Expedition and Research Program (STEP) (2019QZKK0702), and the Australian Research Council (grant FL160100168). This is contribution XXX from GIG-CAS.

References

Axen, G. J., van Wijk, J. W., & Currie, C. A. (2018). Basal continental mantle lithosphere displaced by flat-slab subduction. *Nature Geoscience*, *11*(12), 961–964. https://doi.org/10.1038/s41561-018-0263-9

Burtman, V. S., & Molnar, P. (1993). Geological and geophysical evidence for deep subduction of continental crust beneath the Pamir. *Geological Society of America Special Paper*, *281*, 1–76. https://doi.org/10.1130/SPE281-p1

Cawood, P. A., Hawkesworth, C. J., & Dhuime, B. (2012). Detrital zircon record and tectonic setting. *Geology*, *40*(10), 875–878. https://doi.org/10.1130/g32945.1

Cawood, P. A., Kroner, A., Collins, W. J., Kusky, T. M., Mooney, W. D., & Windley, B. F. (2009). Accretionary orogens through Earth history. *Geological Society, London, Special Publications*, *318*(1), 1–36. https://doi.org/10.1144/sp318.1

Chapman, J. B., Scoggin, S. H., Kapp, P., Carrapa, B., Ducea, M. N., Worthington, J., et al. (2018). Mesozoic to Cenozoic magmatic history of the Pamir. *Earth and Planetary Science Letters*, *482*, 181–192. https://doi.org/10.1016/j.epsl.2017.10.041

Chung, S. L., Chu, M. F., Zhang, Y. Q., Xie, Y. W., Lo, C. H., Lee, T. Y., et al. (2005). Tibetan tectonic evolution inferred from spatial and temporal variations in post-collisional magmatism. *Earth-Science Reviews*, *68*(3–4), 173–196. https://doi.org/10.1016/j.earscirev.2004.05.001

Cowgill, E., Forte, A. M., Niemi, N., Avdeev, B., Tye, A., Trexler, C., et al. (2016). Relict basin closure and crustal shortening budgets during continental collision: An example from Caucasus sediment provenance. *Tectonics*, *35*(12), 2918–2947. https://doi.org/10.1002/2016TC004295

Dan, W., Wang, Q., White, W. M., Zhang, X.-Z., Tang, G.-J., Jiang, Z.-Q., et al. (2018). Rapid formation of eclogites during a nearly closed ocean: Revisiting the Pianshishan eclogite in Qiangtang, central Tibetan Plateau. *Chemical Geology*, *477*, 112–122. https://doi.org/10.1016/j.chemgeo.2017.12.012

DeCelles, P. G., Ducea, M. N., Kapp, P., & Zandt, G. (2009). Cyclicity in Cordilleran orogenic systems. *Nature Geoscience*, *2*(4), 251–257. https://doi.org/10.1038/ngeo469

DeLong, S. E., Schwarz, W. M., & Anderson, R. N. (1979). Thermal effects of ridge subduction. *Earth and Planetary Science Letters*, *44*(2), 239–246. https://doi.org/10.1016/0012-821X(79)90172-9

Eagles, G. (2016). Plate kinematics of the Rocas Verdes Basin and Patagonian orocline. *Gondwana Research*, *37*, 98–109. https://doi.org/10.1016/j.gr.2016.05.015

Grove, T. L., Till, C. B., & Krawczynski, M. J. (2012). The role of H_2O in subduction zone magmatism. *Annual Review of Earth and Planetary Sciences*, *40*, 413–439. https://doi.org/10.1146/annurev-earth-042711-105310

Gutscher, M. A., Maury, R., Eissen, J. P., & Bourdon, E. (2000). Can slab melting be caused by flat subduction? *Geology*, *28*(6), 535–538. https://doi.org/10.1130/0091-7613(2000)028<0535:csmbcb>2.3.co;2

Huangfu, P., Wang, Y., Cawood, P. A., Li, Z.-H., Fan, W., & Gerya, T. V. (2016). Thermo-mechanical controls of flat subduction: Insights from numerical modeling. *Gondwana Research*, *40*, 170–183. https://doi.org/10.1016/j.gr.2016.08.012

Ishizuka, O., Tani, K., & Reagan, M. K. (2014). Izu-Bonin-Mariana forearc crust as a modern ophiolite analogue. *Elements*, *10*(2), 115–120. https://doi.org/10.2113/gselements.10.2.115

Jiang, Y.-H., Liao, S.-Y., Yang, W.-Z., & Shen, W.-Z. (2008). An island arc origin of plagiogranites at Oytag, western Kunlun orogen, northwest China: SHRIMP zircon U–Pb chronology, elemental and Sr–Nd–Hf isotopic geochemistry and Paleozoic tectonic implications. *Lithos*, *106*(3), 323–335. https://doi.org/10.1016/j.lithos.2008.08.004

Johnson, J. A., Hickey-Vargas, R., Fryer, P., Salters, V., & Reagan, M. K. (2014). Geochemical and isotopic study of a plutonic suite and related early volcanic sequences in the southern Mariana forearc. *Geochemistry, Geophysics, Geosystems*, *15*(3), 589–604. https://doi.org/10.1002/2013GC005053

Klepeis, K., Betka, P., Clarke, G., Fanning, M., Hervé, F., Rojas, L., et al. (2010). Continental underthrusting and obduction during the Cretaceous closure of the Rocas Verdes rift basin, Cordillera Darwin, Patagonian Andes. *Tectonics*, *29*(3), TC3014. https://doi.org/10.1029/2009TC002610

Le Maitre, R. W. (2002). *Igneous rocks: A classification and glossary of terms: Recommendations of the International union of geological sciences subcommission on the systematics of igneous rocks* (2 ed.). Cambridge University Press.

Li, C., Zhai, Q., Dong, Y., & Huang, X. (2006). Discovery of eclogite and its geological significance in Qiangtang area, central Tibet. *Chinese Science Bulletin*, *51*(9), 1095–1100. https://doi.org/10.1007/s11434-006-1095-3

Li, Y.-P., Robinson, A. C., Gadoev, M., & Oimuhammadzoda, I. (2020). Was the Pamir salient built along a Late Paleozoic embayment on the southern Asian margin? *Earth and Planetary Science Letters*, *550*, 116554. https://doi.org/10.1016/j.epsl.2020.116554

Li, Z.-X., & Li, X.-H. (2007). Formation of the 1300-km-wide intracontinental orogen and postorogenic magmatic province in Mesozoic South China: A flat-slab subduction model. *Geology*, *35*(2), 179–182. https://doi.org/10.1130/g23193a.1

Liu, K., Zhang, J., Xiao, W., Wilde, S. A., & Alexandrov, I. (2020). A review of magmatism and deformation history along the NE Asian margin from ca. 95 to 30 Ma: Transition from the Izanagi to Pacific plate subduction in the early Cenozoic. *Earth-Science Reviews*, *209*, 103317. https://doi.org/10.1016/j.earscirev.2020.103317

Liu, W., Wang, H., Tong, L., Wu, Y., Huang, C., & Hu, J. (2013). Geochemical characteristics and metamorphic P-T paths of the Bulunkuole Group in Taxkorgan, western Kunlun. *Acta Petrologica Sinica*, *29*(3), 923–937.

Maloney, K. T., Clarke, G. L., Klepeis, K. A., Fanning, C. M., & Wang, W. (2011). Crustal growth during back-arc closure: Cretaceous exhumation history of Cordillera Darwin, southern Patagonia. *Journal of Metamorphic Geology*, *29*(6), 649–672. https://doi.org/10.1111/j.1525-1314.2011.00934.x

Marien, C. S., Hoffmann, J. E., Garbe-Schönberg, C. D., & Münker, C. (2019). Petrogenesis of plagiogranites from the Troodos Ophiolite Complex, Cyprus. *Contributions to Mineralogy and Petrology*, *174*(4), 35. https://doi.org/10.1007/s00410-019-1569-3

Matte, P., Tapponnier, P., Arnaud, N., Bourjot, L., Avouac, J. P., Vidal, P., et al. (1996). Tectonics of Western Tibet, between the Tarim and the Indus. *Earth and Planetary Science Letters*, *142*(3), 311–330. https://doi.org/10.1016/0012-821X(96)00086-6

McCarthy, A., Chelle-Michou, C., Müntener, O., Arculus, R., & Blundy, J. (2018). Subduction initiation without magmatism: The case of the missing Alpine magmatic arc. *Geology*, *46*(12), 1059–1062. https://doi.org/10.1130/g45366.1

Metcalfe, I. (2021). Multiple Tethyan ocean basins and orogenic belts in Asia. *Gondwana Research*. https://doi.org/10.1016/j.gr.2021.01.012
Modzalevskaya, T. L., Popov, L. E., Ghobadi Pour, M., & Dufour, M. S. (2017). First report on the Early Devonian (Lochkovian) brachiopods from eastern Central Pamirs, Tajikistan. *Journal of Asian Earth Sciences*, *138*, 427–438. https://doi.org/10.1016/j.jseaes.2017.02.030
Ramos, V. A. (2005). Seismic ridge subduction and topography: Foreland deformation in the Patagonian Andes. *Tectonophysics*, *399*(1), 73–86. https://doi.org/10.1016/j.tecto.2004.12.016
Robinson, A. C. (2015). Mesozoic tectonics of the Gondwanan terranes of the Pamir plateau. *Journal of Asian Earth Sciences*, *102*, 170–179. https://doi.org/10.1016/j.jseaes.2014.09.012
Robinson, A. C., Ducea, M., & Lapen, T. J. (2012). Detrital zircon and isotopic constraints on the crustal architecture and tectonic evolution of the northeastern Pamir. *Tectonics*, *31*(2), TC2016. https://doi.org/10.1029/2011TC003013
Schellart, W. P., Freeman, J., Stegman, D. R., Moresi, L., & May, D. (2007). Evolution and diversity of subduction zones controlled by slab width. *Nature*, *446*(7133), 308–311. https://doi.org/10.1038/nature05615
Schellart, W. P., & Strak, V. (2021). Geodynamic models of short-lived, long-lived and periodic flat slab subduction. *Geophysical Journal International*, *226*(3), 1517–1541. https://doi.org/10.1093/gji/ggab126
Schmidt, J., Hacker, B. R., Ratschbacher, L., Stübner, K., Stearns, M., Kylander-Clark, A., et al. (2011). Cenozoic deep crust in the Pamir. *Earth and Planetary Science Letters*, *312*(3–4), 411–421. https://doi.org/10.1016/j.epsl.2011.10.034
Sisson, V. B., Pavlis, T. L., Roeske, S. M., & Thorkelson, D. J. (2003). Introduction: An overview of ridge-trench interactions in modern and ancient settings. In V. B. Sisson, T. L. Pavlis, S. M. Roeske, & D. J. Thorkelson (Eds.), *Geology of a transpressional orogen developed during ridge-trench interaction along the North Pacific margin* (pp. 1–18). Geological Society of America.Special Paper. https://doi.org/10.1130/0-8137-2371-X.1
Stern, R. J. (2005). Evidence from ophiolites, blueschists, and ultrahigh-pressure metamorphic terranes that the modern episode of subduction tectonics began in Neoproterozoic time. *Geology*, *33*(7), 557–560. https://doi.org/10.1130/g21365.1
Sun, S. S., & McDonough, W. F. (1989). Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes. In A. D. Saunders, & M. J. Norry (Eds.), *Magmatism in the ocean basins* (Vol. *42*, pp. 313–345). Geological Society London Special Publications. https://doi.org/10.1144/GSL.SP.1989.042.01.19
Tang, G.-J., Wyman, D. A., Wang, Q., Li, J., Li, Z.-X., Zhao, Z.-H., & Sun, W.-D. (2012). Asthenosphere–lithosphere interaction triggered by a slab window during ridge subduction: Trace element and Sr–Nd–Hf–Os isotopic evidence from Late Carboniferous tholeiites in the western Junggar area (NW China). *Earth and Planetary Science Letters*, *329–330*, 84–96. https://doi.org/10.1016/j.epsl.2012.02.009
Tang, W., Wang, S., Liu, Y., Yao, X., & Li, M. (2020). Origin of Carboniferous intra-oceanic arc granitoids from the eastern Pamir and implications for the Paleo-Tethyan ocean. *Journal of Asian Earth Sciences*, *204*, 104558. https://doi.org/10.1016/j.jseaes.2020.104558
Thorkelson, D. J. (1996). Subduction of diverging plates and the principles of slab window formation. *Tectonophysics*, *255*(1–2), 47–63. https://doi.org/10.1016/0040-1951(95)00106-9
Wang, Y., Qian, X., Cawood, P. A., Liu, H., Feng, Q., Zhao, G., et al. (2018). Closure of the East Paleotethyan Ocean and amalgamation of the Eastern Cimmerian and Southeast Asia continental fragments. *Earth-Science Reviews*, *186*, 195–230. https://doi.org/10.1016/j.earscirev.2017.09.013
Wu, C., Chen, H., Hollings, P., Xu, D., Liang, P., Han, J., et al. (2015). Magmatic sequences in the Halasu Cu Belt, NW China: Trigger for the Paleozoic porphyry Cu mineralization in the Chinese Altay–East Junggar. *Ore Geology Reviews*, *71*, 373–404. https://doi.org/10.1016/j.oregeorev.2015.06.017
Xiao, W. J., Windley, B. F., Chen, H. L., Zhang, G. C., & Li, J. L. (2002). Carboniferous-Triassic subduction and accretion in the western Kunlun, China: Implications for the collisional and accretionary tectonics of the northern Tibetan Plateau. *Geology*, *30*(4), 295–298. https://doi.org/10.1130/0091-7613(2002)030<0295:ctsaai>2.0.co;2
Xu, Z., Qi, X., Liu, F., Yang, J., Zeng, L., & Wu, C. (2005). A New Caledonian Khondalite Series in West Kunlun, China: Age Constraints and Tectonic Significance. *International Geology Review*, *47*(9), 986–998. https://doi.org/10.2747/0020-6814.47.9.986
Yang, W., Liu, L., Cao, Y., Wang, C., He, S., Li, R., & Zhu, X. (2010). Geochronological evidence of Indosinian (high-pressure) metamorphic event and its tectonic significance in Taxkorgan area of the Western Kunlun Mountains, NW China. *Science China Earth Sciences*, *53*(10), 1445–1459. https://doi.org/10.1007/s11430-010-4081-1
Yin, A., & Harrison, T. M. (2000). Geologic evolution of the Himalayan-Tibetan Orogen. *Annual Review of Earth and Planetary Sciences*, *28*(1), 211–280. https://doi.org/10.1146/annurev.earth.28.1.211
Yin, J., Xiao, W., Sun, M., Chen, W., Yuan, C., Zhang, Y., et al. (2020). Petrogenesis of Early Cambrian granitoids in the western Kunlun orogenic belt, Northwest Tibet: Insight into early stage subduction of the Proto-Tethys Ocean. *GSA Bulletin*, *132*(9–10), 2221–2240. https://doi.org/10.1130/b35408.1
Yuan, C., Sun, M., Zhou, M.-f., Zhou, H., Xiao, W.-j., & Li, J.-l. (2002). Tectonic Evolution of the West Kunlun: Geochronologic and Geochemical Constraints from Kudi Granitoids. *International Geology Review*, *44*(7), 653–669. https://doi.org/10.2747/0020-6814.44.7.653
Zanchi, A., Poli, S., Fumagalli, P., & Gaetani, M. (2000). Mantle exhumation along the Tirich Mir Fault Zone, NW Pakistan: Pre-mid-Cretaceous accretion of the Karakoram terrane to the Asian margin. *Geological Society, London, Special Publications*, *170*(1), 237–252. https://doi.org/10.1144/gsl.Sp.2000.170.01.13
Zhai, Q.-G., Wang, J., Hu, P.-Y., Lee, H.-Y., Tang, Y., Wang, H.-T., et al. (2018). Late Paleozoic granitoids from central Qiangtang, northern Tibetan plateau: A record of Paleo-Tethys Ocean subduction. *Journal of Asian Earth Sciences*, *167*, 139–151. https://doi.org/10.1016/j.jseaes.2017.07.030
Zhang, C.-L., Zou, H.-B., Ye, X.-T., & Chen, X.-Y. (2018). Tectonic evolution of the NE section of the Pamir Plateau: New evidence from field observations and zircon U-Pb geochronology. *Tectonophysics*, *723*, 27–40. https://doi.org/10.1016/j.tecto.2017.11.036
Zi, J.-W., Cawood, P. A., Fan, W.-M., Tohver, E., Wang, Y.-J., McCuaig, T. C., & Peng, T.-P. (2013). Late Permian-Triassic magmatic evolution in the Jinshajiang orogenic belt, SW China and implications for orogenic processes following closure of the Paleo-Tethys. *American Journal of Science*, *313*(2), 81–112. https://doi.org/10.2475/02.2013.02